# Theory & Design for Mechanical Measurements Laboratory ME 435L Lab Manual

Revised and Updated
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by

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*(Note: this laboratory manual is a work in progress, this version supersedes all previous versions and the material in this manual is subject to change at any time based upon the motivation of author)*

# PRESSURE TRANSIENT FOURIER ANALYSIS EXPERIMENT


## Objectives

1. To calibrate a typical strain gage pressure transducer.

2. To determine by Fourier Analysis (harmonic analysis) the equation for a fluid dynamic transient curve and to compare the experimentally determined curve with a computer generated curve so as to determine the number of harmonics necessary to obtain reasonable accuracy.

## Discussion

The transient flow of incompressible fluids in ducts of constant area is of importance in many fields of engineering. The fundamental significance of solving problems involving transient flow phenomena is that such solutions provide a complete history of the flow field and allow for detailed interpretation of how steady state conditions were obtained, and why certain characteristics and phenomena dominate once steady state conditions do exist.

The fluid dynamic principles involved in conducting such transient studies are not within the framework of this course. We are, however, concerned with instrumentation and the proper evaluation of data obtained by means of mechanical measurements resulting from such studies. Of such concern here are the resulting dynamic (transient in this case) output signals. Such signal information as the fundamental frequency, the harmonic components with their relative amplitudes, frequencies, and phase relations are often requested from the recorded waveform. This type of information is most easily obtained by performing a harmonic analysis of the output signal.

The principle of a Fourier Analysis is that a given arbitrary function of a real variable, time in this case, can be represented as a sum of sine and cosine functions in which amplitudes of the functions are determined by the Fourier Analysis (see sections 2.4 and 2.5 of Reference 1). The time period in this experiment corresponds to the time period from initiation of flow to the completion of one full cycle of the pressure transient. A mathematical representation of the amplitudes to be determined in the present problem would appear as shown in the equation below, *p(t)* is the pressure curve fit reconstruction obtained by harmonic analysis of the experimental pressure trace, and the remaining symbols defined in Reference 1:

$$p(t) \approx \frac{A_o}{2} + \sum_{n=1}^{N/2} C_n \sin(\omega_n t + \phi_n)$$

A computer program then solves for the coefficients and phase angles of the expansion. The program performs the DFT calculation described in Reference 1, Section 2.5.

**Equipment**

1. Pressure transducer – Strain Gage type Viatran Model 119
2. Op Amplifier Circuit Board
3. Flow initiation supply tank
4. HP 34970A Data Acquisition/ Switch Unit
5. HP 35670A Dynamic Signal Analyzer
6. Hand held voltmeter

**References**

1. Figliola and Beasley, "Theory and Design for Mechanical Measurements", 4th Ed., Wiley, 2006

**Useful Conversion Constant**

(1 in. $H_2O$ = 0.036136 psi = 249.082 N/$m^2$)

**Procedure**

1. Acquire Calibration Curve Data

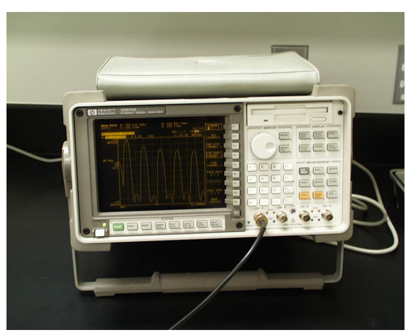
   a) Fill the sight glass of the tank to 10 inches
   b) Measure the voltage across the un-amplified input of the Op-Amp board using a hand held voltmeter.

c) Measure the amplifier voltage by holding the arrow key on the HP 34970A to freeze the voltage reading, so that you can write it down on your lab sheet.
d) Release 1 inch of water form the sight glass and repeat voltage measurement of part b) until sufficient data has been gathered (4 or 5 points should suffice)
e) Make note of the manufacturer's calibration data shown in the data sheet attached to the pressure transducer

**Viatran Model 119 Pressure Transducer**

2. Acquire Pressure Transient Data

a) Fill the flow initiation supply tank to ten inches depth. Use the sight glass and ruler attached to the tank.
b) Connect BNC connection from Operational Amplifier Circuit to Channel 1 of HP 35670A Dynamic Signal Analyzer
c) Turn on Signal Analyzer by pushing the small white button at lower left hand corner of display
d) Turn off the HP 34970A Data Acquisition Unit before proceeding to the next step



**Agilent HP 35670A Dynamic Signal Analyzer**

*Initialize the Analyzer*

a) Press the green **[Preset]** hardkey on the Analyzer

b) Press [DO PRESET] softkey (F1)

c) Press the [System Utility] hardkey

d) Press the [**Auto Calibration**] softkey (F2) to toggle Auto-Cal **OFF**

e) Press **[Inst Mode]** hardkey

*f)* Press [CHANNELS **1** 2 4] softkey (F7) until **1** is highlighted

*Set the Record Time Length*

a) Select the time record length

b) Press the **[Freq]** hardkey

c) Press the [RECORD LENGTH] softkey (F8)

d) Enter 0.5 and then press the [S] softkey (F1)

*Display the Time Waveform*

a) Press the **[Disp Format]** hardkey

b) Press the [SINGLE] softkey (F1)

c) Press the **[Active Trace]** hardkey

d) Press the [A] SOFTKEY (F1)

e) Press the **[Meas Data]** hardkey

f) Press the [CHANNEL **1** 2 3 4] softkey (F1) until **1** is highlighted (make sure box around [CHANNEL **1** 2 3 4] lights up). Is the box highlighted ? Make sure it is before proceeding.

g) Press the [TIME CHANNEL 1] softkey (F5)

*Set Up Event Triggering*

a) Press the **[Trigger]** Hardkey

b) Press the [CHANNEL **1** 2 3 4] softkey (F3) until **1** is highlighted (make sure box around [CHANNEL **1** 2 3 4] lights up)

c) Press the [TRIGGER SETUP] softkey (F6)

d) Press the [CHANNEL LEVEL] softkey (F1)

e) Enter 0.9 the press the [V] softkey (F1)

f) Press the [SLOPE POS **NEG**] softkey (F5) until **NEG** is highlighted

*Use Pre-triggering to Acquire Some Data Before the Transient Event Trigger Point*

a) Press the [ALL CHANNELS] softkey (F8)

b) Press the [CHANNEL * DELAY] softkey (F9)

c) Enter -0.5 then press the [S] softkey (F1)

***Set Up the Data Buffer***

a) Press the **[Inst Mode]** hardkey

b) Press the [TIME CAPTURE] softkey (F9)

c) Press the [BUFFER LENGTH] softkey (F5)

d) Enter 2 and then press the [S] softkey (F1)

e) Press the [ALLOCATE BUFFER] softkey (F6)

f) Press the [CONFIRM ALLOCATE] softkey (F1)

***Start the Data Acquisition***

a) Press the [FILL BUFFER] softkey (F2), the analyzer should show in highlighted text in the upper left hand corner above the trace: **WAITING FOR CH 1 TRIGGER**

b) Pull the cork on the bottom of the water tank, as the buffer is filled, the analyzer should display a message such as CAPTURE 25% COMPLETE, etc.

