STUDY OF RUBBER DAMPED SKIN FRICTION GAGES FOR TRANSONIC FLIGHT TESTING

by

Alexander K. Sang

Master's Thesis Submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Aerospace Engineering

(APPROVED)

Dr. J. A Schetz, Chairman

Dr. B. Grossman

Dr. W. Pulliam

February, 2001

Blacksburg, VA

Keywords: Skin Friction, Aerodynamics, Rubber, Damping, Flight testing

Copyright 2001, Alexander K. Sang
Study of Rubber Damped Skin Friction Gages for Transonic Flight Testing

Alexander K. Sang

(ABSTRACT)

A non-intrusive direct-measuring skin friction device with a rubber RTV sheet over the surface of the floating head, gap and housing was developed for application in 3D, unsteady, transonic flight conditions. Design conditions required optimum gage performance at altitudes ranging from 15,000 to 45,000 feet, Mach numbers ranging from 0.6 to 0.99 resulting in shear values of 0.3 to 1.5 psf. under vibration conditions up to 8.0 g_{rms} over a 15 - 2,000 Hz frequency range. The gage consisted of a rubber RTV sheet-coated floating element attached to an aluminum cantilevered beam. A dual-axis, full bridge strain gage configuration was used with the application of semi-conductor strain gages to increase instrument sensitivity. The gage was studied with and without a viscous liquid (glycerin) fill in the housing.

Vibration verification testing was performed at 1.0 g_{rms} in the Virginia Tech modal analysis lab to ensure adequate damping performance over a 0 –3200 Hz frequency range. Tests revealed that the rubber RTV compound sheet provided adequate viscoelastic damping, with or without viscous liquid fill.

Gage performance verification testing was performed on in the Virginia Tech supersonic wind tunnel at shear levels of \( \tau_w = 3.9 \) to 5.3 psf in a Mach 2.4 flow. Skin friction values in good agreement with previous testing and analytical predictions were obtained from the tests with adequate damping in the low vibration environment of the
Virginia Tech supersonic wind tunnel. The gage proved robust as it survived repeated runs including the violent start and unstart processes typical of a supersonic, blowdown wind tunnel.

Flight tests were performed at NASA Dryden Flight Research Center, with the gage mounted in a plate suspended below an F-15 aircraft. This provided a mildly 3D, turbulent boundary layer on a vibrating surface. The gage was tested without liquid fill in the gage cavity, and it performed satisfactorily in this high vibration environment. The gage demonstrated adequate damping and good robustness, surviving the complete flight test intact and remained fully operational. The sensor measured skin friction values 30%-50% higher than those predicted by indirect methods and analogies generally valid for 2D, steady flows. The gage indicated trends in skin friction values for different flight conditions in good agreement with the other methods. Possible reasons for the differences in numerical values are discussed in detail, including potential uncertainties in the gage output and limitations and uncertainties in the methods used for comparison. Finally, suggestions for further development of such gages are provided for flight test applications.
ACKNOWLEDGEMENTS

I would like to thank God for giving me the opportunity for pursuing this degree. I extend my gratitude to Dr. J. Schetz for believing in me and providing the necessary support to accomplish this work. I am grateful for the opportunity to work on this project.

Next, I would like to thank prior members of the skin friction research group; Samantha Magill, Alexander Remington and Yuri Bezuidenhout, individuals who helped to contribute to this work through suggestions and guidance. I would like to recognize the contributions current members of the research group, Ted B. Smith, Matthew MacLean and Wade Pulliam, who not only have been my research partners, but my friends.

I extend my gratitude to Bruce Stanger, Kent Morris, and Greg Dudding, the department machinists and Gary Stafford, the electronics technician, individuals whose technical expertise made this research possible.

I would like to recognize the African crew, specifically Ben Tatuo and Steve Ondiek who made life in "the burg" enjoyable. I thank Lance Jacobsen, Bebago Lugogo and Abayomi Jemibewon, for being my best friends from undergraduate through graduate studies.

I extend my gratitude to Dr. Trong Bui at NASA Dryden, for his advice and help. Thank you for helping the flight tests proceed smoothly.

I thank my American family; Dr. J. Schultz, Patricia K. Schultz, Christopher, Francie and Joanna. Thank you for hosting me through the first few years of my stay in the United States. I would like to thank Sheri Jennings and Ezra Mereng for their continued support, friendship and companionship. I extend my gratitude to my African
family, Prof. Sang, Mrs. Mary Sang, Rispah, Monica, Kigen, my nephews and niece for providing me with both financial and emotional support.

God bless you all!

NASA Flight Research Center, California and Luna Innovations supported this project.

Thank you.
This work is dedicated to everyone who believed in me
- Alexander K. Sang
## TABLE OF CONTENTS

(ABSTRACT)..................................................................................................................... II

ACKNOWLEDGEMENTS ....................................................................................................... III

TABLE OF CONTENTS ........................................................................................................... VI

NOMENCLATURE ................................................................................................................. VIII

LIST OF TABLES .................................................................................................................. XII

1 INTRODUCTION................................................................................................................. 1

1.1 BACKGROUND................................................................................................................. 1
1.2 SKIN FRICTION DRAG ...................................................................................................... 2
1.3 MEASURING TECHNIQUES .............................................................................................. 6
  1.3.1 Indirect Techniques................................................................................................... 8
  1.3.2 Direct Techniques .................................................................................................. 11
1.4 PURPOSE OF THIS STUDY .............................................................................................. 15
  1.4.1 Damping Methods.................................................................................................... 15
    1.4.1.1 Active Damping ............................................................................................... 15
    1.4.1.2 Passive Damping ............................................................................................ 17
1.5 NASA FLIGHT TEST REQUIREMENTS .......................................................................... 18
  1.5.1 Overview................................................................................................................. 18
  1.5.2 Test bed .................................................................................................................. 18
  1.5.3 Requirements......................................................................................................... 20
  1.5.4 Approach................................................................................................................. 21

2 SKIN FRICTION GAGE ................................................................................................... 24

2.1 OVERVIEW ..................................................................................................................... 24
2.2 GAGE DESCRIPTION .................................................................................................... 25
  2.2.1 Sensing Head .......................................................................................................... 25
  2.2.2 Flexure and Base .................................................................................................. 25
  2.2.3 Gage Housings....................................................................................................... 27
  2.2.4 Connector................................................................................................................. 29
  2.2.5 Gage Electronics.................................................................................................... 30

3 GAGE PREPARATION..................................................................................................... 33

3.1 PROBLEMS ENCOUNTERED WHILE USING THE RUBBER RTV ................................. 33
3.2 PREPARATION OF SILICONE RUBBER SHEET........................................................... 37
3.3 GLYCERIN FILLING PROCEDURE. ............................................................................... 41

4 CALIBRATION TECHNIQUES ...................................................................................... 45

4.1 POINT LOADING METHOD .......................................................................................... 45
4.2 DISTRIBUTED SHEAR METHOD .................................................................................. 46
4.3 AREA RATIO................................................................................................................. 47
4.4 GAGE CALIBRATION ................................................................................................... 49
  4.4.1 Gage Sensitivity Results ......................................................................................... 49
  4.4.2 Point load and Distributed Shear Calibration Results ............................................ 51
  4.4.3 Temperature Calibration Results ............................................................................ 53
NOMENCLATURE

A  Area
A\text{GAP}  Gap Area
A\text{HEAD}  Head Area
A_{\text{RATIO \ eff}}  Effective Area Ratio
A_{\text{RATIO \ giz}}  Geometric Area Ratio
B  y intercept
C_f  Skin Friction Coefficient
C_p  Specific heat of the material
D\text{VOUT}  Voltage output from Distributed Shear method
E  Modulus of Elasticity
E_o  Output Voltage
E_i  Excitation Voltage
F  Frequency
G  Gravity
GF  Gage Factor
h  height
K  conversion factor
L  length
M  Mass
P_0  Total Pressure
P_s  Static Pressure
Pr  Prandtl number
PES  Polyethersulfone
psf  Pounds per square foot
PV_{OUT}  Voltage output from Point Loading method
\dot{Q}_{\text{cond,wall}}  Rate of conduction heat transfer
q  Dynamic Pressure
R  Resistance
Re  Reynolds number
S  slope
St  Stanton number
T  Temperature
U_e  Edge velocity
u^*  Friction Velocity
V  Velocity
V  Voltage
x  Axial distance
y  Normal Distance from Wall
z  Vertical distance from Wall
\Delta R  Change in Resistance

**Greek**

\alpha  Thermal diffusivity
\epsilon  Strain
\mu  Dynamic Viscosity
\rho  Material Resistivity, Material density
\tau_w  Wall Shear Stress
\nu  Kinematic Viscosity
LIST OF FIGURES

Figure 1.1: A Flow Analysis on an Arterial System Incorporated with a by-pass............. 2
Figure 1.2: Smoke Photograph of a Low Speed Flow over an Airfoil............................ 3
Figure 1.3: Boundary Layer Profile ............................................................................. 4
Figure 1.4: Defect Law Plot of Turbulent Velocity Profiles ......................................... 6
Figure 1.5: Measurement Apparatus used by Froude .................................................... 7
Figure 1.6: Stanton Tube Method ............................................................................... 9
Figure 1.7: Various Indirect Calibration Techniques .................................................. 10
Figure 1.8: The First Successful Skin Friction Gage built by Dhawan ......................... 11
Figure 1.9: A basic Non-nulling beam design concept used at Virginia Tech............. 13
Figure 1.10: Active Damping Application Techniques .............................................. 16
Figure 1.11: F-15B Mounted With the FTF-II On Its Centerline ............................... 19
Figure 1.12: NASA Flight Test Fixture II ................................................................... 19
Figure 1.13: Random Vibration Test Curves .............................................................. 20
Figure 1.14: Wall Shear levels for Selected flight Conditions using the Clauser Plot Method ........................................................................................................... 21
Figure 1.15: Illustration of Skin Friction Gage With a Rubber Filled Internal Volume. 22
Figure 1.16: Beam Flexure with Rubber RTV Sheet .................................................. 23
Figure 2.1: Skin Friction Sensing Head, Flexure and Base .......................................... 26
Figure 2.2: Aluminum Housing ............................................................................... 28
Figure 2.3: Plastic Housing ....................................................................................... 28
Figure 2.4: Gage Assembly Drawing ........................................................................ 29
Figure 2.5: A Magnification of the Aluminum Flexure with A Pair of Strain Gages Attached ................................................................. 30
Figure 2.6: Skin Friction Gage Pin Circuitry and Pin labeling .................................... 32
Figure 3.1: Grooved Bonding Surface of Outer Housing .......................................... 34
Figure 3.2: Demonstration of the Results of the Previous and Current Rubber RTV Preparation Techniques .............................................................. 34
Figure 3.3: Gage adapter used in Securing Skin Friction Gage to Drilling Machine...... 36
Figure 3.4: Thermocouple bead in the gap between Plastic Housing and Sensing Head .36
Figure 3.5: RTV preparation technique diagram ....................................................... 39
Figure 3.6: Preparation of Rubber Sheet on Drill press ............................................. 40
Figure 3.7: Trimmed surface of Skin Friction Gage .................................................... 41
Figure 3.8: Gage preparation for glycerin filling ......................................................... 42
Figure 3.9: Illustration of Filling of Gage with Glycerin ............................................. 44
Figure 4.1: Point Load Calibration On Skin Friction Gage ......................................... 46
Figure 4.2: Area Ratio concept ............................................................................... 47
Figure 4.3: Gage Sensitivity Comparison WITHOUT the use of the gage adapter.... 50
Figure 4.4: Gage Sensitivity Comparison WITH the use of the gage Adapter .......... 50
Figure 4.5: Calibration Curve of Gage#S2 without the rubber RTV ......................... 51
Figure 4.6: Calibration Curve of Gage#S2 with the rubber RTV ............................... 52
Figure 4.7: Distributed Shear Calibration Results From Calibration Rig .................. 52
Figure 4.8: Temperature Profiles for Room Temperature Flow Calibration ............. 54
Figure 4.9: Temperature Profiles for Cooled Flow Calibration ................................. 54
Figure 4.10: Temperature Profiles for Heated Flow Calibration ...................................... 55
Figure 4.11: Calibration Results at Various Flow Temperatures................................. 55
Figure 4.12: Collapsed Calibration Curves using Temperature Compensation Routine. . 56
Figure 5.1: Schematic of the Calibration Rig............................................................... 58
Figure 5.2: Photograph of the Calibration Rig System................................................... 59
Figure 5.3: Pressure Transducers used in Calibration Rig ............................................ 60
Figure 5.4: Sample Pressure Distribution Curve of Calibration Rig............................ 61
Figure 5.5: Schematic of the Vibration Experimental Setup. ......................................... 62
Figure 5.6: Schematic of the Supersonic Wind tunnel.................................................. 63
Figure 5.7: Wall Mounting Test plate For Skin Friction Gage ........................................ 65
Figure 5.8: Flight-test Fixture Schematic........................................................................ 67
Figure 5.9: Preparation of the F-15B for the Flight Test ............................................. 68
Figure 5.10: Frequency Response of Skin Friction Gage ............................................. 70
Figure 5.11: Phase Response of Skin Friction Gage...................................................... 70
Figure 5.12: Coherence of Frequency Response Functions........................................... 71
Figure 5.13: Frequency Response Function With and Without Glycerin....................... 73
Figure 5.14: X-Axis Acceleration Loads During Wind Tunnel Run............................... 75
Figure 5.15: Y Axis Acceleration Loads During Wind Tunnel Run............................... 75
Figure 5.16: Z- Axis Acceleration Loads During Wind Tunnel Run.............................. 76
Figure 5.17: Wind Tunnel Test Run 01, Gage S2.......................................................... 77
Figure 5.18: Temperature Effect on Output for Gage S2.............................................. 78
Figure 5.19: Wind Tunnel Test Run 02, Gage S2.......................................................... 80
Figure 5.20: Wind Tunnel Test Run 03, Gage S2.......................................................... 80
Figure 5.21: Wind Tunnel Test Run 04, Gage S2.......................................................... 81
Figure 5.22: Wind Tunnel Test Run 03, Gage S3.......................................................... 82
Figure 5.23: Wind Tunnel Test Run 02, Gage S3.......................................................... 83
Figure 5.24: Close-up of aluminum skin friction sensor complex on FTF-II .................... 85
Figure 5.25: CAD drawing of the Skin Friction Sensor Complex................................... 85
Figure 5.26: Co-ordinate System used in data presentation.......................................... 86
Figure 5.27: Flight test Profile ..................................................................................... 87
Figure 5.28: Pressure Profile during Flight Test ............................................................ 87
Figure 5.29: Temperature Profile during Flight Test .................................................... 88
Figure 5.30: Gage Skin Friction Results During Flight Test.......................................... 90
Figure 5.31: Comparison of Shear Values of Various Measuring Techniques .................. 92
Figure 5.32: Flow Visualization of The FTF-II Using Tufts [22].................................... 94
Figure 5.33: Acceleration load effects on gage output................................................. 95
LIST OF TABLES

