Investigation of a Pressure Rise in a Shear Stress Gauge

by

Herbert L. Singleton, Jr.

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY May 1995

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Abstract

Pressure difference spectra made using a shear stress gauge developed at the MIT Acoustics and Vibrations Laboratory consistently show a pressure rise in the 2 kHz region, making the gauge inaccurate for high frequency shear stress measurements. Using a variety of measurement and analytical techniques, the phenomena was investigated. Although no conclusive cause has been found for this high frequency rise, several possibilities including a Helmholtz resonance and microphone phase problems have been ruled out. However several probable causes have been identified, including convection effects, and possibly turbulent eddies near the wall surface.

Thesis Supervisor: Patrick Leehey
Title: Professor of Mechanical and Ocean Engineering
Acknowledgments

Hey. I’m finally done. Now it’s time for payback.

I feel very lucky that there are so many people out there who have always supported me, and have always given me a chance. There have been a lot of you guys out there, and I won’t forget you. (the only reason I’m not naming all of you is that I have to hand this in in about 10 minutes!)

I need to thank Professor Leehey especially for giving me the opportunity to work in a field where I can grow, learn, and most of all, have fun.

I want to thank all the NTS’ers, past and present for always forcing me to stop working and have fun once in a while.

A thank you goes go to Professor Vandiver for giving me the kick in the butt when I needed it the most.

I’m grateful for my mom and dad who’ve always made sure I got what I needed to survive, and even a little extra now and then. And of course I can’t forget my wonderful siblings who always make life interesting.

Finally I need to say thanks to the one who has helped me to grow the most, even though she may not realize it. I love you Kai..

May 18, 1995... let’s do it again sometime.
Contents

1 Introduction 8
  1.1 Background 8
  1.2 Objective 9

2 Procedure and Apparatus 11
  2.1 Shear Stress Gauge 11
  2.2 Wind Tunnel Facility 11
  2.3 Data Acquisition 12
  2.4 Transducers 12
  2.5 Gauge Calibration 12

3 Experiments with Shear Stress Gauge 16
  3.1 Phase-Matching Considerations 16
  3.2 Testing 17
  3.3 Vibrations of the Test Structure and Materials 18
  3.4 Fence 18
  3.5 Observations 19

4 Design of a New Gauge 26
  4.1 Helmholtz Resonator Effects 26
  4.2 Design Considerations 27
  4.3 Calibration 28
  4.4 Experiments 28
4.5 Mesh Experiments ........................................... 29
4.6 Effects of surface roughness ............................... 30

5 Single Hole Microphone Experiments ..................... 33
  5.1 Apparatus .................................................. 33
  5.2 Experiments ................................................ 34
  5.3 Proudness .................................................. 34

6 Conclusion ...................................................... 50
  6.1 Recommendations .......................................... 51

A Convection Effects ............................................ 52
List of Figures

1-1 Typical Shear Stress Spectrum ($U_\infty=20$ m/s) .................. 10

2-1 Yüsel Gür’s original shear stress gauge. Port holes are 0.002” apart.
   Fence is 0.002” thick ........................................... 13
2-2 Wind tunnel facility ........................................... 14
2-3 Experimental setup in the test section of the M.I.T. wind tunnel ... 15

3-1 Microphone calibrator used for phase matching microphone pairs. (dimensions in mm unless specified) Based on a design by F. Kameier .... 20
3-2 Pressure difference spectrum using original phase-matched electret microphones ........................................... 21
3-3 Pressure difference spectrum using new Realistic electret microphones to account for pre-amplification issues ......................... 22
3-4 Gauge calibrator used for phase matching microphones in the shear stress gauge ........................................... 23
3-5 Pressure spectra of upstream and downstream microphones with fence height=0 ........................................... 24
3-6 Pressure difference spectrum measured by shear stress gauge with fence height=0 ........................................... 25