***Examine the Capture Buffer***

c) Press **[Meas Data]** hardkey

d) Press [CHANNEL **1** 2 3 4] to highlight **1**

e) Press the [MORE CHOICES] softkey (F9)

f) Press the [CAPTURE CHANNEL 1] softkey (F6)

e) Press the **[Scale]** hardkey

f) Toggle the [AUTOSCALE] softkey so that ON is highlighted. A display of the pressure transient should appear on the screen of the analyzer

***Save the Capture Buffer to Floppy Disk***

a) Insert a formatted 3.5 inch floppy disk into the floppy drive of the Signal Analyzer

b) Press the **[Save/Recall]** hardkey

c) Press the [DEFAULT DISK] softkey (F9)

d) Press the [INTERNAL DISK] softkey (F3)

e) Press the **[Save/Recall]** hardkey

f) Press the [SAVE DATA] softkey (F1)

g) Press the [FORMAT] softkey (F2) until [ASCII] is highlighted

h) Press the [SAVE TRACE] softkey (F1)

i) Press the [INTO FILE] softkey (F9)

j) Press the [ENTER] softkey (F1) to accept the default filename

***Perform FFT on Captured Data Using the Analyzer***

a) Press the **[Save/Recall]** Hardkey

b) Press the [SAVE DATA] Softkey (F1)

b) Press the [SAVE TRACE] Softkey (F1)

c) Press the [INTO D1] softkey (F1). A message stating “Trace A Saved Into D1” should appear on the screen

d) Press the **[ANALYSIS]** Hardkey

e) Press the [DEFINE FUNCTION] Softkey (F1)

f) Press the [DEFINE F1] Softkey (F1)

g) Press the [OPERATION] Softkey (f5)

h) Press the [FFT( ] Softkey (F6)

i) Press the [DATA REG] Softkey (F2)

j) Press the [DATA REG D1] Softkey (F1)

k) Press the [ENTER] Softkey (F7)

l) Press the [**Meas Data]** Hardkey

m) Press the [MORE CHOICES] Softkey (F9)

n) Press the [MATH FUNCTION] softkey (F7)

o) Press the [F1] Softkey F1. This activates the shortcut to the FFT of Data Register 1 we defined above. Now, the Analyzer screen should show the FFT of the Raw Data you captured above

p) Press the **[Save/Recall]** Hardkey

q) Press the [SAVE DATA] Softkey (F1)

r) Press the [SAVE TRACE] Softkey (F1)

s) Press the [INTO D2] Softkey (F2), a message stating “TRACE A SAVED INTO D2” should flash across the Analyzer’s monitor

t) Press the **[Rtn]** (Return) Softkey

u) Press the [SAVE DATA] Softkey (F1)

v) Press the [FORMAT] Softkey (F2) until [ASCII] is highlighted

w) Press the [SAVE TRACE] Softkey (F1)

x) Press the [INTO FILE] Softkey (F9)

y) Press the [ENTER] Softkey (F1) to save the FFT trace, the default name of the file should be TRAC2.TXT

***Perform Inverse FFT on Captured Data Using the Analyzer***

a) Press the **[Analysis]** Hardkey

b) Press the [DEFINE FUNCTION] Softkey (F1)

c) Press the [DEFINE F2] Softkey (F2)

d) Press the [OPERATION] Softkey (F5)

e) Press the [INVERSE FFT( ] Softkey (F7)

f) Press the [DATA REG] Softkey (F2)

g) Press the [DATA REG D2] Softkey (F2)

h) Press the [ENTER] Softkey (F7)

i) Press the **[Meas Data]** Hardkey

j) Press the [MORE CHOICES] Softkey (F9)

k) Press the [MATH FUNCTION] Softkey (F7)

l) Press the [F2] Softkey (F2), this will invoke the IFFT of the data stored in data register D2. The IFFT trace should now appear on the Analyzer screen.

m) Scale the axes of the IFFT output trace using the **[Trace Coord]** Hardkey and subsequent softkeys if needed

n) Select a particular region of the trace to zoom in on using the **[Scale]** Hardkey and subsequent softkeys if needed

o) Press the **[SAVE/RECALL]** Hardkey

p) Press the [SAVE DATA] Softkey (F1)

q) Press the [SAVE TRACE] Softkey (F1)

r) Press the [INTO FILE] Softkey (F9)

s) Press the Trace Coordinate Hardkey and set the y-axis scale to Liner via the (F1) softkey (note the plot defaults to dB)

t) The Analyzer will label the IFFT trace TRAC3.TXT by default, press [ENTER] (F1) to write the trace to the floppy disk

***Analyze the Time Captured Data Taken Above Using the EXCEL Program to Generate a Set of Frequency Spectrum Plots***

3. Download the EXCEL worksheet FFT Pressure Transient from Dr. Anderson's webpage:

http://www.csupomona.edu/~kranderson1/**ME 435L DFT EXCEL/VBA Worksheet**

Import your data from TRAC1.TXT into the above worksheet and generate amplitude, power and phase plots using the EXCEL worksheet.