Table 1.1: Summary of Viscous Drag Components of Various Systems [4] .................. 3
Table 1.2: Advantages and Disadvantages of Skin Friction Measurement Techniques .. 14
Table 5.1: Technical Specification of the Wind Tunnel ........................................ 65
Table 6.1: Comparison of Natural Frequency Modes at Different gage states ............ 73
Study Of Rubber Damped Skin Friction Gages For Transonic Flight Testing.

1 INTRODUCTION

1.1 Background

In order to determine and maximize the efficiency of any fluid machinery device, the knowledge and quantification of the resistance to the fluid motion in the system is essential. This resistance is commonly known as drag [1]. Drag can be sub-divided into two categories, pressure drag and skin friction drag. Pressure drag is mainly a consequence of fluid separation from the surface causing a pressure imbalance. Skin friction drag is a direct result of viscous interaction of the fluid with the surface in contact. This occurs in a layer adjacent to the body known as the boundary layer [2].

Quantifying drag is vital to the economics of any system. This is well illustrated in a fuel pipeline, where a loss in head pressure due to frictional drag requires the installation of booster stations between the origin and destination. Clearly, the greater the number of stations, the more the operation costs. Hence, a better understanding of the skin friction involved will help minimize this cost by putting an optimum number of booster stations at necessary locations. Frictional drag also affects fluid flow in the human body. The arterial system of the human body is plagued by reduced blood flow due to diseases such as arteriosclerosis or the buildup of arterial plaque. A flow analysis of a partially clogged arterial system with the incorporation of a by-pass channel can be conducted to provide the necessary relief that could possibly prevent a patient from having a potentially fatal heart attack [3]. Figure 1.1 is a computer-generated graphic that illustrates the flow gradient in an arterial system described above.
1.2 Skin Friction Drag

Skin friction drag can account for more than half of the total drag in an aero-hydrodynamic system. As illustrated in Table 1.1, viscous losses could be as high as 90% of the total drag. It is, therefore, necessary to have an understanding of skin friction so as to improve or otherwise make a design economically viable.

Viscous losses depend largely on the operating speed and surface condition of the craft. For example, a rough surface can give rise to a turbulent boundary layer, which leads to an increased loss in momentum in the flow field relative to a laminar boundary layer [4]. A turbulent boundary layer can also form on a smooth surface as velocity increases. A flow is considered completely turbulent when the Reynold's number is above about $10^6$. This is well demonstrated in Figure 1.2, where the boundary layer starts as
laminar over the airfoil surface. As the velocity increases, the boundary layer transitions to turbulent.

Table 1.1: Summary of Viscous Drag Components of Various Systems [4]

<table>
<thead>
<tr>
<th>AERO-HYDRODYNAMIC SYSTEM</th>
<th>PERCENTAGE OF VISCOUS DRAG TO OVERALL DRAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPER SONIC FIGHTER</td>
<td>25-30%</td>
</tr>
<tr>
<td>LARGE TRANSPORT AIRCRAFT</td>
<td>40%</td>
</tr>
<tr>
<td>EXECUTIVE AIRCRAFT</td>
<td>50%</td>
</tr>
<tr>
<td>VTOL AIRCRAFT</td>
<td>70 - 80 %</td>
</tr>
<tr>
<td>UNDER WATER BODIES</td>
<td>70%</td>
</tr>
<tr>
<td>SHIPS AT LOW/HIGH SPEEDS</td>
<td>90 - 30%</td>
</tr>
<tr>
<td>GAS PIPELINES</td>
<td>90%</td>
</tr>
</tbody>
</table>

Figure 1.2: Smoke Photograph of a Low Speed Flow over an Airfoil [5]
Skin friction is expressed as the viscous force per unit area, commonly known as the wall shear stress, $\tau_w$. An expression for shear stress in a Newtonian laminar flow is:

$$\tau_w = \mu \left( \frac{\partial u}{\partial y} \right)_{wall},$$  \hspace{1cm} (1)

where $\mu$ is the viscosity, $\frac{\partial u}{\partial y}$ is the velocity gradient at the wall [6]. The variation of the tangential velocity in a boundary layer is clearly depicted in Figure 1.3. The velocity starts from a finite value and diminishes to zero at the surface interface. As shall be seen later, the wall shear stress is a key component in turbulence modeling.

Figure 1.3: Boundary Layer Profile [7]

Skin friction is usually represented as a coefficient $C_f$, which is simply the wall shear stress normalized by the dynamic pressure. It is defined as
\[ C_f = \frac{\tau_w}{\frac{1}{2} \rho U_e^2}, \]  

(2)

where, \( \rho \) is density, and \( U_e \) is the boundary layer edge velocity.

The skin friction coefficient has an important role in turbulent flow analysis through the friction velocity \( u^* \). The friction velocity is derived from the ratio of wall shear stress to flow density as expressed in Equation 3 [1].

\[ u^* = \sqrt{\frac{\tau_w}{\rho}} = U_e \sqrt{\frac{C_f}{2}}, \]  

(3)

where \( U_e \) is the boundary layer edge velocity. Choosing a velocity scaling parameter based on \( u^* \) as displayed in Equation 4 correlates turbulent boundary layer velocity profiles. \( U \) is the streamwise boundary layer velocity component

\[ \frac{U - U_e}{u^*} = f\left(\frac{y}{\delta}\right) \]  

(4 a)

\[ \frac{U}{u^*} = g\left(\frac{yu^*}{v}\right) \]  

(4 b)

Therefore, improved measurements of \( C_f \) through experimentation will lead to increased accuracy of existing numerical codes. Figure 1.4 displays successfully correlated velocity profiles in the outer region of the boundary layer.
1.3 Measuring Techniques

For simple problems such as laminar flow over a flat plate, analytical methods have been applied to exactly solve for the flow solutions. However, for complex flows such as three dimensional, unsteady, and/or turbulent flows, analytical methods are not dependable. This has led to the development of various measuring techniques, which are used for the quantification of skin friction.

The experimental measurement of skin friction has been performed for the past 130 years. The first known measurement was performed by Froude, who towed a series of planks at varying speeds in a water tank [9]. Figure 1.5 illustrates the device he used.
The development of measuring techniques rapidly increased with the advent of transonic and supersonic flight. A detailed history of the development of measurement techniques can be found in Winter [8].

Measurement techniques can be broadly categorized into two groups - direct and indirect methods. Direct methods determine the surface shear without requiring any knowledge of the flow. A non-intrusive floating element measures the tangential force imparted to the fluid on the surface. Indirect methods require some knowledge or assumption of the flow properties such as the surface heat transfer. This is then correlated to shear through analogy or calibration.

![Diagram of Measurement Apparatus used by Froude](image)

**Figure 1.5: Measurement Apparatus used by Froude [8], [9]**
1.3.1 **Indirect Techniques**

There are various procedures for indirectly measuring wall shear. These include, but are not limited to; sub-layer fence, stanton tube, Preston tube, hot wire and laser doppler anemometry. The following discussion will briefly illustrate the methods employed by a few selected techniques.

Two methods that use pressure measurements are the Preston tube and the sub-layer fence. The Preston tube makes use of a Pitot tube on the wall surface to measure dynamic pressure through the laminar sub-layer and the log region of the boundary layer. This is then correlated to shear by the use of the law of the wall [1]. Unlike the Preston tube, the sub-layer fence measures the difference in pressure across a screen within the laminar sub-layer. Shear is also determined through the similarity law of the laminar sub-layer. Calibration of the sub-layer fence is difficult due to its physical size. Both the Preston tube and the sub-layer fence are intrusive methods, which disturb the flow and are limited to unheated, two-dimensional, steady flow.

A hot wire measures the velocity profile across the boundary layer, through the heat losses experienced by the wire. This in turn can be related to shear through the law of the wall. However, the hot wire is also an intrusive method, with the same limitations. It is also not physically robust.

The Stanton tube method makes the use of a static pressure port and a razor blade that partially conceals the static pressure port. This is illustrated in Figure 1.6. The razor blade functions as a total pressure port, and by virtue of size, allows pressure readings
much closer to the wall compared to a Preston tube. This intrusive method is primarily used in unheated, steady, two-dimensional flows.

A non-intrusive method is the surface hot film technique, which uses Reynolds analogy to correlate heat transfer to shear. Equation 5 represents Reynolds analogy:

\[ St = Pr^{\frac{1}{3}} \frac{C_f}{2}, \]  

(5)

where St is the Stanton number and Pr is the Prandtl number. The method functions by maintaining a fixed temperature of a sensing element embedded in the surface bounding the flow. The losses through convection, which are proportional to the power input, are calibrated to correspond to shear stress through the above relation. A disadvantage of this method is that flow direction cannot be determined from the obtained measurement results.
A summary of indirect measurement techniques is presented in Figure 1.7 that illustrates the operating principle and calibration methods used for various indirect measuring techniques. Further discussion of such methods can be found in Nitsche et al. [11], from which the diagram below was obtained.

Figure 1.7: Various Indirect Calibration Techniques [11]
1.3.2 Direct Techniques

The underlying principle behind all direct measuring methods is the same. A floating element on a beam or flexure, flush to the bounding surface measures the shear applied by the moving fluid. As a consequence, no prior knowledge of the flow is necessary. The deflection of the floating element is calibrated to correspond with the applied shear stress.

![Diagram of a direct measuring method](image)

**Figure 1.8: The First Successful Skin Friction Gage built by Dhawan [12].**

Generally, direct methods are further sub-divided into two categories - nulling and non-nulling designs. In a nulling design, the shear force in the fluid displaces the floating element mounted in the wall bounding the flow. However, a restoring force, equal to the shear, ensures a zero net displacement of the sensing element. The resulting advantage to
this method is that the flow is not disturbed during testing. However, in order to achieve a zero net displacement, a complex mechanical setup is required, leading to problems with the form and function of the gage. A nulling design was first successfully used by Dhawan [12] for skin friction measurements in the subsonic regime for both laminar and turbulent flows. Figure 1.8 illustrates Dhawan's device that was used in this experiment.

In a non-nulling design, the floating element is slightly displaced by the shear forces in the fluid. A common non-nulling concept uses strain gages at the flexure base. The flexure is designed to have axial stiffness, to minimize normal pressure effects, while being weak to tangential forces, increasing instrument sensitivity to shear forces.

The output from the sensors can be easily calibrated to correspond to shear. The concept can be designed to measure strain in two directions. Such an arrangement can be used to measure skin friction in 3D and/or unsteady flows.