4-1 1/8” Microphone Shear Stress Gauge (fence not shown). Holes are 1/64” apart (center to center). Fence is 0.002” thick. .................. 31
4-2 Pressure difference spectrum using new shear stress gauge and Brüel and Kjaer microphones ........................................... 32
5-1 Schematic of gauge used for single-microphone pressure measurements and experimental setup ........................................ 36
5-2 Pressure spectrum of a single microphone at different heights below the wall surface $U_\infty=9.15$ m/s, mesh cap .................. 37
5-3 Pressure spectrum of a single microphone at different heights below the wall surface $U_\infty=18.2$ m/s, mesh cap .................. 38
5-4 Pressure spectrum of a single microphone at different heights, below the wall surface $U_\infty=27.9$ m/s, mesh cap .................. 39
5-5 Pressure spectrum of single microphone at different heights below the wall surface $U_\infty=9.15$ m/s, pinhole cap .................. 40
5-6 Pressure spectrum of single microphone at different heights below the wall surface $U_\infty=18.2$ m/s, pinhole cap .................. 41
5-7 Pressure spectrum of single microphone at different heights below the wall surface $U_\infty=27.9$ m/s, pinhole cap .................. 42
5-8 Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty=18.2$ m/s, mesh cap .................. 43
5-9 Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty=27.9$ m/s, mesh cap .................. 44
5-10 Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty=18.2$ m/s, pinhole cap .................. 45
5-11 Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty=27.9$ m/s, pinhole cap .................. 46
5-12 Proudness experiments by Langeheineken and Dinkelacker ................. 47
5-13 Pressure spectrum of single microphone when pushed well into the boundary layer, $U_\infty=18.2$ m/s, mesh cap .................. 48
5-14 Pressure spectrum of single microphone when pushed well into the boundary layer, $U_\infty=18.2$ m/s, pinhole cap .................. 49
Chapter 1

Introduction

1.1 Background

A shear stress gauge utilizing a surface fence was developed by Yuksel Gür [1] from ideas proposed by Head and Rechenberg. The [3] original concept used Preston tubes to measure pressure across the fence. Gür adapted the fence for use with microphones; this had the advantage of reducing the thermal effects present with hot-wire and preston tube methods, along with providing a greater dynamic range and reducing the averaging effects which are common with these relatively large instruments. It is this more recent gauge which was investigated for this research.

This shear stress gauge utilized two microphones on either side of the surface fence and aligned along the stream-wise direction of flow. The microphones were used to record the pressure differential across the fence; this pressure differential is directly proportional to shear stress according to the 2/3 power law derived by Gur.

The shear stress gauge as developed was only useful for a limited frequency range. Around the range of 2 kHz, the pressure response shows a rise, which is a function of the gauge. Figure 1-1 shows a typical (non-dimensionalized) pressure response and its corresponding peak. This pressure rise makes it difficult to use the gauge for many applications involving shear caused by fluid flows.
1.2 Objective

The objective of this research is to investigate the cause of this pressure rise, and if possible, to eliminate it. If this pressure rise is not in fact caused by the microphones, this research will also investigate the possibility of using low cost microphones in the gauge to lower the cost of the overall gauge.
Figure 1-1: Typical Shear Stress Spectrum ($U_\infty = 20$ m/s)
Chapter 2

Procedure and Apparatus

2.1 Shear Stress Gauge

The shear stress gauge as originally developed by Yuksel Göür is shown in Figure 2-1. Several variations were designed, with the most significant alteration being changing the long rectangular microphone ports to pinhole ports 1/64 inches in diameter. This helped to reduce some of the averaging which occurred because of the relatively large surface area.

2.2 Wind Tunnel Facility

Tests were conducted with the low-turbulence low-speed wind tunnel facility designed by Hanson [2] and located in the Acoustics and Vibrations laboratory at the Massachusetts Institute of Technology (see Figure 2-2). The flow is passed through a test section measuring 15 inches by 15 inches with a flow speed variable over 0 to 30 meters per second. The flow speed is measured using a Betz manometer which measures the pressure difference in the contraction section which is proportional to the velocity.