**Write-Up Questions/Analysis**

Address items (a) through (j) concisely in your lab write-up.

a) Quantitatively explain the wiggle phenomena present in the DFT fit of the Pressure Transient. Why doesn't the DFT fit the end-points correctly ?

b) What did you choose as the fundamental period, $T$ (sec) for purposes of doing the Fourier analysis ? Why ?

c) Compare the experimentally determined sensitivity $K$ of the transducer with the transducer spec sheet data and explain any discrepancies.

d) Using the curve-fit determined via the EXCEL DFT worksheet, calculate the pressure (in. of H2O) for $\omega t$ = 120$^o$ and 180$^o$. Explain any difference between your calculated result and the original experimental data. (Note: when $t = 0$, $\omega t = 0^o$).

Frequency Resolution

The frequency resolution of an FFT analyzer is usually stated in number of lines. The most common offerings are 400 and 800 lines, although some analyzers, such as the HP 35670A, offer variable resolution. A 400 line FFT analyzer, set up to display a 4 kHz span, would have a frequency resolution of 400 Hz per 400 lines, or 10 HZ per line. The length of the time record determines how long a given measurement will take and the maximum frequency that you can measure. For example, an 800 line analyzer measuring a 1 kHz span requires a 0.8 second time record. A 3200 line analyzer measuring the same 1 kHz span requires a 3.2 second time record. This relationship is independent of processing speed. The smaller the span, the longer the time record required. You can easily make calculations to determine values for four inter-related functions; maximum frequency, time-record length, frequency resolution, and frequency span as follows:

e) Maximum frequency = N/2 × 1/time-record length
f) Time record length = number of lines/frequency span
g) Frequency resolution = 1/Time record length
h) Frequency span = Frequency resolution × FFT lines

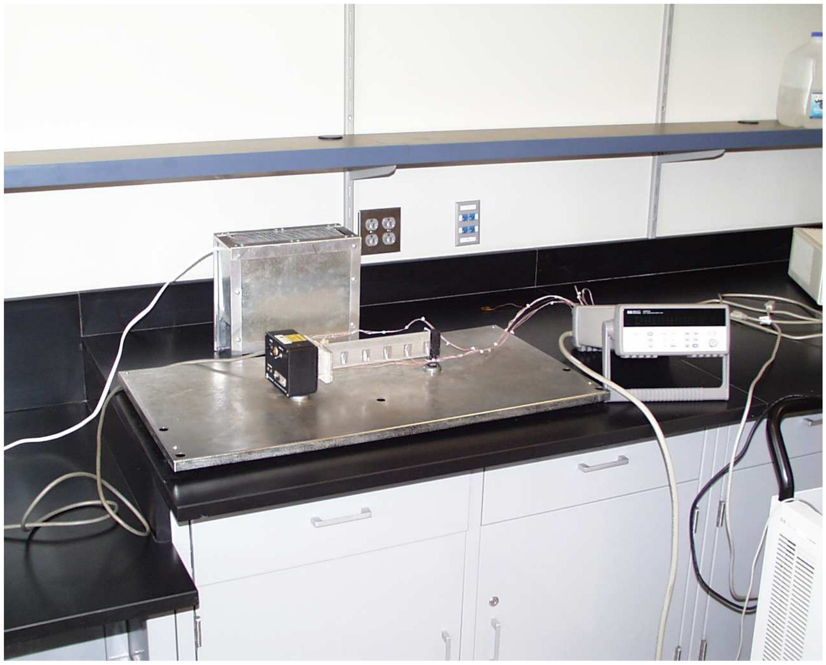
Perform the above calculations for your dataset and lab procedure settings. Compare and comment on the above results with standard Nyquist frequency based calculations for $f_{Nyq,} f_s, \Delta f$ (Figliola and Beasley pg. 238)

i) Using the data you acquired, try and perform a data reconstruction using Figliola and Beasley Eqn (7.10) page 243 as follows:

$$y^*(t) = \frac{1}{\pi}\sum_{r=1}^{4096} y(r\delta t)\frac{\sin[\pi(t/\delta t) - r]}{t/\delta t - r}$$

j) Comment on the applicability of Eqn 7.10 as used in part i) above.

# FIN HEAT LOSS EXPERIMENT



**Objectives**

A. To investigate the heat transfer characteristics of a fin.

B. To gain a basic understanding of how menu-driven data acquisition software can be used to collect experimental/test data with a PC Data Acquisition System

**Equipment**

1. Pentium Computer

2. Teknikit Fin Assembly with heater and fan

3. Agilent Benchlink Software

4. Data Acquisition/Switch Unit (HP 34970A)

**Pre-lab Assignment**

Review or study heat transfer from rectangular fins in an introductory heat transfer text.

Review section 8.5 of Figliola and Beasley

**Test Procedure**

1. Turn on the computer and the HP data acquisition unit.

2. Login to windows NT by typing in user name ”student” and password “engineering” in lower case.

3. Click the Benchlink Data Logger Icon to start the data acquisition program

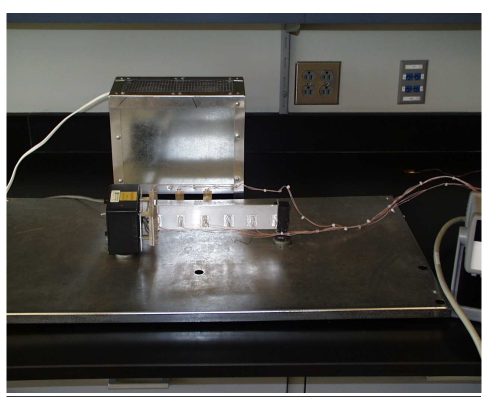
4. After the welcome menu pops up, choose the option: “Load and existing setup from instrument upload” and click OK. Find the setup labeled “nicesetupfortemps”. Click OK again when the upload menu pops up. The software will then upload all of the information needed for the data acquisition unit to communicate with the computer.

5. Note: only channel 101-107 are active in this experiment: TC101 = ambient (taped to base of test stand) TC102 = TC nearest heater and TC 107 = TC nearest fin end.

6. Start the data collection by clicking “Scan” from the top menu bar and then, “Start Scan” and then click OK. Click “Start” to start scanning.

7. Record steady state ambient readings directly from the screen dump given in the small window on the lower right hand side area of the careen by clicking on the window displaying the numerical values of the TC readings and to make its border blue. Then press ALT-PRNT SCRN and dump the bitmap into a Microsoft Word file for your records.