Due to the lack of a restoring mechanism, non-nulling concepts are smaller and simpler in construction, leading to a decrease in time response of the gage. The tilting of the head on the flexure could potentially interfere with the flow due the protrusion of the sensing element into the flow, but with intelligent design, the effects of flow interference by the sensing element can be virtually eliminated. See Figure 1.9.
Figure 1.9: A basic Non-nulling beam design concept used at Virginia Tech

Further information on measuring techniques can be found in Winter [8]. A summary of measuring techniques can be seen in Table 1.2, which was compiled from various literary works and created by Pulliam [10]
## Table 1.2: Advantages and Disadvantages of Skin Friction Measurement Techniques [10]

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Measurements</strong></td>
<td>• Flow and fluid independent</td>
<td>• Small force</td>
</tr>
<tr>
<td><em>(Force)</em></td>
<td>• Able to determine direction</td>
<td>• High cost</td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td></td>
</tr>
<tr>
<td><strong>Semi-Direct Measurements</strong></td>
<td>• Flow condition independent</td>
<td>• Temperature sensitive</td>
</tr>
<tr>
<td></td>
<td>• Provides a global measurement</td>
<td>• Shear stress, shear gradient, time limited</td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td>• Must know flow direction</td>
</tr>
<tr>
<td></td>
<td>• Temperature sensitive</td>
<td>• Requires optical access</td>
</tr>
<tr>
<td>• Oil Film Interferometry</td>
<td>• Flow condition independent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Provides a global measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td></td>
</tr>
<tr>
<td>• Liquid Crystals</td>
<td>• Flow condition independent</td>
<td>• Temperature and pressure sensitive</td>
</tr>
<tr>
<td></td>
<td>• Provides a global measurement</td>
<td>• Requires optical access</td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td>• Low sensitivity</td>
</tr>
<tr>
<td><strong>Indirect Measurements</strong></td>
<td>• Flow condition independent</td>
<td>• Limited time window</td>
</tr>
<tr>
<td></td>
<td>• Provides a global measurement</td>
<td>• Shear stress limited</td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td></td>
</tr>
<tr>
<td>• Analogy</td>
<td>• Dual purpose sensor</td>
<td>• Low precision measurement</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td>• Not able to determine direction</td>
</tr>
<tr>
<td></td>
<td>• High frequency response</td>
<td>• Limited temperature range with high temperature sensitivity</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td>• Requires knowledge of freestream</td>
</tr>
<tr>
<td>• Heat Transfer</td>
<td>• Low cost</td>
<td>• Calibration not available</td>
</tr>
<tr>
<td><em>(Reynolds Analogy)</em></td>
<td>• Dual purpose sensor</td>
<td>• Low precision measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Not able to determine direction</td>
</tr>
<tr>
<td>• Mass Transfer</td>
<td>• Low cost</td>
<td>• Limited temperature range with high temperature sensitivity</td>
</tr>
<tr>
<td>• Flow About Obstacles</td>
<td>• Simple</td>
<td>• Requires knowledge of freestream</td>
</tr>
<tr>
<td>• Sub-Layer Fence</td>
<td>• Low cost</td>
<td></td>
</tr>
<tr>
<td>• Stanton Tube</td>
<td>• Simple</td>
<td>• Susceptible to misalignment</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td>• Assumes Law of the wall</td>
</tr>
<tr>
<td>• Profile Measurement</td>
<td>• Simple</td>
<td>• Requires knowledge of boundary layer conditions</td>
</tr>
<tr>
<td>• Preston Tube</td>
<td>• Low cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Flow calibration required</td>
<td>• Assumes Law of the wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Boundary layer thickness limited</td>
</tr>
<tr>
<td>• Hot-Wire</td>
<td>• Provides high frequency data</td>
<td>• Requires knowledge of boundary layer conditions</td>
</tr>
<tr>
<td></td>
<td>• Simple</td>
<td>• Assumes Law of the wall</td>
</tr>
<tr>
<td>• Laser Doppler Anemometry</td>
<td>• Provides high frequency data</td>
<td>• Fragile and temperature limited</td>
</tr>
<tr>
<td></td>
<td>• Non-intrusive</td>
<td>• Requires knowledge of fluid viscosity</td>
</tr>
<tr>
<td></td>
<td>• Requires optical access</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Requires seed particles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Requires knowledge of fluid viscosity</td>
<td></td>
</tr>
</tbody>
</table>
1.4 Purpose of this Study

The purpose of this investigation was to develop a non-intrusive skin friction-sensing device for high vibration and gravity loads without compromising the resolution of the data acquired. This new concept was needed to alleviate problems encountered by existing sensors under such conditions. To meet this goal, various damping techniques had to be studied and applied in the design of skin friction gage. Below is a brief description of damping techniques that have been used in previous skin friction sensors.

1.4.1 Damping Methods

Damping refers to the dissipation of vibrational energy in a system. All physical systems have intrinsic damping. However, due to the use of the system, damping may need to be augmented to increase energy dissipation. Two methods of damping are currently in use: active damping and passive damping.

1.4.1.1 Active Damping

Active damping methods use devices such as actuators or electro-magnets to exert a force that opposes the motion of the system resonance. This force is constantly modified to respond to the changing vibration environment. This method is complex and involves the use of a feedback or feed-forward system.

1.4.1.1.1 Feedback system

In the presence of a disturbance, a feedback system attempts to reduce the difference between the system output and reference input by passing the measured difference through a compensator that applies a corrective force to the system. The compensator is selected by determining the frequency response of the system.
experimentally or mathematically such that the closed loop system is stable [13], [14], [15]. However, feedback systems are only effective near system resonant peaks. Figure 1.9 illustrates the operation of a feedback system.

![Feedback System Diagram](image)

**Figure 1.10: Active Damping Application Techniques [16].**

1.4.1.1.2 Feed-forward System

Unlike a feedback system, a feed-forward approach passes the reference input signal through an adaptive filter, which produces an output of that is applied to the system by secondary sources. The idea is the production of a secondary disturbance that is applied to the system such that it cancels the effect of the primary disturbance at the location of the sensor. A major limitation to a feed-forward adaptive filtering is finding the appropriate reference signal correlated to the disturbance [16], [17].
1.4.1.2 Passive Damping

Passive damping methods include the use of viscoelastic materials, tuned mass dampers, magnetic dampers, coulomb damping and viscous damping. Viscoelastic materials are commonly used to coat systems at points of high strain energy. This results in minimal change in the existing system and is robust and reliable. However, materials used for such damping are temperature dependent. A tuned mass damper absorbs energy at a single vibration mode. This proves to be a limitation in a system experiencing a wide band of vibration. Magnetic dampers convert the motion of the system into heat energy through the eddy currents induced by the system as it oscillates between the poles of the magnet. However, for high vibrational loads, the size of magnets needed to absorb sufficient amounts of energy becomes a limitation. A possible solution to this problem is the use of electro-magnets, a procedure that has been investigated with some success by Remington at Virginia Tech [18]. It could not provide sufficient damping for a very high vibration flight environment.

The most common method of damping is viscous damping. This is caused by energy losses that occur in liquid lubrication surrounding the vibrating object. The friction the vibrating object experiences as it moves through the fluid generates the viscous force, which is proportional to the velocity [19]. Viscous damping has been the method of choice in the design of many current skin friction gages [20].
1.5 NASA Flight Test Requirements

1.5.1 Overview

In order for the skin friction gage to be available as a measuring instrument, it needed to be able to perform favorably in a very high vibration flight test environment. This would expose the gage to high gravity and vibration loads, including both temperature and pressure effects due to changes in altitude. NASA has set guidelines for the evaluation of instruments intended for use in the flight research test bed. These tests would ensure that the measuring device and the associated electronics meet the environmental and vibration requirements set forth.

1.5.2 Test bed

The test vehicle intended for the evaluation of the skin friction gage is the F-15B. See Figure 1.11. A Flight Test Fixture (FTF II) 107 in. long and 32 in. high, is mounted on the centerline of the aircraft. It has three rows of Richwine static pressure taps along its face with a boundary layer trip located 6.42 inches from the leading edge. The skin friction gage is mounted flush to the FTF II fixture surface. Figure 1.12. Illustrates the layout of the FTF II [21], [22]. Further description of the test bed will be presented in Section 4.4 of this document.
Figure 1.11: F-15B Mounted With the FTF-II On Its Centerline [23]

Figure 1.12: NASA Flight Test Fixture II
1.5.3 Requirements

According to NASA Specifications, the gage would be subject to Category II testing requirements (turbojet powered aircraft tests) [24]. These requirements stipulated that a random vibration test equivalent to \(8.0\text{g}_{\text{rms}}\) at a frequency range of 15 - 2000 Hz be performed. This is represented by curve A in Figure 1.13.

![Random Vibration Test Curves](image)

**Figure 1.13: Random Vibration Test Curves [24].**

The flights test are to be conducted at transonic speeds at altitudes ranging from 15,000 - 45,000 feet, corresponding to a shear range of 0.3 to 1.45 pounds per square foot.
(psf) as illustrated in Figure 1.12. Further information regarding the flight test requirements can be found in NASA ADFRF Process Specification No. 21-2 [24].

**Figure 1.14: Wall Shear levels for Selected flight Conditions using the Clauser Plot Method [22]**

### 1.5.4 Approach

After the analysis of several damping methods, it was decided to employ visco-elastic damping through the use of a rubber RTV sheet on the gage surface. Viscous damping through the use of silicone oil would provide further damping. Previous skin friction gages at Virginia Tech used viscous damping due to several inherent advantages [20]. By filling the volume around the sensing head and flexure, pressure gradient effects are eliminated. The fluid also acts as a temperature stabilizer, minimizing the temperature gradients that the gage is exposed to during the flight test as will be
demonstrated in a chapter 6 of this document. However, gages that previously employed this method of damping deteriorated with time due to fluid loss through the small gap around the sensing element.

A proposed solution to this problem was to fill the gap with a substance that would check this flow. Previous studies had tried using silicone rubber in the entire inner volume of the gage, but loss in gage resolution due to increased resistance forces limited further development [25].

Figure 1.15: Illustration of Skin Friction Gage With a Rubber Filled Internal Volume [25]
A study showed that a rubber RTV compound used to cover the sensing element and gap with a thin sheet as illustrated in Figure 1.16 could be a possible solution [26]. The apparent advantage of this method was that fluid could be retained in the gage cavity, thus keeping the inherent benefits while eliminating the maintenance requirements. However, several aspects need further investigation, including, but not limited to, RTV adhesion characteristics, trapped air in the fluid volume and the scaling of the design to meet sensitivity requirements of this study.

![Figure 1.16: Beam Flexure with Rubber RTV Sheet](image)

This study was performed to help the successful integration of a rubber RTV compound sheet into a skin friction design capable of meeting the NASA flight test requirements.
2 SKIN FRICTION GAGE

In this chapter, a detailed description of the skin friction gage will be given with insight into the material selection process of each component. Information on the gage circuitry will be presented with a brief introduction to the underlying working principles of a strain gage.

2.1 Overview

In order to meet the vibration requirements, a primarily viscoelastic damping method was employed on a non-nulling gage design. RTV 566, a rubber compound obtained from GE Silicones [27] was applied on the gage surface to contain the fluid. In some cases, glycerin was used to fill the inner volume of the gage to provide additional viscous damping. This development was a result of previous studies at Virginia Tech [26]. Several benefits were realized by the use of this compound. In addition to containing the fluid, it provided sufficient damping, minimizing the need for the use of a fluid in the volume cavity. This benefit has allowed the investigation of possible use of fiber optic displacement sensors in future skin friction gage designs.

The use of the rubber compound presented new challenges as well. First, the RTV did not bond well to materials such as aluminum despite the use of a metal primer. It was suspected that an oxide layer formed on the aluminum surface preventing adhesion. However, the RTV compound successfully bonded to polyethersulfone (PES), a high temperature plastic. Second, the RTV sheet reduced gage sensitivity. This sensitivity reduction was aggravated by accumulation of the compound in the gap
between the sensing head and plastic housing, requiring the modification of the procedure used in the application of the rubber RTV compound onto the gage surface.

In order to improve gage sensitivity, a full-bridge circuit was used with semiconductor strain gages mounted on the base of the flexure. To account for temperature effects, two thermocouples were integrated into the design to monitor the strain gage and the rubber RTV temperature. Further discussion on the issue will be presented in Section 3.1.

2.2 Gage Description

The skin friction gage used in this study consisted of six components; a sensing head, flexure, base, upper housing, lower housing and the connector.

2.2.1 Sensing Head

The sensing head was made of polyethersulfone (PES). This reduced mass compared to a metal head and aided in bonding the rubber sheet. It had a head diameter of 0.75 inches. This was chosen in conjunction with the flexure described below to meet the design shear levels. The primary feature of the component was its form as a truncated cone with tapered edges from the bottom, a quality that reduced the entrapment of air bubbles during the filling of the volume cavity. A 0.25 inch threaded hole allowed for the fastening of the component to the flexure.