The shear stress gauge is positioned flush in the test section, as shown in Figure 2-3 with the fence protruding out into the boundary layer. The surface fence is perpendicular to the direction of the flow.
2.3 Data Acquisition

Data was collected using a Masscomp 5400 32-bit computer. Signals from the microphones were first amplified (if necessary) through Brüel and Kjaer 2607 measuring amplifiers, and were low-passed filtered at all times through a Frequency Devices 9015 programmable filter to prevent aliasing. Programs written in Fortran were used to collect and store the data.

Limited data analysis was also made with Ono Sokki and Hewlitt Packard Fast Fourier Transform analyzers, primarily to confirm data output by the Masscomp.

2.4 Transducers

The microphones used in making the shear measurements varied from gauge to gauge. Gür used 1/2 inch diameter electret microphones for his first gauge; later designs utilized Realistic 1/4 inch diameter electret microphones. Brüel and Kjaer 1/8 inch microphones were also used for calibration purposes, and for use in another shear gauge design (Figure 4-1).

All microphones and measuring amplifiers were calibrated with a Brüel and Kjaer 4220 pistonphone, which is known to generate a 250 Hz sine wave at 124 dB (re 20μPa).

2.5 Gauge Calibration

The shear stress gauge was calibrated by comparing the pressure across the fence measured by the microphones, with that given by a Preston tube. A method of using the Preston tube to measure shear stress was developed by Patel [7]. The results of these Preston tube measurements can then be used to determine the accuracy of the shear stress gauge.

Using his calibration methods, it is possible to calibrate the shear stress gauge.
Figure 2-1: Yüsel Gür's original shear stress gauge. Port holes are 0.002" apart. Fence is 0.002" thick.
Test Section in Reverberant/Anechoic Chamber

(Test Section: 38 cm x 38 cm)

General Specifications

Contraction Ratio: 20 to 1
Test Section: 38 cm x 38 cm
Figure 2-3: Experimental setup in the test section of the M.I.T. wind tunnel
Chapter 3

Experiments with Shear Stress Gauge

3.1 Phase-Matching Considerations

It was thought that the 2 kHz rise in the pressure spectrum might be due to an imperfect phase match in the electret microphones used in the gauge. Five Realistic 1/4 inch diameter electret microphones (model #33-1063) were purchased for use in the gauge. Each was tested using the Ono Sokki FFT analyzer to find the pair with the best phase response.

Research done by Gür indicates that a phase difference of less then 5° over the frequency spectrum would yield acceptable results. It was possible to find a pair of microphones with an acceptable phase difference of less then 5° over the frequency range of .1 to 10 kHz.

The calibration was carried out by using the home-made calibrator shown in Figure 3-1 by the following method: an earphone speaker was attached to the top port of the microphone calibrator. Microphone pairs were inserted into the 1/4 inch diameter holes such that each microphone could be compared to every other microphone.. Random noise and swept frequency tones were played through the earphone. Since the geometry of the microphone holes are identical, the pressure throughout the cavity is equal so the phase difference between the responses of the microphones...
should be zero. The signals were collected by the FFT analyzer which generated phase information. Lissajous patterns were also generated with a Nicolet oscilloscope to confirm these results.

The gauge calibrator in Figure 3-4 was designed and constructed to assist with phase calibration. The gauge calibrator allows the phase responses of the microphone to be tested while the microphones are in the gauge, to account for any effects that the gauge geometry may have on the phase response of the microphones.

3.2 Testing

Testing consisted of inserting the shear stress gauge flush into the test section, with the fence perpendicular to the flow as shown in Figure 2-3. The microphone output, after amplification and filtering, was routed to the Masscomp 5400 computer which samples at 30 kHz. 500 samples were normally taken, with each sample consisting of 1024 spectral averages. The data acquisition program originally written by Kay Herbert for wall pressure spectrum measurements [4] is used to record the pressure responses of each microphone as well as taking the difference between the two signals.