**FREE CONVECTION DATA GENERATION**



8. Turn on the heater power.

9. Data collection will start when the data acquisition begins scanning all the channels at the interval you have set. Start scanning by clicking “Scan” from the top menu bar and then “Start Scan.” Click on “Settings” to change scan time to 1 sec. And then

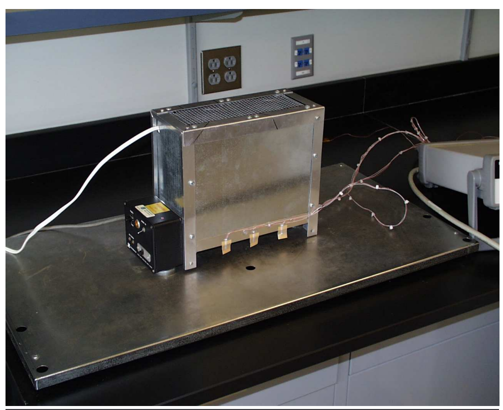
click “OK”. Click “Start” to start scanning. As the fin becomes heated, the temperature traces will gradually become off scale. You can adjust the reference temperature, time/div, and units/div per channel during scanning to optimize your display. Use the Benchlink output as a visual aid to declare steady state.

10. After steady state is reached, you can stop scanning by selecting “Scan” and then “Stop Scan”. A “Scan Stopped” dialog box will pop up. When prompted, enter the data file name and press OK. This file now contains your data set for the free convection part of the experiment. You can use the data browser (under view function) to rewind the data to the time segment that you are interested and note the beginning and end of the time frame.

11. Repeat Step 7 above to read off steady state temperatures from the data logger for the free convection data generation.

12. DO NOT TURN OFF THE HEATER POWER, you will need to have it on for the next phase of the test.

## FORCED CONVECTION DATA GENERATION



13. Place the Fan/Duct Apparatus on top of the Fin Unit. Turn on the fan. Resume data collection by selecting “Scan” and then “Start Scan” to start scanning. Adjust units/div and Reference as fin is cooled for optimal display. Once steady state is reached, stop scanning by selecting “scan” and then “stop scan”. Make sure you save the file under a separate name this time. This file now contains your data set for the forced convection part of the experiment.

14. Repeat Step 7 above to read off steady state temperatures from the data logger for the forced convection data generation.

15. Exit program and turn off all equipment.

**Analysis and Report**

1. Measure and record the overall dimensions of the fin and the thermocouple locations. Include a dimensioned sketch in your report. The fin is made of aluminum with a thermal conductivity of 138 W/m-K.

2. From the computer printout, obtain the fin temperatures from the scan immediately before the fan was turned on. These are the steady-state free convection temperatures. The steady-state forced convection temperatures are obtained from the very last scan.

3. Plot fin temperature vs. length for both the steady-state free convection and the forced convection case on a single sheet of graph paper for comparison.

4. Plot the temperature difference ratio $\theta/\theta_b$ vs. length for both the free convection and the forced convection case where $\theta$ is the difference between the local fin temperature and ambient temperature, and $\theta_b$ is the difference between the fin base temperature and ambient temperature on a single sheet of graph paper for comparison.

5. Compute the theoretical free convection Nusselt number using the heat transfer handbook correlation [cf. Ch 9 of Incropera & DeWitt]

$$Nu_{free,theory} = \frac{h_{free,theory} L}{k} \approx \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}} \right\}^2$$

where the Rayleigh number is given by,

$$Ra_L = Gr_L Pr = \frac{g\beta (T_s - T_\infty) L^3}{\nu\alpha}$$

6. Compute the theoretical forced convection Nusselt number using the heat transfer handbook correlation [cf. Ch 7 of Incropera & DeWitt]

$$Nu_{forced,theory} = \frac{h_{forced,theory} L}{k} \approx 0.664 Re^{1/2} Pr^{1/3}$$

where the Reynolds number based upon the flow rate, $\dot{m}$ of the fan is given by

$$Re = \frac{VL}{\nu} = \frac{\dot{m}L}{\mu A}$$

7. What is the combined theoretical Nusselt number when free and forced convection are present ? (Incropera & DeWitt, 4th Ed. Eqn. 9.64, pg. 515 $Nu^n_{combined,theory} = Nu^n_{free,theory} \pm Nu^n_{forced,theory}$) What is the theoretical combined free and forced exponent, $n$ ?

8. Free convection Heat Transfer Analysis

- Divide the fin into "i" segments with each TC in the middle of each segment. The two end segments will only be half the size of the others. Calculate the local free convection heat transfer coefficient at each segment using the following expression for free convection from a vertical plate in air at ambient conditions.

$$h_i = 1.45\left[\left(T - T_\infty\right)/ y\right]^{0.25} \quad (\text{W/m}^2 - \text{K})$$

where

$h_i$ = local heat transfer coefficient at segment "i" (W/m$^{2}$-K)
$T$ = average temperature of fin of segment "i" (°C or K) = ambient temperature (°C or K)
$T_\infty$ = ambient temperature (°C or K)
$y$ = vertical height of fin (m)

- Next compute the area weighted average experimental free heat transfer coefficient, given as follows:

$$h_{free,experimental} = \frac{\sum h_i A_i}{\sum A_i}$$

where

$A_i$ = surface area of segment "$i$"

There are three cases for which fin heat transfer can be analytically modeled:

CASE 1: The fin is very long ($T_{end} \cong T_\infty$)

For this case, the temperature profile can be calculated as:

$$\frac{\theta}{\theta_b} = \frac{(T_x - T_\infty)}{(T_{base} - T_\infty)} = e^{-mx}$$

where

$$m = \sqrt{\frac{h_{free,experimental} P}{kA_c}}$$

and the parameters which have not yet been defined are:

$x$ = lateral distance from fin base (m)
$T_x$ = fin temperature at distance x from the base (°C or K)
$h_{free,experimental}$ = average free experimental heat transfer coefficient (W/m$^2$-K)
$P$ = perimeter around the fin cross section (m)
$k$ = thermal conductivity of the fin material (W/m-K)
$A_c$ = cross sectional area of the fin (m$^2$)

CASE 2: The fin is of finite length and loses heat by convection from its end also.

$$\frac{\theta}{\theta_b} = \frac{\left[\cosh(m(L-x)) + \left(\frac{h}{mk}\right)\sinh(m(L-x))\right]}{\left[\cosh(mL) + \left(\frac{h}{mk}\right)\sinh(mL)\right]}$$

where $m$ is as defined for Case 1 and $L$ = length of fin from base (m)

CASE 3: The fin is of finite length and its end is insulated.

$$\frac{\theta}{\theta_b} = \frac{\cosh(m(L-x))}{\cosh(mL)}$$

On a single sheet of graph paper, plot the theoretical $\theta/\theta_b$ vs. fin length for all three cases using the average heat transfer coefficient, $h_{free,experimental}$ obtained above. Then plot the measured values of $\theta/\theta_b$ for the free convection case on the same graph. Compare the curves and discuss in your report which case applies to this fin and why.