2.2.2 Flexure and Base

The flexure, made of aluminum, had a shaft of length 1.5375 inches and a diameter of 0.15 inches based on a comparative sizing study. Aluminum was chosen because of its low density, which reduced vibration effects. The high heat conductivity
of aluminum would act as a heat sink for the semi-conductor strain gages, which are temperature sensitive. To account for temperature effects on the strain gages, a type K thermocouple was buried into an opening created at the center of the flexure.

Micron Instruments installed a matched set of eight SS-060-033-500P-S(4) semi-conductor strain gages on the base of the flexure. These allowed for the data acquisition on two perpendicular axes, a trait necessary in measuring skin friction in a 3D-flow regime. An illustration of the sensing element, flexure and base can be seen in Figure 2.1.

![Skin Friction Sensing Head, Flexure and Base](image)

Figure 2.1: Skin Friction Sensing Head, Flexure and Base
A primary goal in the gage design was robustness. This would increase the effective life of the gage. To achieve this, protection of the strain gages was necessary. The first step was the introduction of a 10-pin connector that isolated the gage wiring from the data acquisition equipment. Next, solder pads located on the base were used to isolate the delicate strain gage wires from the wire leads from the connector. Further, the wires were looped around to provide strain relief and anchored to the base via epoxy. The base had two oil fill holes that allowed the filling of the inner cavity. See Figure 2.1.

2.2.3 Gage Housings

A two-piece housing was used in the skin friction gage design. The bottom piece was constructed of aluminum and housed the beam and sensing element. To improve the design robustness, a deflection constraint was incorporated into the top surface of the aluminum housing. PES was the material of choice for the top piece of the housing. This allowed for easier application of the rubber compound onto the gage surface. Further detail on the gage housings can be obtained from Figures 2.2 and 2.3.
Figure 2.2: Aluminum Housing

Figure 2.3: Plastic Housing
2.2.4 Connector

A 10-pin plug connector, supplied by SpaceCraft Components Corporation [28], was used to interface the skin friction gage with the data acquisition equipment. Each bridge circuit used four pins from the connector. The remaining two pins, made of chromel and alumel were used for the thermocouple buried in the flexure. A matching socket was used to route the wires to the data acquisition equipment. Figure 2.6 illustrates the pin labeling of the connector. The connector was secured to the base of the flexure base as demonstrated by Figure 2.4.

Figure 2.4: Gage Assembly Drawing
2.2.5 Gage Electronics

In a full-bridge circuit, all four strain gages in the Wheatstone bridge are placed on the base of the cantilever beam as illustrated in Figure 1.9. In each axis, a strain gage pair with the same vertical alignment is placed in the tensile region while a similarly aligned pair is placed in the compressive region $180^\circ$ from the first pair. For a dual-axis scheme, a similar strain gage layout is done perpendicular to the primary axis. Figure 2.5 displays a strain gage pair attached to the base of the aluminum flexure.

![Figure 2.5: A Magnification of the Aluminum Flexure with A Pair of Strain Gages Attached](image)

Strain gages are elements that convert strain into electrical output through change in resistance. A change in length in the conducting wire inside the strain gage causes a resistance change based on Equation 6:

$$ R = \frac{\rho L}{A} $$

(6)
where $R$ is the nominal strain gage resistance, $\rho$ is the material resistivity, $L$ is the length and $A$ is the cross-sectional area of the conducting wire. A linear relationship between strain and the resistance change is illustrated in Equation 7:

$$\varepsilon = \frac{1}{GF} \frac{\Delta R}{R} \quad (7)$$

where $\varepsilon$ is the strain, $GF$ is the gage factor and $\Delta R$ is the resistance change. $R$ and $GF$ are both provided by the manufacturer. In this study, the semi-conductor strain gages had a nominal resistance of $550 \pm 50 \, \Omega$ and a Gage Factor of $140 \pm 10$ [31].

As forces are applied to the sensing element, bending occurs on the flexure causing a change in strain that results in a corresponding change in circuit output based on Equation 8:

$$E_o = E_i GF \, \varepsilon \quad (8)$$

where $E_o$ is the output voltage and $E_i$ is the excitation voltage supplied to the Wheatstone bridge. A relationship between gage output and the applied forces is obtained through the calibration of the instrument, a necessary step in the measurement of skin friction as will be seen later in this document.

In this study, a 2310 Strain Gage Conditioning Amplifier manufactured by Measurements Group Inc. [29] supplied each circuit an excitation voltage of 5 Volts and an output Gain of 250. Further, the amplifier enabled data acquisition through portals that linked the amplifier to a data acquisition board via BNC cabling. Figure 2.6 displays the gage circuitry used in the skin friction unit.
Figure 2.6: Skin Friction Gage Pin Circuitry and Pin labeling
CHAPTER 3 – GAGE PREPARATION

3 GAGE PREPARATION

In this chapter, a brief discussion of problems and solutions encountered while using the silicone RTV will be presented. The final application technique of the RTV to the skin friction gage will be listed.

3.1 Problems Encountered While using the Rubber RTV

A major problem encountered in previous studies with the use of the rubber RTV was its adhesion to the gage surface during testing [26] due to the aggressive nature of the supersonic wind tunnel "starting". A temporary solution developed was the design of a metal flap that covered the gage surface during the beginning and end of each wind tunnel run, otherwise leaving it exposed to the flow. Despite its successful use, a more permanent solution was desired.

It was determined that bonding could be improved by creating grooves on the bonding surface and machining down the outer lip of the housing allowing the rubber compound to wrap around the outer edge as illustrated in Figure 3.1.

A new problem encountered in this study was the unwanted filling of the gap between the sensing head and the plastic housing with the rubber RTV mixture, as demonstrated in Figure 3.2a, causing loss in gage sensitivity. The previous application procedure required the gage bonding surface to be placed onto the liquid RTV mixture without any support of the gage. This allowed the weight of the assembly to squeeze the RTV mixture into the gap leaving a thin layer of the RTV on the actual bonding surface and a ring of RTV in the gap as illustrated in Figure 3.2a. This was only a minor problem
with the earlier gages, which were small and made entirely of plastic. The gages designed for the present application were larger and heavier, thus greatly amplifying the problem.

Figure 3.1: Grooved Bonding Surface of Outer Housing

Figure 3.2: Demonstration of the Results of the Previous and Current Rubber RTV Preparation Techniques
To counter this problem, a gage adapter was designed. It had an inner cavity into which the gage assembly could be inserted and fastened. The adapter had a shank designed for insertion into a milling machine as illustrated in Figure 3.3. This setup allowed the gage to be held at a desired height above the surface upon which the liquid RTV mixture was spread, and this reduced gap filling with rubber RTV resulting in increased gage sensitivity. The rubber sheet formed with the use of the gage adapter is illustrated in Figure 3.2b

A known characteristic of rubber compounds is the change of its modulus of elasticity with temperature. For wind tunnel testing, the exposure time to the flow is on the order of seconds, negating this effect. However, for flight-testing, the testing time varies from 30 minutes to several hours at varying altitudes making the temperature effect a major concern. To account for this effect, a thermocouple was buried into the silicone RTV sheet over the gap between the sensing head and the housing. This enabled the calibration of the unit at different flow temperatures, emulating the final test environment the gage would experience. Epoxy was used to attach the thermocouple wiring to the plastic housing in a manner allowing the bead to float in the gap between the sensing element and the housing with the necessary stiffness to impinge and embed itself in the silicone RTV sheet as it was applied to the gage surface. Figure 3.4 shows the assembled gage with the thermocouple bead as described above. Calibration results will be presented in the next chapter.
Figure 3.3: Gage adapter used in Securing Skin Friction Gage to Drilling Machine.

Figure 3.4: Thermocouple bead in the gap between Plastic Housing and Sensing Head
3.2 Preparation of Silicone Rubber Sheet

Previous studies conducted at Virginia Tech established a baseline procedure in the application of the Silicone RTV to the gage surface. The procedure was further improved with the assistance of Matthew MacLean. Below is the modified procedure.

1. For successful application of the silicone RTV, the following materials are necessary.
   a) Rubber Gloves and a Facemask.
   b) RTV 566A Compound.
   c) RTV 566B Compound.
   d) SS4004 Primer.
   e) Acetone.
   f) Tooth picks.
   g) Smooth flat surface (e.g. Aluminum plate).
   h) Clear tape
   i) Stiff thin metal rod.
   j) Wire
   k) Access to a drill press machine.
   l) Exacto knife
   m) Plastic sheet

2. Before handling any of the chemicals, put on the protective clothing i.e. facemask, gloves and apron.

3. Clean the flat, smooth surface (aluminum plate) with acetone as to ensure that no old rubber remains. Cover one side of the aluminum plate or surface of choice with a smooth plastic sheet. Tape the sheet down ensuring the surface remains wrinkle-free.
4. Secure wire of appropriate thickness on the plastic sheet with clear tape. The wire diameter is determined by the thickness of the rubber sheet one requires on the gage surface. The wire should be 110% of the desired rubber RTV thickness. Secure a second row parallel to the first with a separation distance equal to one and a half times the skin friction gage diameter. See Figure 3.5

5. Apply a thin layer of SS4004 primer with a Q-tip or a similar utensil to the intended gage surface. Allow primer to dry. This is noticed by a change in color of the primer from orange to pink. Quicker drying is possible by blowing air on the gage surface. After 30 seconds of the first application, apply a second coat to the surface. Continue procedure for 8 to 10 layers. Allow a 30 to 60 minutes break after final application before continuing. This allows the acetone in the silicone-based primer to completely evaporate, which would otherwise react with the silicone RTV producing undesirable results.

6. Insert the skin friction gage into the gage adapter illustrated in Figure 3.3 with the primed surface protruding by 1-1.5 inches. Secure the gage to the adapter by fastening the setscrews on the side of the gage adapter.

7. Insert the shank of the gage adapter into the drill press and secure to the press by means specified by the manufacturer.

8. Place the plastic covered aluminum sheet underneath the skin friction gage and gage adapter assembly. Slowly lower the gage assembly until the primed surface appears to be touching the plastic covering the aluminum sheet.
9. Reset the height counter or otherwise take note of indicated height. This will help set the required thickness of the rubber RTV compound on the surface of the skin friction gage. Raise the gage adapter assembly and remove the aluminum sheet.

10. Pour approximately 60 ml (1/4 Cup) of RTV 566A compound uniformly between the two wire guides. Add 1-2 drops of RTV 566B into the compound on the aluminum sheet. Mix the two compounds with a blunt object (e.g. a toothpick or the non-pointed end of a nail). Ensure thorough mixing is done.

11. Use the metal rod to spread the rubber mixture across the plate. This is best done rolling the metal rod over the guiding wires as illustrated in Figure 3.5. Starting at one end of the aluminum plate, slowly roll the rod down the plate, spreading the rubber RTV across the plate.

![Figure 3.5: RTV preparation technique diagram](image)

Figure 3.5: RTV preparation technique diagram
12. After evenly spreading the mixture, peel off the guide wires and place the metal sheet below the gage adapter assembly. One needs to work quickly and carefully as the hardener added to the mixture causes the mixture to immediately set.

13. Lower the gage adapter assembly to the required height as illustrated in Figure 3.6. Use a toothpick or another stiff blunt object to lump the mixture around the gage. Insure the RTV is lumped to at least the height of the O-ring groove. The lumping of the RTV compound will cause the rubber sheet to wrap around the edge of the gage surface after it has completely cured as a single continuous surface assuring sheet adhesion during testing. Allow 24 hours for the compound to cure.

Figure 3.6: Preparation of Rubber Sheet on Drill press
14. After the 24-hour curing cycle, use the Exact-o knife to cut the plastic sheet around the skin friction gage. Raise the gage assembly and loosen the skin friction gage from the adapter. Remove the skin friction gage and use the Exact-o knife to trim the rubber sheet as illustrated in Figure 3.7 below.