Several matched pairs of the electret microphones were inserted in the shear stress gauge and tested in the wind tunnel. Pressure spectra collected by the best of these pairs is shown in Figure 3-2 for several flow speeds. The gauge response continues to show the rise at 2 kHz, a rise which was evident in several testing runs.

This rules out any phase concerns due to the physical system since both the microphone and gauge calibrations show a good phase match. There were concerns that the problem might lie in the pre-amplifier of the electret microphones. To test this hypothesis, several new microphones with different amplification circuitry (Realistic #33-1063) were purchased, calibrated, and used to collect data. As before, the best pair was used to collect data and is shown in Figure 3-3. The pressure rise is still prominent in the pressure-difference plots as well as in the individual microphone responses. Having now accounted for the response of the microphones, the problem with the pressure spike clearly lies elsewhere.
3.3 Vibrations of the Test Structure and Materials

To insure that the 2 kHz rise was not due to a resonance in the wind tunnel or test section, accelerometer measurements were taken of the test section, and of the gauge in the test section. Vibration was minimal across the velocity range of the wind tunnel and there was nothing extraordinary in the 2 kHz region.

The gauge is essentially a brass cylinder. The natural frequency of a cylinder is

\[ f_n = \frac{AE}{L} \]  

(3.1)

where \(A\) is the cross sectional area of the cylinder, \(E\) is the Young’s modulus and \(L\) is the length of the cylinder. Inserting the appropriate values for the brass structure results in \(f_n = 90 \text{ kHz}\), meaning this is more then likely not the problem.

To take into account possible longitudinal vibration of the gauge, the speed of wave through a beam, \(c\) is given by

\[ c = \sqrt{\frac{E}{\rho}} \]  

(3.2)

where \(\rho\) is the density of the material (about \(8.50 \times 10^3 \text{ kg/m}^3\) for brass), and \(E\) is the Young’s modulus (\(100 \times 10^9 \text{ Pa}\)). Using the relation \(\lambda = \frac{\pi}{f}\) where \(\lambda\) is the wavelength, the worst possible wavelength at 2 kHz is about 1.7 meters. Since this value is much greater then the size of the gauge, it is unlikely that longitudinal vibration plays a role.

Transverse vibration is also not an issue since the gauge is tightly clamped in the test section in a hole with very little tolerance, and secured with a set screw.

3.4 Fence

In normal gauge operation, both microphones exhibited the pressure rise, although the effect tended to be more prominent in the downstream microphone. To see if the
surface fence was causing this effect, several runs were made with the surface fence retracted into the gauge.

The results of these runs indicate that the pressure responses of both microphones are roughly equal, and both still show the pressure rise, as shown in Figure 3-5; several differences to arise however in these set of pressure spectra. The rise is now at a slightly higher frequency (≈ 4.5 kHz rather then 2 kHz). When the responses of the two microphones are differenced (Figure 3-6), the pressure spike shifts in frequency with flow speed, from about 1 kHz at 9.1 m/s to 4 kHz at 24.2 m/s.(the low low-frequency response is due to the absence of the fence and was expected).

3.5 Observations

It seems that the suspected phase problems with the microphones have very little to do with the pressure spike. A new issue arises however when looking at the effect the fence height has on the response. The pressure spectra in Figure 3-6 imply a speed dependence, which could indicate that turbulent eddies may be involved, but there is no conclusive evidence to support this.

This phenomena may be due to a convection effect resulting from the port holes being too close together. The gauge was originally designed such that decaying eddies would not influence the data. However the convection effect which was thought to be small might be the cause of this seemingly flow dependent occurrence. A more detailed discussion is presented in Appendix A.

One very probable cause of the pressure spike is a Helmholtz resonance. The fit of the microphones in the shear stress cavity forms a small volume which couples the microphones with the surface through a port 1/64 inches in diameter. This cavity may excite a resonance when air flow is passed over the port, much like blowing on the mouth of a jug. This system is known as a Helmholtz resonator.