9. Forced Convection Heat Transfer Analysis

**Assuming** Case 1 above is appropriate for the **forced convection case**, determine the average forced convection heat transfer coefficient, $h_{forced,experimental}$. This may be done by plotting $\theta/\theta_b$ for the forced convection case on semi-log coordinates (plot Log ($\theta/\theta_b$) on the *y*-axis vs. fin distance, *x* (meters) on the *x*-axis), and then determining the coefficient m by calculating the best straight line using the base point $\theta/\theta_b = 1$ and the best straight line.. Once the numerical value for *m* has been found, you can solve for the average heat transfer coefficient, $h_{forced,experimental}$.

10. Using the values computed above for $h_{free,experimental}$ and $h_{forced,experimental}$ compute estimates for the Nusselt numbers,

$$Nu_{free,experimental} = \frac{h_{free,experimental} L}{k}$$

$$Nu_{forced,experimental} = \frac{h_{forced,experimental} L}{k}$$

11. Compute $Nu^n_{combined,experimental} = Nu^n_{free,experimental} \pm Nu^n_{forced,experimental}$) What is the experimental combined free and forced exponent, *n* ?

12. In your abstract and summary include a ***<u>table</u>*** of the following format

Table 1 "Summary of Results for Fin Heat Loss Experiment"

| Parameter | Theory | Experimental | % error | % uncertainty |
|---|---|---|---|---|
| $h_{free}$ [W/m^2-K] | | | | |
| $h_{forced}$ [W/m^2-K] | | | | |
| $Nu_{free}$ | | | | |
| $Nu_{forced}$ | | | | |
| $Nu_{combined,theory}$ | | | | |
| $Nu_{combined,experimental}$ | | | | |

13. Comment on the trends observed in the summary of results of step 12.

**References**

1.Figliola and Beasley, "Theory and Design for Mechanical Measurements"

2. Incropera and DeWitt," Introduction to Heat Transfer"

# STRAIN GAGE ACCELEROMETER EXPERIMENT

## Objective

The objective of this laboratory experiment is to determine the characteristics of a strain gage type accelerometer, including its natural frequency, damping ratio and sensitivity.

## Equipment

1. ENTRAN Strain gage accelerometer
2. ENTRAN PS-15 Bridge balance unit
3. B & K Piezoelectric accelerometer
4. Piezoelectric accelerometer charge amplifier
5. CROWN Electro-dynamic shaker
6. CROWN Power amplifier
7. HP Signal generator
8. HP Dual-beam oscilloscope

**Pre-lab Assignment**

Derive the differential equation governing accelerometer response to a sinusoidal input. From this equation, prove that the relative displacement of the accelerometer seismic mass with respect to the accelerometer housing $z$, is a function of the input acceleration, the magnification factor, and the accelerometer natural frequency; Also determine the phase lag relation. This should be done by each student independently prior to the laboratory period and included in your report as an appendix.

Review pp. 73, 87-95, 487-488 of Figliola and Beasley

**Procedure**

1. Study and understand the equipment set-up, and draw a block diagram showing all components and connections.

2. Turn on the CROWN power amplifier, HP signal generator, HP scope, ENTRAN bridge power supply, and piezoelectric charge amplifier.

3. Make sure that FULL SCALE = 20 on the charge amplifier. NOTE: the sensitivity of the piezoelectric accelerometer as output by the charge amplifier is given by: $K_{PIEZO} = \frac{5 \text{ Volts}}{\text{FULL SCALE g's}}$, where FULL SCALE is the setting the user makes on the charge amplifier. (*i.e.* with the "FULL SCALE" knob set at 20, if the accelerometer is forced at ±10 g, the charge amplifier will produce an output signal of $\frac{5 \text{ Volts}}{20 \text{ g's}} \times \pm 10 \text{ g's} = \pm 2.5 \text{ Volts} = 5 \text{ Volts Peak - to - Peak}$ ).

4. Record the voltage excitation from the ENTRAN PS-15 Bridge Power Supply. Denote this number as $V_e$ (Volts).

5. Use the function generator (**Freq. Button**) to set the minimum sine frequency to 100 Hz (the shaker is not linear below 100 Hz), turn the function generator amplitude up to ±10 g by adjusting **Amp. Button** to a level of 380 mV on the function generator.

6. Verify that the ±10 g input at 100 Hz is set by measuring the piezoelectric accelerometer output on CH2 of the oscilloscope screen (**Voltage Button -> Measure Voltage Peak-Peak CH2**) and verify that it is indeed 5 Volts peak-to-peak. NOTE: This level of input ±10 g vibration is to remain constant for all further test readings, and must be checked before taking data at each frequency.

7. **Determine natural frequency of strain gage accelerometer:** Determine the strain gage accelerometer natural frequency, by noting the frequency at which its output lags that of the piezoelectric accelerometer by 90°. Use a Lissajous pattern to do this.

A Lissajous pattern is generated when the two signals are combined (this can be done by pushing the "main-delayed" button and selecting the XY mode on the screen, see sheets near experimental hardware for more clarification). Adjust the frequency on the function generator until the Lissajous pattern is a circle. Note the value of frequency at which this occurs as being the natural frequency of the strain gage accelerometer $f_n = \frac{\omega_n}{2\pi}$.