![Figure 3.7: Trimmed surface of Skin Friction Gage.](image)

3.3 Glycerin filling procedure.

If a gage is not properly filled with glycerin, a large pressure difference between the flow and the gage cavity pressure develops during wind tunnel testing and flight-testing. Any trapped air bubbles will expand and cause the RTV sheet to bulge in the gap between the sensing head and housing. The resulting force would dominate the gage signal, rendering all obtained information useless. It is, therefore, imperative to develop a filling technique to eliminate this problem by ensuring no air is trapped within the gage cavity. Below is a description of the method used to fill the gages with glycerin.
1. For successful filling of the skin friction gage with glycerin the following materials are necessary:

   a) Small Sharp Needle   b) Clear tape and scissors
   c) Plastic sheet        d) Glycerin
   e) Aluminum Ring        f) Plastic cone
   g) Allen wrench         h) Vacuum chamber
   i) Vacuum pump

2. Holding the gage in an upright position, use the needle to pierce the RTV sheet in the gap at several locations.

![Gage preparation for glycerin filling](image)

**Figure 3.8: Gage preparation for glycerin filling**

3. Place the gage on a clean flat surface with the RTV coated side facing downward. Using the Allen wrench, remove both set screws that are used to seal the filling holes as illustrated in Figure 3.8a.
4. Slide the aluminum ring onto the bottom side of the gage. Ensure the top lip of the ring is slightly below the rim of the connector. This will ensure no glycerin spills into the pin cavity of the connector. Use the Allen wrench to secure the ring. See Figure 3.8b.

5. If a plastic cone is available, go to step 6. Otherwise, use the scissors to cut a 6 in. by 6 in. square from the plastic sheet. Roll the sheet in a fashion to obtain a conical shape. Secure the plastic sheet flaps using the clear tape. Use the scissors to snip an opening on the pointed end of the cone.

6. Place the opening of the cone into the cavity formed by the aluminum ring and the connector and slowly funnel glycerin as illustrated in Figure 3.9. Ensure fluid level is slightly below the lip of the rim. Air escaping from the gage cavity will form over the filling holes. Wait for 1 - 2 minutes then re-fill the reservoir of glycerin until the frequency of bubbles is drastically reduced.

7. Ensure the inside surface of the vacuum chamber is clean. With the glycerin reservoir filled, place the connector into the vacuum chamber. Seal the chamber and turn on the vacuum pump. When the pump reaches the lowest pressure possible, hold the level for 3 - 4 minutes then turn off the pump. Slowly re-pressurize the chamber to room temperature, then turn on the pump. Repeat this process 2-3 times. This cycling process will help dislodge any air bubbles attached to the interior surfaces of the gage cavity. After 2-3 cycles, check the glycerin reservoir level and fill as necessary.
8. When the glycerin level does not change remove the gage from the chamber.

The gage is now ready for calibration.
4 CALIBRATION TECHNIQUES

In this chapter, the calibration methods used in this study will be described. Advantages and disadvantages of each method will be presented. The effective area concept will be introduced to the reader and will be used to illustrate the relation between the calibration techniques used.

In this study, two calibration methods were used:

a) Point loading

b) Distributed Shear

4.1 Point loading Method

This is the preferred method of calibration for oil-filled gages due to its simplicity. It is also a highly accurate method due to the negligible shear stress contribution of the oil in the gage cavity. A known weight is placed parallel to the direction of flow and perpendicular to the sensing element. This is usually achieved by hanging a paper cone by sewing thread attached to the floating element with clear tape as illustrated in Figure 4.1a. A tare value of the cone and string is usually taken to zero the balance. Different weights ranging from 50 milligrams to 5 grams are placed in the cone while the corresponding output is recorded. The gage is then rotated 180 degrees and the procedure repeated. The whole process is repeated on the cross-stream axis.

The mass calibration is then related to shear through Equation 9:

\[ \tau_w = \frac{K \cdot M}{A} \]  

(9)
where $K$ is the conversion factor from mass to force units, $M$ is the mass of the calibration weight and $A$ is sensing head area. A calibration curve can then be generated in the form of:

$$\tau_w = S \cdot V + B$$  \hspace{1cm} (10)

where $S$ is the slope of the calibration curve and $B$ is the $y$-intercept, which is generally zero.

**Figure 4.1: Point Load Calibration On Skin Friction Gage**

### 4.2 Distributed Shear Method

The rubber RTV sheet applied to the gage surface has a non-negligible contribution to gage shear. The RTV compound provides a larger surface area on which the fluid interacts, increasing the shear stress seen by the strain gages. For an accurate calibration, a known weight or shear force would need to be distributed evenly over the
entire gage surface. A calibration rig intended to meet this objective was designed [26], and it will be described in the Facilities Chapter.

4.3 Area Ratio

In cases where a distributed shear-calibrating device was not available, it was necessary to establish a correlation to enable accurate data interpretation with the use of a point-load calibration method. To achieve this, the area ratio concept was formulated. The concept is has two sub-sets, an effective area ratio and a geometric area ratio. The geometric area ratio is based on dimensions measured from the gage and represented in Equation 11:

\[ A_{\text{RATIOgeo}} = \frac{A_{\text{GAP}} + A_{\text{HEAD}}}{A_{\text{HEAD}}} \]  

(11)

where \( A_{\text{GAP}} \) is the gap area and \( A_{\text{HEAD}} \) is the floating head area as illustrated in Figure 4.2. The geometric area ratio of the gages used here was 2.0.

--

Figure 4.2: Area Ratio concept
Since the rubber sheet has some flexibility, one cannot assume that the shear acting on the rubber sheet has the same effect as the shear acting on the solid head. Further, shear acting on the rubber sheet that covers the rim of the housing might also contribute to the net force on the flexure. Thus, one must determine what we have called the effective area ratio. The effective area ratio quantifies the area contribution of the rubber RTV as a percentage of the floating head area. This allows for the use of Equation 9 in a point load calibration method illustrated in Figure 3.7b.

The effective area ratio is obtained by comparing a calibration from a point load method to a distributed shear calibration under the same conditions. A point load calibration method produces a mass vs. output curve, whereas the distributed shear calibration produces a shear vs. output curve. To obtain the area ratio, both calibrations are compared using Equation 12 and 13 below

\[
\tau_w = DV_{OUT} \tag{12}
\]

\[
K \cdot M = PV_{OUT} \tag{13}
\]

where \(DV_{OUT}\) is voltage output based on the distributed shear method and \(PV_{OUT}\) is output based on the point load method. In order to make \(PV_{OUT}\) equal to \(DV_{OUT}\), Equation 13 will need to be converted to shear by dividing by the product of the effective area ratio and the head area producing Equation 14

\[
\tau_w = DV_{OUT} = PV_{OUT} = \frac{K \cdot M}{A_{\text{RATIO}_{\text{eff}}} \cdot A_{\text{HEAD}}} \tag{14}
\]

Solving Equation 14 for the effective area ratio we get
where \( \tau_w \) is obtained from the distributed shear calibration curve and \( K \) and \( M \) are obtained from the point load curve. \( A_{\text{HEAD}} \) is a known value. In this study, the effective area ratio for the various instruments used ranged from 1.35 to 2.00, which compares to the geometric area ratio of 2.0.

### 4.4 Gage Calibration

#### 4.4.1 Gage Sensitivity Results

Without the use of the gage adapter, a rubber RTV thickness of 0.06 in. was obtained in the gap between the sensing element and housing leading to a 90% loss sensitivity in a point load calibration comparison illustrated in Figure 4.3. With the improved application technique (see Section 3.1), better control of RTV thickness was obtained. A 0.025 in. thickness was used leading to a 55% sensitivity gain over that which was obtained under a similar calibration.

A distributed shear calibration revealed that the 35% to 100% of the gap area contributed to gage shear. This different area value used in Equation 9 implied the gage was 23% more sensitive than was depicted by the point load calibration method. See Figure 4.4. In order to obtain the orange-point load calibration curve to be displayed in Figure 4.4 for comparative purposes, only the head area was applied in Equation 9, neglecting the area contribution of the surrounding surfaces. This would enable a visual determination of the contribution of the surrounding surfaces to gage shear.
CHAPTER 4 – CALIBRATION TECHNIQUES

Figure 4.3: Gage Sensitivity Comparison WITHOUT the use of the gage adapter

Figure 4.4: Gage Sensitivity Comparison WITH the use of the gage Adapter.
4.4.2 Point load and Distributed Shear Calibration Results

Figures 4.5 and 4.6 are the point load calibration curves of the gage used in this study. Figure 4.7 presents calibration rig results of the gage displaying the fact that the obtained calibration lies within the bounding geometric area ratios of 1.0 and 2.0. The bounding values are obtained by using Equation 11. Neglecting gap area would produce the minimum value, while including it would result in the maximum value. Shear acting on the rim of the housing could possibly contribute to the total shear resulting in a scenario where the effective area ratio is greater than the maximum geometric area ratio.

![Figure 4.5: Calibration Curve of Gage#S2 without the rubber RTV](image-url)
CHAPTER 4 – CALIBRATION TECHNIQUES

**CALIBRATION CURVE OF GAGE #S2 WITH RUBBER RTV COMPOUND E = 5 VOLTS G = 250**

- **y = -0.144x + 0.0055**
- **y = 0.1406x - 0.0064**
- **y = 0.1457x + 0.001**
- **y = -0.1547x - 0.0053**

**Figure 4.6: Calibration Curve of Gage#S2 with the rubber RTV**

- **Corresponds to an EFFECTIVE AREA RATIO = 1.35**
  - **Y = 173.71x + 4.094**
  - **R^2 = 0.9411**
- **AREA RATIO EFFECTIVE = 1.0**
- **AREA RATIO EFFECTIVE = 2.0**

**Figure 4.7: Distributed Shear Calibration Results From Calibration Rig**
4.4.3 Temperature Calibration Results

A distributed shear calibration was performed on the gage to simulate the varied temperature environment that would be experienced during flight-testing. The tests were performed in the calibration rig at three different flow conditions. Fluid temperature, strain gage temperature, and the silicone RTV sheet temperature were monitored and recorded during testing. Figures 4.8, 4.9 and 4.10 display the temperature calibrations for room temperature, cooled and heated flow conditions. It can be noted that despite a 45 °F change in fluid temperature between the heated and cooled flow conditions, only a 4 °F gage temperature change is experienced. This stable temperature environment is favorable to semi-conductor strain gages, which are highly susceptible to thermal drift. A 32 °F temperature change in the silicone RTV resulted, producing a varying gage calibration as illustrated in Figure 4.11. The resulting trend implied an increase in gage sensitivity with a decrease in temperature. It could be also noted that for a change of 45 °F in fluid temperature, a 23% change in the calibration slope was experienced.
CHAPTER 4 – CALIBRATION TECHNIQUES

Temperature Profile For Room Temperature Calibration for Case WITH GLYCERIN

![Temperature Profile for Room Temperature Calibration](image)

Figure 4.8: Temperature Profiles for Room Temperature Flow Calibration

Temperature Profile For COOLED FLOW Calibration for Case WITH GLYCERIN

![Temperature Profile for Cooled Flow Calibration](image)

Figure 4.9: Temperature Profiles for Cooled Flow Calibration
CHAPTER 4 – CALIBRATION TECHNIQUES

Temperature Profile For HEATED FLOW Calibration for Case WITH GLYCERIN

Figure 4.10: Temperature Profiles for Heated Flow Calibration

Comparison of Calibration at Various Temperatures

Room Temperature Calibration
\[ y = 108.84x \]
\[ R^2 = 0.9507 \]

Heated Flow Calibration
\[ y = 119.22x \]
\[ R^2 = 0.9474 \]

Cooled Flow Calibration
\[ y = 92.18x \]
\[ R^2 = 0.9952 \]

Figure 4.11: Calibration Results at Various Flow Temperatures
The use of gaussian quadratures was implemented to generate a temperature compensation routine based on data obtained in the calibration rig. The resulting scheme collapsed the heated and cooled calibration curves displayed in Figure 4.11 onto the room temperature curve. The study of the aforementioned figure revealed that the rubber RTV has greater sensitivity to cooling than heating. Figure 4.12 exhibits the reduction scheme applied to the data in Figure 4.11.

\[ y = 108.84x \]

**Figure 4.12: Collapsed Calibration Curves using Temperature Compensation Routine.**
5 TEST FACILITIES

This section provides a detailed description of the facilities used to test and analyze the performance of the designed skin friction gage. A description of the Calibration Rig and associated equipment will first be presented, followed by a similar demonstration of the vibration bench and the supersonic wind tunnel.

5.1 Calibration Rig

The calibration rig is designed to provide a distributed shear calibration on skin friction gages using a synthetic grade glycerin flowing under fully-developed conditions in a 2-D channel. See Figure 5.1. The fully-developed condition refers to the situation where the boundary layer on the top and bottom surfaces of the channel grow and finally converge at the channel centerline, impeding further boundary layer development resulting in an identical mean flow velocity profile [30]. A tank 43 inches tall with a 9-inch diameter supplies glycerin to a 16 inch long and 1/4 inch high two-dimensional channel lined with pressure ports. The top surface of the 2-D channel is made of a hard plastic that has a portal through which the skin friction gage is mounted. A flow valve located at the end of the channel controls the stream of glycerin. When the valve is open the glycerin flows into a collecting tank located below the channel opening. The tank and bottom portion of the flow channel are constructed of aluminum and are lined with copper tubing which channel heated or cooled fluid allowing for the alteration of the flow temperature.