The effect this volume has on the 2 kHz resonance is difficult to predict. Therefore a new experiment was designed so that the effects of this resonance on the pressure rise could be explored.
Figure 3-1: Microphone calibrator used for phase matching microphone pairs. (Dimensions in mm unless specified) Based on a design by F. Kameier
Figure 3-2: Pressure difference spectrum using original phase-matched electret microphones
Pressure Difference Spectrum - New Realistic Electret Mikes

Figure 3-3: Pressure difference spectrum using new Realistic electret microphones to account for pre-amplification issues
Figure 3-4: Gauge calibrator used for phase matching microphones in the shear stress gauge
Figure 3-5: Pressure spectra of upstream and downstream microphones with fence height=0
Pressure Difference Spectrum (zero fence height)

Figure 3-6: Pressure difference spectrum measured by shear stress gauge with fence height=0
Chapter 4

Design of a New Gauge

4.1 Helmholtz Resonator Effects

A Helmholtz resonator consists of a volume connected to an outer environment through a relatively small opening. The microphones in the shear stress gauge form such a volume which may have inadvertently resulted in the pressure rise. By setting the volume to a known value, it should be possible to move this resonance to a frequency outside the pertinent measurement range, eliminating the problem.

The resonant frequency for a Helmholtz resonator is given by

\[ \omega_0 = c \sqrt{\frac{S}{L'} V} \]  \hspace{1cm} (4.1)

[5] where \( c \) is the speed of sound (about 340 m/s), \( S \) is the area of the opening (.001m\(^2\)), \( L' \) is the effective length of the neck formed by the opening (4.75mm assuming a flanged end) and \( V \) is the volume of the cavity coupled to the air.

Using the ratio of radii of the pinhole opening to the 1/4" electret microphone
opening, $r_o/r_{mike}$, an expression can be created relating the Helmholtz resonance to the opening length:

$$f_o = \frac{c}{2\pi r_{mike}} \sqrt{\frac{1}{L'h}}$$  \hspace{1cm} (4.2)

Substituting in constants, expression 4.2 reduces to

$$f_o = \frac{5.41 \times 10^3}{\sqrt{L'h}}$$  \hspace{1cm} (4.3)

Reasonable values for $h$ (with respect to the gauge) were substituted into equation 4.3 to see if a Helmholtz resonance may be a factor:

<table>
<thead>
<tr>
<th>$h$(mm)</th>
<th>.01</th>
<th>.05</th>
<th>.1</th>
<th>.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_o$(kHz)</td>
<td>24.8</td>
<td>11.1</td>
<td>7.8</td>
<td>3.5</td>
<td>2.48</td>
</tr>
</tbody>
</table>

It seems that for a value of $h=1$ mm, the system has a Helmholtz resonance around the frequency range of the pressure spike. Furthermore, as this length is lessened, the frequency of this resonance is dramatically affected.

It was also noted that the microphone cavity was probably cone shaped rather then right-angular due to the use of an angular drill bit. An analysis of this extra volume shows that the Helmholtz resonator frequency is somewhat dependent on the volume of the cone (more so than the length of the tube) but the effective length of the tube was accurate enough so that it was used to simplify the calculations.

### 4.2 Design Considerations

To investigate the effect of the Helmholtz resonator on the pressure rise, a gauge was designed such that the Helmholtz effect would be intentionally placed at a value outside of the effective measurement range (in this case, $\approx$11 kHz). The length $h$ was made as small as possible, about 5/64 inch; a length shorter then that would lead to deformation of the gauge surface as the amount of brass between then the cavity and the outer wall became thinner and weaker.

This new gauge was designed to be used with Brüel and Kjaer type 4138 1/8 inch diameter microphones. This design has the added benefit of completely ruling out any
phase matching considerations since these microphones are phased-match to within 1° up to 50 kHz. Mesh caps were used to minimize any additional Helmholtz effects. The height of the surface fence remained the same as the previous gauge. This new gauge is shown in Figure 4-1.