8. **Collect data for transducer sensitivity calculation:** Record the strain gage accelerometer output at frequencies ranging from 100 Hz to 3000 Hz, in increments of 100 Hz. Use the **Freq. Button** on the function generator to increment the frequency. At each new frequency, adjust the amplitude of the function generator using the **Amp. Button** so that CH2 on the scope reads 5 Vp-p. For example, at 200 Hz, you will need to change the amplitude on the function generator to approximately 0.370 V in order that the signal on CH2 registers as 5 Vp-p on the scope. Record the peak-to-peak voltage of CH1 at each frequency. **Fine tune the amplitude on the function generator for all other frequencies measured in order to ensure that 5 Vp-p = ±10 g is the constant input at each new frequency and complete the entries in the table below.**

| Forcing Frequency (Hz) | Function Generator Voltage Amplitude (mV) | Scope CH2 Peak-Peak Voltage (should be const. @ 5 Vp-p) | Scope CH1 Peak-Peak Voltage (mV) |
|---|---|---|---|
| 100 | | | |
| 200 | | | |
| 300 | | | |
| 400 | | | |
| 500 | | | |
| 600 | | | |
| 700 | | | |
| 800 | | | |
| 900 | | | |
| 1000 | | | |
| 1100 | | | |
| 1200 | | | |
| 1300 | | | |
| 1400 | | | |
| 1500 | | | |
| 1600 | | | |
| 1700 | | | |
| 1800 | | | |
| 1900 | | | |
| 2000 | | | |
| 2100 | | | |
| 2200 | | | |
| 2300 | | | |
| 2400 | | | |
| 2500 | | | |
| 2600 | | | |
| 2700 | | | |
| 2800 | | | |
| 2900 | | | |
| 3000 | | | |

## Data Analysis

1. Explain why a piezoelectric accelerometer can be used as the reference standard for calibration of the strain gage accelerometer in this experiment.

2. Report the natural frequency, $f_n$ (Hz) and $\omega_n = 2\pi\, f_n$ (rad/sec) of the strain gage accelerometer you found via step 7 in the test procedure. How does your measured value compare to those expected from the ENTRAN website or other strain gage type accelerometers ?

3. From your experimental data of step 8 of the procedure, determine the average DC sensitivity of the strain gage accelerometer, in units of $K_{SG}$ [mV/g]. Compare the value you computed for $K_{SG}$ to the manufacturer's reported average value of $K_{vendor}$ = 2.72 mV/g. Formulate a percentage error $e = \frac{K_{vendor} - K_{SG}}{K_{vendor}} \times 100$ and explain any discrepancies you discover.

4. From the experimental data of steps 7 & 8 of the procedure, determine the damping ratio $\zeta$ of the strain gage accelerometer by plotting your data against the equation for the magnitude ratio given below (Figliola & Beasley Eqn. 3.21 and Fig. 3.16):

$$dB = 20LOG_{10}(M(\omega)) = 20LOG_{10}\left[\frac{1}{\sqrt{(1-r^2)^2 + (2\,\zeta\, r)^2}}\right]$$

   When plotting your experimental data, you must normalize as follows: Plot $20 * LOG_{10}\left[\frac{\text{OUTPUT (mV)}}{K_{SG}\ \text{(mV/g)} \times 20\text{g}}\right]$ on a log y-scale vs. frequency on a linear x-scale in order to have a properly scaled plot from which to determine the damping ratio from.

   By plotting your data overlaid with some theoretical dB magnitude curves (via Eqn. 3.21 above), you may infer what damping ratio the transducer has. How does the value of damping you measured compare to what you expected for this type of transducer ?

5. Determine the frequencies at which the dynamic error of the strain gage accelerometer will be 90 to 95%, (*i.e.* the frequencies for which $M(\omega)$=0.90 and $M(\omega)$=0.95). Calculate the phase lag, $\phi(\omega) = -Tan^{-1}\left(\frac{2\,\zeta\, r}{1-r^2}\right)$, and the time lag,

$t_{lag} = \frac{\phi}{\omega}$ at these $\omega_{90\%}$ and $\omega_{95\%}$ limits. Comment on your results, *i.e.* is it a good idea to operate this accelerometer at these limits, what happens to your data if you operate at these values of frequency ? Explain.

6. Compute the resonance frequency of the strain gage accelerometer, recalling that $\omega_R = \omega_n \sqrt{1-2\zeta^2}$ , based upon your value of $\zeta$ from part 4, do you expect the strain gage accelerometer to witness resonance ? Explain.

7. Compute the bandwidth (range of useful input frequencies) of the strain gage accelerometer using the following expression: $\omega_{BW} = (-1.196\zeta + 1.85)\omega_n$, (rad/s) $f_{BW} = 2\pi\omega_{BW}$ (Hz) and plot the linear range of the strain gage accelerometer transducer with the bandwidth clearly labeled on the plot.

8. Compute Maximum Magnitude of the strain gage accelerometer $M_{P_\omega} = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$, also include a calculation of the uncertainty in this quantity.

9. Compute the Percent Overshoot of the strain gage accelerometer $P.O. = 100\exp(-\pi\zeta / \sqrt{1-\zeta^2})$, also include a calculation of the uncertainty in this quantity.

10. Compute the Rise Time of the strain gage accelerometer $t_r = \frac{2.16\zeta + 0.60}{\omega_n}$, also include a calculation of the uncertainty in this quantity.

11. Compute Time to Peak of the strain gage accelerometer $t_P = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}}$, also include a calculation of the uncertainty in this quantity.

12. Compute the Settling Time of the strain gage accelerometer $t_s = \frac{4}{\zeta\omega_n}$, also include a calculation of the uncertainty in this quantity.

13. Use the data from steps 9-12 above to re-construct a unit-step response plot of the strain gage accelerometer. Use EXCEL or MATLAB to fit a curve to the points computed in steps 9-12. Does the curve you generated resemble a typical second-order unit-step response ? Discuss your findings.