The operating principle of the calibration rig is based on Equation 16:

\[
\tau_w = -\frac{dp}{dx}h
\]  \hspace{1cm} (16)
where \( \frac{dp}{dx} \) is the pressure gradient, and \( h \) is the channel height measured from the centerline. With the flow valve closed, the head pressure generated by the fluid in the glycerin tank is equally transmitted along the length of the channel. When the flow valve is opened, the pressure at the exit drops to room pressure, creating a pressure difference along the length of the channel. Measurement is done after the flow reaches steady state.
Different shear values can be obtained by varying the fluid level in the glycerin tank. This results in a change in the pressure gradient represented in Equation 16 due to the alteration of the head pressure. A self-priming pump is used to transfer glycerin from the collecting tank into a horizontally mounted 55-gallon tank installed 3 feet above the calibration rig that acts as a reservoir for the glycerin tank. A photograph of the rig is given in Figure 5.2

![Figure 5.2: Photograph of the Calibration Rig System](image)

The pressure ports are affixed with NPC-1220 pressure sensors manufactured by Lucas NovaSensors. See Figure 5.3. The sensors have a pressure range of 0 -5 psi with
temperature compensation from 0 to +60 °C and are supplied with 1.235 input Voltage [31]. Sensor output is transferred via BNC cabling to a data acquisition board, which is then recorded into a computer. A program script written in LabVIEW is used to control data capture from pressure transducers and the skin friction gage [32].

![Figure 5.3: Pressure Transducers used in Calibration Rig](image)

The calibration rig can produce shear values ranging from 0 to 110 Pa. Figure 5.4 displays a linear pressure distribution curve obtained from a sample run in the calibration rig resulting in \( \frac{dp}{dx} = 0.1189 \) psi/inch which corresponds to a shear value of 102 Pa.

Further information regarding the design and use of this device can be found in Chapter 4 of Ref. [26].
5.2 Vibration Test Apparatus

Vibration testing was performed at the Virginia Polytechnic Modal Analysis Laboratory. The equipment used provided an experimental determination of the natural frequency and vibration modes of the skin friction gage. Information on the gage response to simulated NASA flight test vibration curves was also obtained.

The equipment used during the vibration testing consisted of the hardware listed below and illustrated in Figure 5.5:

1. 75 pound Modal Shaker,
2. PCB 288D01 Impedance Head,
3. 2310 Signal Conditioning Amplifier,

The axis requiring testing is mounted perpendicular to the plane of vibration. The gage is mounted with a slip ring with a short #10-32 rod. The rod is then fastened to a hexagonal nut on the top surface of the modal shaker. During testing, the dynamic signal analyzer generates a random signal that is passed through the amplifier before being supplied to modal shaker. The gage output is modified using a Measurements Group 2310 Signal Conditioning Amplifier and then passed back to the dynamic signal analyzer for processing. The impedance head contains an accelerometer and a force transducer that allows the dynamic signal analyzer to assess and correct the input signal. A sampling rate of twice the highest frequency of the signal is required for optimum results to be obtained.

![Schematic of the Vibration Experimental Setup.](image-url)
5.3 Supersonic Wind tunnel

Thorough ground testing of the gages was desired before flight tests. These tests were conducted in the Virginia Tech supersonic wind tunnel. The wind tunnel was originally designed and constructed at the NASA Langley Research Center. It has a 9 by 9 inch interchangeable test section, which can be mounted with a variety of two-dimensional steel nozzle blocks that operate at different Mach numbers. Currently, Mach 2.4, 3 and 4 nozzle blocks are available. The tunnel has been in operation at Virginia Tech since 1963. Figure 5.6 is an illustration of the wind tunnel.

![Supersonic Wind tunnel schematic](image)

**Figure 5.6: Schematic of the Supersonic Wind tunnel.**


More information, including following tunnel specifications, can be obtained from the Virginia Tech Aerospace Department web site [33]. The air pumping system consists of
an Ingersoll-Rand Type 4-HHE-4 4-stage reciprocating air compressor driven by a 500 hp, 480V Marathon Electric Co. motor. The compressor can pump the storage system up to 51 atm. A drying and filtering system is provided which includes both drying by cooling and drying by absorption. The air storage system consists of two tanks with a total volume of 23 m$^3$. The tunnel control system includes quick opening butterfly valve and a hydraulically actuated pressure regulating 30.5-cm diameter valve. The settling chamber contains a perforated transition cone, several damping screens, and probes measuring stagnation pressure and temperature. The working section of the tunnel is equipped with a remotely controlled model support that allows one to vary the position of a model in the vertical plane. Large doors containing the windows in the nozzle and working sections ensure good access to the model. After passing through the test section and diffuser, air is then discharged to the atmosphere through a vent located outside of the building.

The main pressure measuring system includes a PSI Model 780B electronically scanned pressure system. The system is IBM PC computer controlled and presently can handle 32 pressure inputs (0 to 1 atm) simultaneously but, if a need arises, it can be expanded up to 512 pressure inputs. In addition to the electronically scanned pressure system, there are two Scanivalve systems available, each allowing the recording of up to 48 pressures (0-3 atm) during a run of a few seconds duration.

Temperature and heat transfer measurements can be made using an automatic multipoint thermocouple reference system and high-speed potentiometric recorders. Data acquisition is all IBM PC based using modern software such as LabVIEW. Table 4.1 further lists tunnel specifications.
Table 5.1: Technical Specification of the Wind Tunnel

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Section size</td>
<td>23 x 23 cm</td>
</tr>
<tr>
<td>Stagnation pressure</td>
<td>3-20.5 atm</td>
</tr>
<tr>
<td>Mach number</td>
<td>2.4-4 and 0.2 -0.8</td>
</tr>
<tr>
<td>Reynolds number per meter</td>
<td>2 x 10^6 to 5 x 10^6</td>
</tr>
<tr>
<td>Run duration, depending on Mach number and Stagnation pressure.</td>
<td>8 - 60 sec</td>
</tr>
<tr>
<td>Dew point</td>
<td>Below - 40 deg C</td>
</tr>
<tr>
<td>Maximum model diameter at M=3</td>
<td>9 cm</td>
</tr>
<tr>
<td>Storage tank volume</td>
<td>23 m^3</td>
</tr>
<tr>
<td>Maximum air pressure in the storage tanks</td>
<td>51 atm</td>
</tr>
<tr>
<td>Total power rate of the compressor plant</td>
<td>500 hp</td>
</tr>
</tbody>
</table>

For this work, a port was machined in a plate mounted on the floor of the test section as illustrated in Figure 5.7.

Figure 5.7: Wall Mounting Test plate For Skin Friction Gage.
5.4 Flight Test Fixture

The Flight Test Fixture (FTF-II) was developed by NASA Dryden Flight Research Center for use as a test bed for aerodynamic and fluid mechanics research. More information, including the following presentation, can be found in the NASA Technical Memorandum 4782 [22]. The FTF-II is a low aspect ratio, fin-like shape 107.0 in. long, 32 in. high, and 8.0 in. wide with an elliptical nose section and blunt trailing base. See Figure 5.8. The avionics pylon located in the upper 19 in. of the FTF-II is a permanent structure housing avionics, research instrumentation and equipment common to most flight experiments. The lower 13-in. of the FTF-II is the vertical test article that, in the current configuration, matches the contour of the upper avionics pylon. The vertical test article is removable and may be replaced by other aerodynamic shapes. Normally, only instrumentation specific to individual research experiments is installed in the lower vertical test article.

All FTF-II side panels are removable with quick internal access through the four left side panels that use external fasteners flush to the surface. The two right side panels extend the length of the fixture and are attached using internal fasteners to minimize discontinuities for aerodynamic experiments such as boundary-layer experiments or surface flow visualization studies.

The FTF-II is mounted in the centerline of the NASA F-15B airplane, a two-seat version of the F-15 aircraft. It is a high performance, supersonic, all-weather, air-superiority fighter built by McDonnell Douglas Aerospace [34]. Two Pratt & WHITNEY F100-PW-100 turbofan engines with afterburners power the F-15B. The aircraft has a length of 63.7 feet, a wingspan of 42.8 ft. and a basic operating weight of 27,500 lbm.
Figure 5.8: Flight-test Fixture Schematic [22]

The FTF-II data acquisition capability is primarily located in the fixture avionics pylon and uses a 12-bit pulse code modulation system capable of multiplexing data at sample rates as many as 200 samples per second, depending on the number of data
channels. Flight data is transmitted to the ground for storage and post-processing. A tape recorder located in the F-15B airplane is used as a backup or to record high frequency data if required for a specific flight experiments. For this particular study, the gage was mounted in Bay T4 of the vertical test article as illustrated in Figure 5.8. Figure 5.9 shows the preparation of the flight test vehicle for use the testing of the skin friction gages.

Figure 5.9: Preparation of the F-15B for the Flight Test
6 TEST RESULTS

In this chapter, experimental results from the various test facilities mentioned in Chapter 5 will be presented. Gage vibration tests results will first be documented, followed by gage performance verification in the wind tunnel. Data from the flight test will then be presented and analyzed.

6.1 Vibration Test Results

Vibration tests were performed at the Virginia Tech Modal analysis laboratory. The gage was mounted on the VTS Modal shaker perpendicular to the plane of vibration. Random noise input at a level corresponding to $1 \text{ g}_{\text{rms}}$ (10.3 mV pk) was supplied from a dual functioning Hewlett Packard 35665A dynamic signal analyzer. The device also measured the frequency response, phase and the coherence of the system over a 0 – 3500 Hz range. This was the smallest available range that would include the NASA specified limits of 0 to 2,000 Hz. Vibration tests were repeated at three different gage conditions;

a) No Rubber RTV Sheet,

b) With Rubber RTV Sheet, NO glycerin fill,

c) With Rubber RTV Sheet and glycerin fill.

This enabled the evaluation of the damping contributions of the rubber RTV sheet and the glycerin contained within the gage cavity.

Plots of the gage frequency response function, phase and coherence are shown in Figure 6.1, Figure 6.2 and Figure 6.3 respectively. It should be noted that Figure 6.1 is a semi-log plot in the y direction.
CHAPTER 6 – TEST RESULTS

FREQUENCY RESPONSE OF SKIN FRICTION GAGE

Figure 6.1: Frequency Response of Skin Friction Gage

PHASE PLOT FOR FREQUENCY RESPONSE

Figure 6.2: Phase Response of Skin Friction Gage
Figure 6.3: Coherence of Frequency Response Functions

Figure 6.3 shows that excellent coherence of the three studied cases was obtained over the entire frequency domain, validating the accuracy of the frequency response data. This verifies the adequacy of the test results.

The analysis of the response of the gage without the rubber RTV sheet displayed three vibration modes at 287 Hz, 524 Hz and 1052 Hz, respectively. See the green curve in Fig. 6.1. The second mode dominated the entire frequency spectrum. A theoretical calculation of the gage natural frequency was performed using BEAM6 vibration program [35]. The program used the gage geometry and material properties as inputs to estimate the gage vibration characteristics. The program only predicted one bending mode at 637 Hz, which coincides with the second dominant experimental mode. The difference between the theoretical and the nearest measured value at 524 Hz could be attributed to several factors. The BEAM6 program assumes the gage flexure is a perfectly cantilevered beam, thus predicting a slightly stiffer model than the actual beam, which may slightly bend at the base. Another possible contribution was the estimation of the
beam geometry. BEAM6 could not model the conical floating head as it had only cubical or cylindrical elements in its volume library. A layer of cylindrical elements with increasing diameter was used to simulate the conical floating head.

The disagreement in the number of modes predicted by BEAM6 could be attributed to two possible reasons. One or all of the excluded modes could be natural frequencies of the plastic housing, the aluminum housing or the connector. An experimental analysis would include all system modes, whereas the theoretical prediction would only display the vibration modes of the cantilevered beam. It is also possible that some of the excited system modes were due to torsion, which cannot be predicted by the BEAM6 program.

The rubber RTV sheet provides strong damping across the entire frequency domain (see the blue curve in Figure 6.1). It can be particularly noticed that the second mode peak is reduced from a value of 3350 to 15. The first and third modes see a 5620% and 667% reduction, respectively. All three-vibration modes shift from their original values after the addition of the rubber RTV compound as summarized in Table 6.1.

The addition of glycerin into the gage cavity further reduces the first and third modes by 67% and 50%, however the second mode sees only a 2% reduction and is further shifted to a frequency of 844 Hz. This is all evident on the red curve in Fig. 6.1. The addition of glycerin added a fourth vibration mode at 1160 Hz to the gage system as illustrated in Figure 6.4, which shows details of the behavior in that range.
Table 6.1: Comparison of Natural Frequency Modes at Different gage states.