4.3 Calibration

The Brüel and Kjaer microphones were calibrated with the same microphone calibrator shown in Figure 3-1; special adapters were used to make up for the smaller diameter of the 1/8 inch microphones. The new gauge was calibrated with the gauge calibrator in Figure 3-4.

4.4 Experiments

The new shear stress gauge was positioned in the test section of the wind tunnel exactly as the previous gauge (Figure 2-3). Since the sensitivity of the microphones was much less then that of the electrets (about .8 mV/Pa as opposed to about 3 mV/Pa for the electrets) the microphone signals were amplified using the Brüel and Kjaer 2607 measuring amplifiers. Otherwise, tests were conducted in exactly the same manner as the previous experiments.

The new gauge was used to make pressure measures over the operating range of the wind tunnel. As shown in Figure 4-2 the expected Helmholtz resonance at 11 kHz does appear; however the 2 kHz rise appears as well. Overall the behavior was the same as the previous gauge, except for occasional low-frequency noise which was found to be a product of the measuring amplifiers.

Brüel and Kjaer microphones using pinhole caps and mesh were both used in the gauge in an attempt to identify any changes which may be associated with the microphone diaphragm area exposed. No significant changes were found.

This experiment conclusively determined that the pressure spike is not due to a Helmholtz resonator. The microphones and dimensions in both gauges were different,
yet the pressure rise appears in the response of both gauges and at the same frequency. This pressure effect now seems to have three possible causes:

- the problem lies in the geometry of the gauge in general, and the microphone cavity in particular, since the microphones themselves are not at fault.

- turbulent eddies are interacting with the gauge ports and/or the microphones.

- possible convection effects which may be a function of the distance between the microphone ports.

These three problems are not necessarily mutually exclusive, but were treated as such to see if either had a causal effect on the pressure spike.

### 4.5 Mesh Experiments

There were concerns that even at 1/64 inch in diameter, the gauge ports may still be large enough that the microphones may still be averaging the response over the exposed surface area. Turbulent eddies may also be causing unanticipated affects across the microphone diaphragms.

An experiment by Ronneberger [9] experimented with fine pieces of mesh stretched over a microphone port used in wall pressure measurements. In an attempt to repeat this experiment, thin pieces of mesh cloth were stretched over the port holes. The effect of this on the pressure rise was negligible. The response over the spectrum overall was lower due to parts of the cloth blowing over the fence and disrupting the flow. It was impossible to position the cloth so that it did not interfere with the flow, so these experiments were discontinued.

Also it is likely that the mesh was not fine enough to produce the desired effect even if it was possible to positioned the cloth correctly, so this was research was abandoned.
4.6 Effects of surface roughness

The shear stress gauge is located flush against a plexiglass panel in the test section of the MIT wind tunnel. Original experiments were performed with the wall section as is. The plexiglass was later painted with black paint, and this resulted in a noticeable change in roughness. Experiments performed with both gauges and both sets of microphones resulted in a slightly lower pressure rise, although it was still distinct.

It is probable that the additional roughness has enough of an effect on the boundary layer to cut the pressure response at the surface of the test section; however this does not address how the pressure spike occurs, and so this was no longer pursued, although it does lead credence that turbulent eddies are interfering with the pressure measurements.
Figure 4-1: 1/8” Microphone Shear Stress Gauge (fence not shown). Holes are 1/64” apart (center to center). Fence is 0.002” thick.
Figure 4-2: Pressure difference spectrum using new shear stress gauge and Brüel and Kjaer microphones
Chapter 5

Single Hole Microphone Experiments

5.1 Apparatus

The Brüel and Kjaer 1/8 inch microphones were used in tube experiments to explore the effects of the geometry on the shear stress gauge and on the pressure rise. The experimental apparatus consisted of the brass cylinder in Figure 5-1 and a single microphone outputting a signal through a measuring amplifier, and into the Masscomp computer. The position of the microphone in the tube could be varied so that it could be set flush with the gauge surface, or to a known height above or below the surface. The brass cylinder was set flush in the same test section as the shear stress gauges. Pressure spectra were taken using this setup over several flow speeds and different microphone positions to observe any relation between pressure peaks and microphone position.