## THERMAL CONDUCTIVITY MEASUREMENT EXPERIMENT


**Fig. 1.** Thermal conductivity test apparatus showing major components of the test-stand.

**Equipment Inventory**

1. HP Vectra Computer with GPIB Card
2. LabVIEW data acquisition and analysis development package
3. HP 34970A Data Acquisition/ Switch Unit
    a. HP 34907A Multifunction Module
    b. HP 34902A 16 CH Multiplexer Module
4. HP 6642A System DC Power Supply (2)
5. NESLAB RTE-211 Chiller
6. Guarded Heat Transfer Apparatus
7. 5/8” Wrench

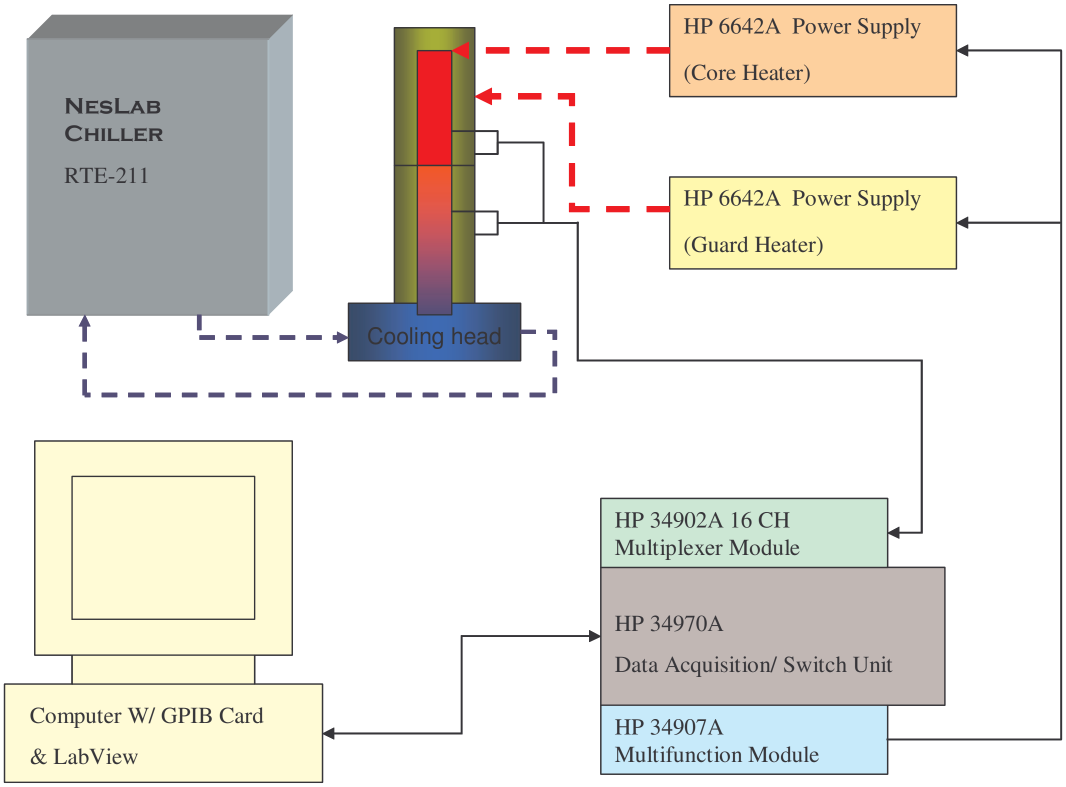



**Fig. 2.** Thermal Conductivity Measurement Apparatus Flow Chart

**Table I.** Thermocouple listing

| HP 34970A Slot 10X | T/C Junction Box | Test Apparatus | |
|---|---|---|---|
| 1 | 1 | Rod 1 | Hot Side |
| 2 | 2 | Rod 2 | |
| 3 | 3 | Rod 3 | To |
| 4 | 4 | Rod 4 | |
| 5 | 5 | Rod 5 | Cold Side |
| 6 | 6 | Guard 1 | Hot Side |
| 7 | 7 | Guard 2 | To |
| 8 | 8 | Guard 3 | Cold Side |
| 9 | 9 | Heater | |
| 10 | 10 | Guard Heater | |
| 11 | Spare 11 | | |
| 12 | Spare 12 | | |
| 13 | Spare 13 | | |
| Not Used 14 | 14 | | |
| Not Used 15 | 15 | | |
| Not Used 16 | 16 | | |

**Equipment Initialization**

1) NESLAB RTE-211 Chiller
   a) Turn on NESLAB RTE-211 Chiller by use of **Main Power** switch on side of unit.
   b) Check NESLAB RTE-211 Chiller set point
      i) Press and hold the **Display** button on the front of the NESLAB RTE-211 Chiller unit to check Chiller set point. The Display Should read $10\ ^{o}C$ . If Display does not read $10\ ^{o}C$ use the Fine and Course adjustment knobs to adjust the temperature while the **Display** button is still being held.
   c) Turn Refrigeration on/off switch to **on**
   d) Turn Refrigeration Max/Min switch to **Max**
2) HP Vectra Computer with GPIB Card
   a) Turn Computer Monitor
   b) Turn on HP Vectra Computer with GPIB Card
      i) When login dialog box appears press the **Esc** key. The Windows desktop will appear.
3) HP 34970A Data Acquisition/Switch Unit
   a) Turn on HP 34970A by pressing the **Power** button located at the lower left corner on the front of the unit.
4) Source Heater HP 6642A System DC Power Supply (**Bottom Unit**)
   a) Turn on HP 6642A System DC Power Supply by moving the **Line** switch to on
   b) Set Max current by pressing the function **Current** (Gray Current) button then the **5** button then **Enter**.
   c) Turn on the output by pressing the **Output on/off** button.
      i) The arrow on the display will be over **CV**
5) Guard Heater HP 6642A System DC Power Supply (**Top Unit**)
   a) Turn on HP 6642A System DC Power Supply by moving the Line switch to on
   b) Set Max current by pressing the function **Current** (Gray Current) button then the **5** button then **Enter**.
   c) Turn on the output by pressing the **Output on/off** button.
      i) The arrow on the display will be over **CV**
6) Test Rod
   a) For first test sample, follow these steps
      i) Remove insulation from around Heat Conduction Test Apparatus
      ii)

**Caution:**
**Heater and Rod Assembly May Be Hot**

      iii) ***Ensure Heater assembly and Rod assembly joints are approximately 1/8 inch apart from one another in order to separate the two pieces later DO NOT CLAMP DOWN THE PIECES FLUSH !!! (see Fig. 3 below)***. If not go to step (6b)