<table>
<thead>
<tr>
<th>$F_n$ Number</th>
<th>THEORETICAL Natural Frequency (Hz)</th>
<th>Measured Natural Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WITHOUT RTV</td>
<td>WITH RTV NO glycerin</td>
</tr>
<tr>
<td>1</td>
<td>287</td>
<td>184</td>
</tr>
<tr>
<td>2</td>
<td>1052</td>
<td>648</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>964</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

6.2 Vibration Test Conclusions

From the vibration test results presented, it can be concluded that the use of glycerin in the gage cavity is no longer a requirement for proper system function. The rubber sheet alone provides adequate damping. Test flight protocol necessitates gage
installation in the test bed up to several days before test commencement. A glycerin filled gage exposed over such a length of time would be subject to seepage of air into the gage cavity. The air would tend to load the sensing element due to pressure effects during testing, resulting in erroneous results. Lack of glycerin in the gage cavity would eliminate this effect, but also eliminate the thermal stability provided by glycerin for the semiconductor strain gages, which are temperature sensitive.

6.3 Supersonic Wind Tunnel Results

Gage verification was performed in the Virginia Tech Supersonic wind tunnel shown in Figure 5.6. Two gages were simultaneously mounted with one installed on the sidewall of the tunnel (Gage S2) and the other on the bottom surface of the two-dimensional nozzle block (Gage S3). The wind tunnel was run at flow conditions corresponding to $P_0=55$ psi, $T_0=300$ K and $M=2.4$ allowing the upper limit of the shear levels expected during flight-testing to be obtained.

The vibration environment in the wind tunnel is much less severe than that in flight. Acceleration measurements performed on the wind tunnel displayed loads ranging between $1.00 \times 10^{-14}$ to $1.00 \times 10^{-8} \text{ g}^2/\text{Hz}$ vertically (z), laterally (y) and longitudinally (x) as displayed in Figure 6.5, Figure 6.6 and Figure 6.7 [18]. It should be noted that the following spectral density plots display the supersonic wind tunnel vibration in the nominally steady test flow between startup and shut down. These vibration levels can be compared with the much higher levels for flight testing in Figure 1.13.
Figure 6.5: X-Axis Acceleration Loads During Wind Tunnel Run [18]

Figure 6.6: Y Axis Acceleration Loads During Wind Tunnel Run [18]
Figure 6.7: Z- Axis Acceleration Loads During Wind Tunnel Run [18]

The skin friction gages were tested in the wind tunnel with no glycerin in the gage cavity to simulate flight test operation. Pressure ports, aligned to the cross flow axis of the gages, were connected via short Tygon tubing. The tubing was then attached to the oil-fill holes of the skin friction devices. This allowed for a pressure balance on both sides of the rubber RTV sheet during the wind tunnel tests.

Previously measured and predicted skin friction values on the bottom surface in the wind tunnel under similar conditions typically range from $C_f = 0.0015$ to 0.002 [18].

The gages were tested numerous times to verify operability and repeatability. The results can be seen in Figs. 6.8 - 6.14.
Figure 6.8: Wind Tunnel Test Run 01, Gage S2

Figure 6.8 shows the first run with gage S2 on the tunnel sidewall. The wind tunnel has a violent startup and shut down, as evidenced by the output spike displayed in both the streamwise and cross-flow axes of the gage. This is a result of the rapid pressure change experienced during both the start up and shut down phase. Such output spikes are noticeable in all skin friction data collected for gages S2 and S3. After startup, the streamwise axis gives a skin friction reading within the expected range of $C_f = 0.0015 - 0.002$. We do not have previous test data for the tunnel sidewall location, but one can expect skin friction values in the same range as on the bottom nozzle surface. In both the streamwise and cross-stream output of gage S2, signal noise was minimal, leading to smooth data curves over the entire wind tunnel run.
However, the gage output seems to drift slightly toward the lower bound as the run continues. Several reasons could be attributed to this phenomenon. One possible reason is the change in wind tunnel temperature during the run. Figure 6.9 displays the streamwise skin friction measurement compared to the wind tunnel total temperature.

Figure 6.9: Temperature Effect on Output for Gage S2.

The gage output appears to have a delayed response to temperature. This is an expected result, since the RTV sheet would absorb energy before displaying a corresponding change in temperature. Another possible cause of the change in the skin friction reading is gage drift. As can be seen in the 5 - 6 second range of Figure 6.8 after tunnel shutdown, the red line, signifying streamwise shear, displays a value slightly less than zero, despite starting at an initial value of zero. This implies that the semi-conductor
gages drifted during the course of the run. However, it is also possible that the violent shut down of the wind tunnel could cause the gage to slightly drift from its starting value.

The cross-stream component output produces a negative shear value. Ideally, a zero reading would be expected in this nominally 2D flow. This output could be a result of several factors. A slight misalignment of the gage would cause the cross-stream axis to experience a deflective force from the flow. This would not only generate output in the cross-stream direction, but would also reduce the measured output in the streamwise direction. A pressure difference between the gage cavity and the flow could also contribute to cross-stream output. This would generate a normal force that would be experienced in both the streamwise and cross-stream axes. However, from studying the cross-stream gage output, the contribution of this effect is minimal, since the output readings are small. In order to better quantify this effect, a pressure transducer could be placed inside the gage cavity.

In the 1.5 – 2.5 sec. segment in Figure 6.8, the cross-stream component of gage S2 (blue curve) appears to achieve a steady state before drifting for the rest of the wind tunnel run. This phenomenon is also repeated in Figs. 6.10 and 6.11 for the same gage. A possible reason for this peculiarity could be the aforementioned reasons related to tunnel temperature variation.

Results for Run 02 with Gage S2 in Figure 6.10 display similar trends to those in Figure 6.8. However, the measured streamwise skin friction values range from 0.0015 – 0.0018, slightly lower than the first run. The data obtained remained within the expected range.
Figure 6.10: Wind Tunnel Test Run 02, Gage S2.

Figure 6.11: Wind Tunnel Test Run 03, Gage S2.
Output for Runs 03 and 04 with Gage S2 continue to display similar trends to the earlier wind tunnel runs as can be seen in Figure 6.11 and 6.12. A $C_f$ value between 0.0017 and 0.002 was obtained in Run 03, whereas Run 04 produced slightly higher $C_f$ values between 0.002 and 0.0022. Data obtained from Gage S2 throughout wind tunnel testing was within the expected range.

Figure 6.13 and Figure 6.14 show results for wind tunnel runs with Gage S3 located on the bottom nozzle surface. In Figure 6.13, Gage S3 measures $C_f$ values between 0.0014 and 0.0018. The streamwise output in Gage S3 experienced large signal fluctuation than the off-axis component or either component of Gage S2. This could be attributed to noise introduced into the measuring system. A possible reason is a faulty cable. This is the wiring that connects the signal-conditioning device to the data acquisition system. A faulty BNC connector, due to a possibly weak solder connection,
could result in the introduction of unwanted noise into the system. In order to interpret the obtained data, an averaging over 10 samples was performed. Data averaging increases uncertainty in the analysis. However, the output from Gage S3 is within the range of acceptable values. The cross-stream output of Gage S3 is unaffected by the noise experienced by the streamwise signal. It maintains a skin friction coefficient reading of nearly zero through a large segment of the wind tunnel runs displayed in Figs. 6.13 and 6.14. However, in the latter part of each run, the cross-stream output drifts, giving a positive $C_f$ reading. This can not be attributed to gage drift as the output returns to zero at the end of both runs, however the phenomenon could be a result of temperature effects as mentioned earlier in this discussion.

In Run 02 (Figure 6.14), Gage S3 obtains a streamwise $C_f$ value ranging between 0.0014 and 0.0018. This value is again well within the acceptable skin friction coefficient range expected in the Virginia Tech supersonic wind tunnel at these conditions.

![Figure 6.13: Wind Tunnel Test Run 03, Gage S3.](image-url)
6.4 Supersonic Wind tunnel Test Conclusions

The tests must be judged as very successful. First, skin friction measurements obtained were in good concurrence with the predicted values. Second, good repeatability was achieved. Third, the rubber sheet provided adequate damping without a viscous liquid fill in the gage housing.

The skin friction gages experienced an output drift during the later portions of the wind tunnel runs. This phenomenon could be attributed to several reasons, including, but not limited to, pressure and/or temperature effects on the rubber RTV compound. Noise was inadvertently introduced into the data obtained in the streamwise direction of Gage S3. This led to data averaging, increasing the uncertainty in the data interpretation. However, the averaged skin friction values were within the expected range.
The variation in the skin friction values obtained by the two gages in could be also be attributed to their mounting locations in the nozzle block. Gage S2 was mounted on the sidewall, whereas Gage S3 was mounted on the nozzle floor. This would likely lead to a skin friction value measurement at a different point of boundary layer growth. Further, skin friction values on the sidewall are not available from other skin friction gages or analytical predictions.

### 6.5 Flight Test Results

Flight test evaluation of a non-fluid filled skin friction gage was performed at NASA Dryden Flight Research Center (DFRC), Edwards Air force Base, California. A previous attempt at testing the skin friction gage with glycerin resulted in errors due to pressure effects. It was concluded that air seeped into the gage cavity due to the extensive period between gage installation onto the Flight Test Fixture (FTF-II) and the actual flight test. At this level of development, reducing the period between gage installation from days, as is currently the case, to hours can only minimize this effect. Due to the protocol involved, this is not a viable solution. Further studies are required to help extend the shelf life of a fluid-filled gage.

The skin friction gage was installed in the vertical test article of the Flight Test Fixture (FTF-II) that is mounted at the centerline tank location of the F-15B aircraft. A heat flux sensor, Preston tube and a boundary layer rake were installed in the aluminum skin friction sensor complex to provide information on the total temperature, total pressure and indirect skin friction measurements against which the current gage results would be compared. See the photograph Figure 6.15. Figure 6.16 gives a dimensional
illustration of the skin friction sensor complex. Note that sizeable distances separate these different measurement devices.

**Figure 6.15:** Close-up of aluminum skin friction sensor complex on FTF-II.

**Figure 6.16:** CAD drawing of the Skin Friction Sensor Complex [36]
The flight test profile required data acquisition at altitudes of 15,000 ft, 30,000 ft, and 45,000 ft at Mach numbers ranging from 0.6 to 0.9. During each test period, the flight test vehicle maintained straight and level flight to eliminate acceleration loads from being registered by the skin friction gage. Figure 6.17, exhibits the coordinate system used in the presentation of the flight test data. Figs. 6.18 - 6.20 show the flight profile and the flight conditions during the time span of the test.

Figure 6.17: Co-ordinate System used in data presentation [37].
Figure 6.18: Flight test Profile

Figure 6.19: Pressure Profile during Flight Test
Three Type K thermocouples monitored temperature. One measured temperature inside the flexure beam near the semi-conductor strain gages and another monitored the rubber RTV sheet temperature. A secondary thermocouple on the aluminum test plate monitored the wall temperature. Analysis of the data displayed in Figure 6.20 reflects a wall temperature change of 100°F. It can be noticed that the rubber RTV sheet temperature is consistently leading the wall temperature during testing. This effect is noticeable throughout the entire flight test but is more pronounced after about 18 minutes. This behavior can be explained through the concept of thermal diffusivity and Fourier’s Law of heat conduction.

Thermal diffusivity is the ratio of heat conducted to the heat stored in a material. It is represented in Equation 17 [38]:

$$\alpha = \frac{k}{\rho C_p}$$

(17)
where \( \alpha \) is the thermal diffusivity, \( k \) the thermal conductivity, \( \rho \) is the density, and \( C_p \) is the specific heat of the material. At room temperature Aluminum has \( \alpha = 9.45 \times 10^{-05} \) m\(^2\)/s, whereas for a compound comparable to the rubber RTV sheet, \( \alpha = 1.57 \times 10^{-07} \) m\(^2\)/s [39]. The larger the thermal conductivity, the faster the propagation of heat through the medium. By having a larger thermal conductivity, the aluminum skin friction sensor complex will have a higher heat transfer rate, reducing the surface temperature. The heat transfer rate can be represented in Fourier’s Law of heat conduction, which is used here for purposes of simplicity, for one-dimensional, steady conditions.

\[
\dot{Q}_{\text{cond,wall}} = -kA \frac{dT}{dx}
\]  

(18)

where \( \dot{Q}_{\text{cond,wall}} \) is the rate of conduction heat transfer, \( A \) is the surface area and \( \frac{dT}{dx} \) is the temperature gradient across the material. The integration of Equation 18 yields [38]:

\[
\dot{Q}_{\text{cond,wall}} = kA \frac{T_1 - T_2}{L}
\]  

(19)

where \( T_1 \) is temperature and the rear face of the material, \( T_2 \) is the temperature at the front face of the material and \( L \) is the material thickness. We see that the rate of heat conduction through the material is proportional to the thermal conductivity, the material surface area, and the temperature difference, but inversely proportional to the material thickness. The rubber RTV sheet is 30 times thinner and has a thermal conductivity value 1500 times smaller than the aluminum of the skin friction sensor complex. Applying this observation to Equation 19, it can be concluded that the heat transfer through the material will be orders of magnitude less than that of the aluminum sheet. This, in turn, indicates that the surface temperature of the RTV sheet will be maintained due to minimal loss of energy through heat transfer into and through the material.
A further study of Figure 6.20 shows that the flexure beam temperature, near the strain gages, had a slow, gradual response to the wall temperature change. This could be attributed to the insulation provided by the plastic floating element, housing and rubber RTV sheet which act as thermal barriers, reducing heat transfer to the bottom aluminum gage pieces from the test environment conditions.