It should be noted that the geometry of this tube differs significantly from the shear stress gauges in that the microphone cavity is of a constant width. This has the result of completely eliminating any Helmholtz resonances since the cavity opening is on the order of the volume length.
5.2 Experiments

Originally the microphone was kept below the surface of the test section. Using shims of variable thickness, the microphone was varied from a maximum height of .1 inches below the surface to about .35 inches below the surface. Figures 5-2 through 5-7 show the results of experiments using three different flow speeds and different microphone caps. There is a negligible difference in the responses suggesting that at least below a certain point, there is no effect in increasing the volume in front of the microphone. There is virtually no difference due to the different microphone caps which is to be expected since the mesh pinhole caps expose about the same total surface area to the flow.

The pressure rise is apparent in the responses, although the frequency of the spike shifts with flow speed, again suggesting a flow dependence. However the microphone is more then likely too deep in the port to provide any useful information concerning the cause of the pressure spike.

5.3 Proudness

Experiments performed by Langeheineken and Dinkelacker [6] involved making pressure measurements using an identical microphone in a similar experimental setup, the major difference being that a microphone cap was not used. This exact experiment was not replicated out of concerns of damaging the relatively expensive microphones. However the next experiments did involve taking measurements at heights at, below and above the surface of the wall.

As shown in Figure 5-12, Langeheineken and Dinkelacker observed an increase in the one-third octave band centered at 2 kHz as the microphone was pushed into the boundary layer. The experiments performed in the MIT wind tunnel proved almost the opposite; as seen in Figures 5-8 through 5-11 the pressure response measure over several speeds and with two different caps decreases as the microphone is raised, with the 2 kHz peak almost eliminated as the microphone is raised above the surface.
It was noted that the boundary layer in the M.I.T. wind tunnel was unusually large, and probably much thicker than that of the tunnel used by Langeheineken and Dinkelacker. Taking this into account, the microphones were pushed further into the boundary layer. As shown in Figures 5-13 and 5-14 there is a point (≈ 6mm) where there the effect noted by Langeheineken and Dinkelacker finally occurs. However it is unclear as to whether this effect is due to the same phenomena witnessed by Langeheineken and Dinkelacker, or simply due to eddies shed of the microphone structure.

The results do make clear that the boundary layer in the region from 0 to 6 mm exhibits an unknown behavior, and this is probably related to the pressure rise. This makes sense in the context of the shear stress gauge, since the microphone downstream of the gauge, which measures the turbulence created by the gauge experiences the worst pressure response. When the fence is lowered, the shear stress gauge acts as two tubes, with equal pressure responses (Figure 3-5).
Figure 5-1: Schematic of gauge used for single-microphone pressure measurements and experimental setup
Figure 5-2: Pressure spectrum of a single microphone at different heights below the wall surface $U_\infty=9.15$ m/s, mesh cap
Figure 5-3: Pressure spectrum of a single microphone at different heights below the wall surface $U_\infty=18.2$ m/s, mesh cap
Figure 5-4: Pressure spectrum of a single microphone at different heights, below the wall surface $U_\infty=27.9$ m/s, mesh cap
Figure 5-5: Pressure spectrum of single microphone at different heights below the wall surface $U_\infty = 9.15$ m/s, pinhole cap
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Figure 5-10: Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty = 18.2 \text{ m/s}$, pinhole cap
Figure 5-11: Pressure spectrum of single microphone just below, just above and at the surface of the wall, $U_\infty = 27.9$ m/s, pinhole cap
Figure 5-12: Proudness experiments by Langeheineken and Dinkelacker
Figure 5-13: Pressure spectrum of single microphone when pushed well into the boundary layer, $U_\infty=18.2$ m/s, mesh cap
Figure 5-14: Pressure spectrum of single microphone when pushed well into the boundary layer, $U_\infty=18.2$ m/s, pinhole cap
Chapter 6

Conclusion

The research was not able to conclusively determine the cause of the 2 kHz pressure rise in the shear stress gauge; however several probable causes have been investigated and eliminated. What was originally thought to be a relatively simple problem in phase response has proven to be far more complex.