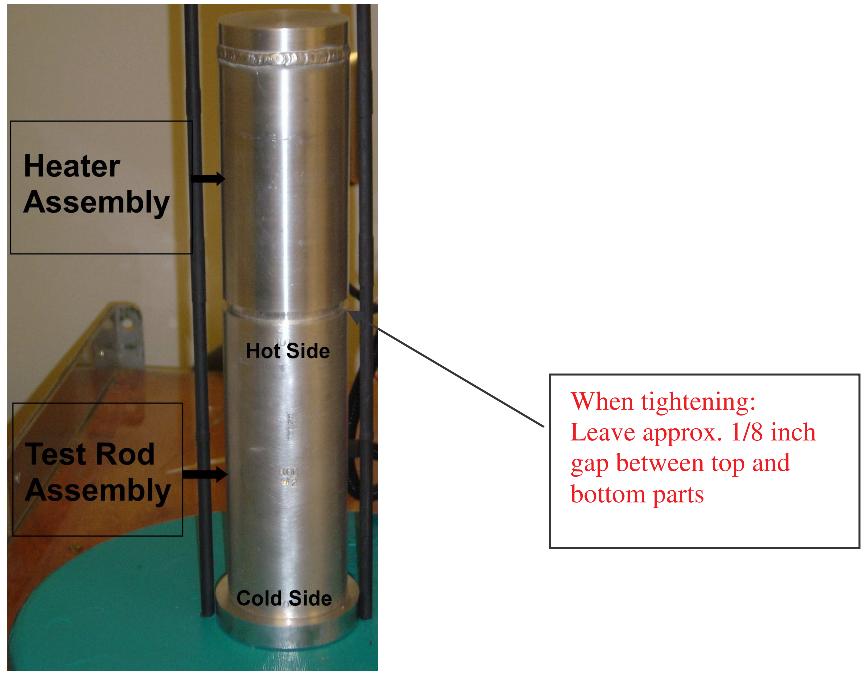



**Fig. 3** Test Rod Assembly

   iv) Ensure T/C 1-10 are connected to the corresponding location on the T/C junction box.
   v) Install insulation around The Heat Conduction Test Apparatus with arrow pointing up
   vi) Go to step 7

b) Test Rod Change out instructions
   i) Remove insulation from around Heat conduction test apparatus.

**Caution:**
**Heater and Rod Assembly May Be Hot**

   ii) Loosen center hold down bolt (5/8)
   iii) Remove insulation block
   iv) Remove Heater Assembly by lifting up and out the rear of the test apparatus.
   v) Remove Test Rod Assembly by lifting up and out the rear of the test apparatus.
   vi) Disconnect T/C 1-8 from the T/C junction box
   vii) Install new test rod with cold side down.
      (1) See Test Rod Assembly for Labeling.
   viii) Connect T/C 1-8 on the T/C junction box
   ix) Install heater on new test rod assembly making sure the heater engages the new test rod.
      (1) **Note:** the interface between Heater assembly and Test Rod assembly will not be flush.
   x) Install insulation block on top of heater assembly

xi) Tighten center hold down bolt (5/8”) until the Heater assembly and the Test Rod assembly interface is flush with one another
xii) Install insulation around the Heat conduction Test Apparatus with arrow pointing up
xiii) Go to step 7

**Table II.** LabView Excel Generated Spreadsheet Header Identification

| Column | Variable |
|---|---|
| A | Time (msec) |
| B | Guard Heater Temp $(^{o}C)$ |
| C | Guard Temp 1 $(^{o}C)$ |
| D | Guard Temp 2 $(^{o}C)$ |
| E | Guard Temp 3 $(^{o}C)$ |
| F | Heater Temp $(^{o}C)$ |
| G | Rod Temp 1 $(^{o}C)$ |
| H | Rod Temp 2 $(^{o}C)$ |
| I | Rod Temp 3 $(^{o}C)$ |
| J | Rod Temp 4 $(^{o}C)$ |
| K | Rod Temp 5 $(^{o}C)$ |
| L | Heater Power (W) |
| M | Guard Heater Power (W) |

7) LabVIEW
   a) Open LabVIEW program **Hot Rod.vi** (this should be on the PC desktop)
   b) If User Login Prompt appears press **OK**
   c) Ensure Heater switch is off
   d) Ensure Guarded Heater switch is off
   e) Ensure Record Data switch is On
   f) Ensure Scan List indicates **101:110**
   g) In File Path type in destination for recorded data
      i) Example: **C:\windows\desktop\rod#_Date.xls**
   h) Ensure Set Point reads **50**
   i) Press the Run arrow
   j) Turn On Heater by pressing the Heater button
   k) Turn On Guard Heater by pressing the Guard Heater button
   l) Wait for Rod temperatures and the Guard temperatures to reach steady state
      i) Steady State is determined when the all of the temperature are horizontal on the 3 graphs
      ii) This will take approximately 30-45 minutes
   m) When the Rod temperatures and the Guard temperatures reach steady state
      i) Turn off Heater by pressing the Heater button

ii) Turn off The Guard Heater by pressing the Guard Heater button
iii) Turn the Record Data switch off by pressing the Record Data button.
(1) This will send the data collected by LabVIEW to the Excel File Specified in step 7f.

n) Proceed to step 6b if testing more than one Rod

8) Shut Down
   a) Turn off Heater power supply (**Bottom** HP 6642A)
   b) Turn off Guard Heater power supply (**Top** HP 6642A)
   c) Turn off HP 34970A Data Acquisition Unit
   d) Set NESLAB Chiller refrigeration Max/Min switch to **Min**
   e) Set NESLAB Chiller refrigeration on/off switch to **off**
   f) Turn **off Main Power** on the NESLAB Chiller
   g) Close LabView Program
      i) If dialog box appears Press the **no to all** button
   h) Shut down the computer
   i) Turn off the monitor

## Write Up Questions / Data Analysis

Address items (a) through (e) concisely in your lab write-up.

(a) Using the data from each test run, determine the numerical value of the empirically determined thermal conductivity (W/m-K) of each metal test sample.

(b) Using your results from part a), determine the type of material of each sample and compare with a handbook for expected values (W/m-K). Quantify differences via percentage error analysis, $e = \frac{\left| k_{empirical} - k_{handbook} \right|}{k_{handbook}} \times 100$ and comment on discrepancies.

(c) Identify all sources of parasitic losses that would introduce an error into your measurement.

(d) Perform a detailed propagation of uncertainty analysis on your results.

(e) Draw an accurate and neat thermal circuit diagram showing the heat path and computed thermal resistance values for this set-up.