**Figure 6.21: Gage Skin Friction Results During Flight Test**

Figure 6.21 shows skin friction gage output during the course of the flight test. The cross-stream output reached the data acquisition system limits 28 minutes into the flight test. Environmental tests performed in the laboratory at NASA Dryden attributed this malfunction to extreme sensitivity to temperature for this axis that resulted in a total collapse in the Wheatstone bridge circuit. Such sensitivity could be credited to several related factors. First, possible pre-loading of the axis during the rubber RTV layout
process could increase the difference in resistance in the component resistors of the affected bridge. However, due to the improved RTV laying technique, this should be a minimal contribution. Second, a major contribution to this effect would be the nature of the gage after installation into the Flight Test Fixture. The weight of the flexure and floating element would cause preliminary deflection of the beam resulting in an increased resistance difference in the gages in the Wheatstone bridge. The introduction of a variable resistor in the bridge circuitry that could be adjusted to reduce the gravity load effect before flight would eliminate this problem.

During the 20 to 70 minute portion of the flight test, the stream-wise axis produces first lower and then higher than expected results based on pre-test estimates. This discrepancy could be attributed to the difference in the rubber RTV sheet and the surrounding aluminum wall temperatures. Studies by various workers state that such a difference can introduce a significant amount of error into the acquired data [40], [41]. Voisinet, in a study of temperature jump effects on direct measurement of skin friction drag, concluded that the percent error on wall shear stress is proportional to the temperature difference between the sensing element and the wall temperature. This error becomes larger at low shear levels, i.e. high Mach numbers and/or low Reynolds numbers [42]. The temperature difference between the rubber RTV sheet and the sensor complex wall is most apparent after the 20-minute mark in the flight test. This, coupled with the lower shear levels experienced at the higher altitudes, likely contributed to the shear reading discrepancy. A possibly larger source of the wall shear error registered by the skin friction gage was the reaction of the rubber RTV sheet at the decreased temperature levels 40°F to 100°F below where we studied rubber RTV sheet response in the laboratory. In Sect. 4.4.3 of this document, an analysis of the rubber RTV sheet behavior
was conducted over temperatures ranging from 63° F to 103° F. The rubber RTV sheet displayed a non-linear response to wall shear with respect to temperature change as evidenced in Figure 4.11. Application of a temperature compensation routine derived from laboratory data within the 20-70 minute data set would likely be erroneous due to this non-linear behavior of the rubber RTV sheet with temperature, especially with the large extrapolation involved.

It was, therefore, decided to conduct a detailed analysis of the portion of the flight test that lay within the studied temperature range in Sect. 4.4.3. This portion corresponded to the 10 – 20 minute segment of the flight test performed at 15,000 feet, at Mach numbers ranging from 0.6 to 0.9. This was accomplished using the measured instantaneous RTV sheet temperature in conjunction with the temperature correction procedure developed in Sect. 4.4.3. The results are shown in Figure 6.22.

![Figure 6.22: Comparison of Shear Values of Various Measuring Techniques.](image-url)
The results obtained from the skin friction gage in this segment of flight were also compared to those from other independent theoretical and experimental methods as illustrated in Figure 6.22. Included are results from several indirect experimental methods that are generally accepted as valid in 2D, steady flows. Dr. Trong Bui of NASA DFRC provided these results. The skin friction gage predicted trends in skin friction behaviour in good agreement with the other data, but the skin friction values were 30-50% higher than the average of the other techniques and analyses.

One can speculate on a number of possible reasons for the observed differences. First, the temperature mismatch between the RTV sheet and the surrounding wall is a possible factor in the gage reading difference. The temperature differences were small in this time period, but large errors are sometimes attributed to small temperature differences. Second, a slight pressure difference across the RTV sheet could elevate the gage shear reading. To quantify this effect, future designs need to incorporate a pressure transducer inside the gage cavity. Third, voltage-signal drift, a feature common with semi-conductor strain gages is a potential contributor to this increased level of shear. A possible solution would be the use of sensing elements insensitive to such phenomena, such as fiber-optic sensors. Fourth, unlike the steady, 2D comparative methods used, the current skin friction sensor takes into account the actual 3D, unsteady nature of the flow environment. Tuft flow visualization performed on the Flight Test Fixture (FTF-II) at Mach numbers spanning the Mach 0.9 flight condition of interest here indicate that the flow over the surface in the vicinity of the measurements is mildly 3D as illustrated in Figure 6.23. In addition, one can see that the flow near the skin friction gage differs somewhat from that near the Preston tube and the boundary layer rake. That makes direct comparison of the various results difficult.
Finally, it is worth noting that the various measuring techniques used for comparison here predict skin friction to within ±18%. According to Hopkins et al [43] the Van Driest II theory with the Karman Schoenherr incompressible friction law predicts skin friction to within ±10%. The Clauser Plot methods use the same data as the Karman Schoenherr theory, hence skin friction uncertainty would be comparable to the above. Allen determined that the Fenter-Stalmach Preston Tube method has an error band of +17%, -8%, and the Allen Preston tube method has an error band of +15%, -12% [44].

Figure 6.23: Flow Visualization of The FTF-II Using Tufts [22]
Lastly, the gage design exhibited excellent performance with respect to aircraft vibration. Figure 6.24 shows a 1% - 3% change in the normalized gage output due to noise at portions of straight and level flight. However, the gage exhibited sensitivity to a g-loading parallel to the measuring axis. On the other hand, the instrument showed negligible sensitivity to a perpendicular loading.
7 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this investigation was to develop a non-intrusive, direct-measuring skin friction sensing device for 3D flows with high vibration and gravity loads without compromising the resolution of the data acquired. This new concept was needed to alleviate problems encountered by existing sensors under such conditions. The design utilized polyethersulfone (PES), a high temperature plastic, and aluminum for the construction of gage entities. Two perpendicular axes of semi-conductor strain gages in a full-bridge configuration mounted at the base of the aluminum cantilever flexure were used for data capture. A rubber RTV compound sheet was applied to the gage surface to provide viscoelastic damping and retention of damping fluid in the gage. The gage utilized two type K thermocouples that enabled temperature measurement of the rubber RTV sheet and that of the surroundings of the semi-conductor strain gages.

Rubber RTV adhesion problems were initially encountered. The bonding was improved by the creation of grooves on the bonding surface and milling down the outer lip of the housing, allowing the rubber compound to wrap around the outer edge. Due to increased weight of the gage relative to previous gages that applied the rubber RTV compound, unwanted filling of the gap between the sensing head and the plastic housing with the rubber RTV mixture was experienced causing loss in gage sensitivity. A new rubber RTV application technique was developed that allowed the control of RTV sheet thickness, thus eliminating this problem.

A distributed shear calibration was performed on the gage to simulate the varying temperature environment that would be experienced during flight-testing. The tests were performed in the fully-developed flow channel of the calibration rig at three different
flow conditions. Fluid temperature, strain gage temperature, and the silicone RTV sheet temperature were monitored and recorded during testing. Tests indicated that the rubber RTV sheet and the polyethersulfone sensing element and housing helped isolate the aluminum components of the gage from the varying flow temperature, providing a stable temperature environment for the semi-conductor strain gages, which are susceptible to thermal drift. Tests further indicated a trend implying an increase in gage sensitivity with a decrease in rubber sheet temperature. The results obtained were used to generate a temperature compensation routine that was applied to the flight test data.

Vibration tests were performed at the Virginia Tech Modal analysis laboratory. The gage was mounted on a modal shaker perpendicular to the plane of vibration that generated a random noise at a level corresponding to 1 g_{\text{rms}}. Frequency response, phase and the coherence measurements were taken over a 0 – 3500 Hz range. Test results showed that the rubber RTV sheet provided adequate viscoelastic damping. Glycerin in the gage cavity had a minimal additional contribution to overall damping, thus it was no longer a requirement for proper system function.

Gage verification testing was performed in the Virginia Tech Supersonic wind tunnel. Two gages were simultaneously mounted with one installed on the sidewall and the other on the bottom surface of the two-dimensional nozzle block. The wind tunnel was run at flow conditions corresponding to P_0=55 psi, T_0=300 K and M=2.4 yielding the upper limit of the expected shear levels during flight-testing to be obtained. Skin friction measurements obtained were in very good agreement with predicted values and previous measurements. The skin friction gages experienced a small output drift during the later portions of the wind tunnel runs. This phenomenon could be attributed to several reasons,
including pressure difference effects and/or temperature effects on the rubber RTV compound. Successful operation without a viscous liquid fill in the gage housing was demonstrated. Also, the gages proved robust. The rubber sheet remained intact and attached, even after the violent processes of tunnel start and unstart.

Flight test evaluation of the skin friction gage without liquid fill was performed at NASA Dryden Flight Research Center (DFRC). The gage was installed in the vertical test article of the Flight Test Fixture on an F-15 aircraft through an aluminum skin friction sensor complex that contained a heat flux sensor, Preston tube and a boundary layer rake which provided information on the total temperature, total pressure and indirect skin friction results against which the gage results would be compared. The flight test profile included data acquisition at altitudes of 15,000 ft, 30,000 ft, and 45,000 ft at Mach numbers ranging from 0.6 to 0.9. During each test period, the flight test vehicle maintained straight and level flight to eliminate acceleration loads from being registered by the skin friction gage.

Detailed data analysis was performed on the 10 – 20 minute segment of the flight test, where the temperature difference between the rubber sheet on the gage and surrounding aluminum wall was within nominally acceptable limits. This includes data obtained at 15,000 feet, at Mach numbers ranging from 0.6 to 0.9. The gage design worked very well in providing adequate damping in this high vibration environment. The gage also demonstrated robustness, in that it survived this difficult environment and returned to the ground fully operational. The gage indicated trends in skin friction values for different flight conditions in good agreement with the other methods. The instrument predicted skin friction values 30-50% higher than the average of the 2D, steady
comparative analysis and measurement techniques used. The surface temperature mismatch between the rubber RTV and the aluminum sensor complex or a pressure difference across the RTV sheet surface could have contributed to a skin friction measurement difference. The theoretical and indirect measurement methods used for comparison do not take into account the vibration environment or the actual 3D, unsteady nature of the flow, and those methods are subject to uncertainties of ± 12 - 18% themselves, even for 2D, steady flows. Also, the different measurements were obtained at locations that are rather far apart and tuft visualization show that the flow pattern differs somewhat at the different locations. Further, all of the other methods are intrusive to the flow, while the skin friction gage developed here is non-intrusive and applicable to 3D, unsteady flows.

For future gage designs utilizing the rubber RTV sheet, it is recommended that an extensive study be performed on its dependency to temperature over the temperature ranges experienced during the flight test. Further, sensing elements less sensitive to drift, such as fiber optic displacement sensors, need to be researched and applied in future gage designs. The inclusion of a pressure transducer inside the skin friction gage cavity would be needed to quantify the pressure effects experienced by the instrument.

A further investigation on the liquid filling methods used will be required in order to reduce air seepage into the gage cavity, thus increasing the shelf life of the instrument for flight testing applications. In laboratory testing, the liquid fill has been found to be very helpful in minimizing any errors due to temperature or pressure mismatches across the rubber sheet. An effort should be made to obtain those benefits for flight test gages.
REFERENCES:


[27] GE Silicones, "RTV 566 specification sheet"


http://www.deutschconnectors.com/catalog.html


[37] Durham, W., Aircraft Dynamics and Control, Virginia Polytechnic, Institute and State University, Blacksburg, VA, 1997


http://www.britannica.com/bcom/eb/article/0/0,5716,117180+5,00.html


VITA

The author was born on July 19, 1975 in Nairobi, Kenya. He received his 4th through 7th grade education in Roosevelt Elementary School in Elkhart, Indiana. He completed primary education in Kilimani Primary school in Nairobi, Kenya. His high school education was obtained in Mang’u High School located in Thika, Kenya. Graduate and Undergraduate studies in Aerospace Engineering was pursued in Virginia Polytechnic Institute and State University from August 1994 to February 2001.