The problem seems to lie in the combination of the gauge geometry and the behavior of the boundary layer close to the flow surface. The experiments reveal that something unusually is happening in the region of 1 to 2 millimeters above the wall surface. Convection seems to be at least part of the problem, but since the convection effects do not show up in the single hole experiments but the pressure rise is still occurs, it probably is not the only culprit.

One positive outcome of this experiment is that since the problems do not seem dependent on the microphones, low-cost transducers could be used to provide accurate measurements at a fraction of the cost of other methods. The Realistic electret microphones used in this experiment cost under $25, and were relatively durable.

Unfortunately this research is not complete simply because it is difficult to see what behavior could affect and is affecting the gauge.
6.1 Recommendations

The best way to proceed with the development of a shear stress gauge is to develop a design utilizing flush-mounted microphones. The single-hole experiments in Chapter 5 have shown that the pressure rise disappears when the microphone is about flush with the surface, so it seems reasonable that the fence would work as intended if the transducers were flush on both sides of the gauge.

Experiments similar to the wall pressure measurements but with two transducers close together would probably be useful in exploring the convection effects. However since the pressure rises has appeared in essentially every experiment performed for this research, it seems that an exploration of the boundary layer near the wall would produce the best results since the convection effects do not appear often or under the normal operating conditions of the shear stress gauge.
Appendix A

Convection Effects

It is suspected that the seemingly flow-dependent pressure rise in Figure 3-6 may be due to a convection effect. The cross spectral pressure, $\Phi_{\Delta P}$ is given by

$$\Phi_{\Delta P} = \Phi_A + \Phi_B - 2\Ree\Phi_{AB} \tag{A.1}$$

where $\Phi_A$ and $\Phi_B$ are the individual pressure spectra of transducers A and B, and $\Ree\Phi_{AB}$ is the real part of the cross section from transducers A and B.

The cross spectrum can be expressed as

$$\Phi_{AB} = \Phi_A A\left(\frac{r_1\omega}{U_c}\right)B\left(\frac{r_3\omega}{U_c}\right)e^{\frac{wr_1}{U_c}} \tag{A.2}$$

where $r_1$ and $r_3$ are the separation of the transducer ports, and $U_c$ is the convection velocity. The shear stress gauge was designed so that $\Phi_A = \Phi_B$, resulting in

$$\Phi_{\Delta P} = 2(\Phi_A - \Ree\Phi_{AB}) \tag{A.3}$$

$$\Phi_{\Delta P} = 2\Phi_A \left(1 - \cos\frac{wr_1}{U_c}\right) \tag{A.4}$$

For the shear stress gauge and wind tunnel facility, typical values are $r_1 = 1/32" = .8\text{mm}$, $\delta^* = 1/4" = 6.5\text{ mm}$ and $U_c = .7U_\infty$.  

52
To solve for the maximum of equation A.4, \( \frac{\omega \delta^*}{U_c} = \frac{\pi}{2} \). To express this in terms of the boundary layer thickness, \( \delta^* \),

\[
\frac{\omega \delta^*}{U_\infty} = \frac{\pi \delta^* U_c}{2 r_1 U_\infty}
\] (A.5)

For \( U_\infty = 12 \text{m/s} \), and a boundary layer thickness of 6 mm, this results in \( \omega = 16,000 \) rad/sec, or \( f = 2.5 \text{kHz} \), which is the approximate region of the pressure rise in Figure 3-6. This derivation describes pressure convection, and it theoretically could be at least partially involved in the 2 kHz pressure rise affecting the shear stress gauge.
Bibliography


