

Lecture 5: Identification of Structural Damping

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Learning Objectives



- Objective 1: Experimentally measure strains on a specimen under steady-state vibration and base accelerations
- Objective 2: Perform frequency and steady-state response analyses using a 3D finite element model
- Objective 3: Identify the structural damping factor by calibrating numerical strains with experimental strains as increasing the strains





Strain Theory





Mechanical Properties of Engineering Materials

	Young's modulus E (GPa)	Shearing Modulus G (GPa)	Tensile Strength (MPa)	Poisson's Ratio v
Carbon steel (C0.1-0.25%)	205	78	363-441	0.28-0.3
Carbon steel (C>0.25%)	206	79	417-569	0.28-0.3
Spring steel (quenched)	206-211	79-81	588-1667	0.28-0.3
Nickel steel	205	78	549-657	0.28-0.3
Cast iron	98	40	118-235	0.2-0.29
Brass (casting)	78	29	147	0.34
Phosphor bronze	118	43	431	0.38
Aluminum	73	27	186-500	0.34
Concrete	20-29	9-13		0.1



- Strain gage converts mechanical strains to electric signals.
- If a wire is under tension, its cross sectional area (A) decreases and length (L) increases, resulting in increase of resistance (R).



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- A change in resistance (R) is proportional to the strain experienced by the strain gage.
- When a strain is introduced, the strain sensitivity (called as gage factor) is given as



K : Gage factor (6)

- Ideal strain gage changes resistance only due to the mechanical deformation of the surface where it is attached.
- However, it is notable that other factors, such as temperature, material properties, the adhesive that bonds the gage to the surface can also affect the resistance change.



- □ Wheatstone bridge circuit is a general-purpose measuring circuit.
- Total resistance between A and C is $1/R_t = 1/(R_1 + R_2) + 1/(R_3 + R_4)$.

$$R_{i} = \frac{(R_{i} + R_{2})(R_{3} + R_{4})}{R_{1} + R_{2} + R_{3} + R_{4}}$$
(7)

$$I = \frac{V_{in}}{R_{i}} = V_{in} \frac{R_{1} + R_{2} + R_{3} + R_{4}}{(R_{1} + R_{2})(R_{3} + R_{4})} = \frac{V_{in}}{R_{1} + R_{2}} + \frac{V_{in}}{R_{3} + R_{4}}$$
(8)

$$I = I_{ABC} + I_{ADC}, \quad I_{ABC} = \frac{V_{in}}{R_{1} + R_{2}} \text{ and } I_{ADC} = \frac{V_{in}}{R_{3} + R_{4}}$$
(9)

$$V_{out} : \text{Output Voltage}$$

$$V_{in} : \text{Input (Excitation) Voltage}$$

$$R_{1} : \text{Resistance of Strain Gage}$$

$$R_{2}, R_{3}, R_{4} : \text{Constant Resistance}$$



- One or more of the resistors will change in accordance with strain.
- Output voltage (V_{out}) is the potential difference between terminal B and D.
- □ The voltage drop-downs in the arm AB and the arm AD are as

$$V_{AB} = I_{ABC} R_{1} = \frac{V_{in}}{R_{1} + R_{2}} R_{1}$$
(10)
$$V_{AD} = I_{ADC} R_{4} = \frac{V_{in}}{R_{3} + R_{4}} R_{4}$$
(11)

□ Then, the output voltage is

$$V_{out} = V_{AB} - V_{AD} = \frac{V_{in}}{R_1 + R_2} R_1 - \frac{V_{in}}{R_3 + R_4} R_4 = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} V_{in} = \frac{\frac{R_1}{R_2} - \frac{R_4}{R_3}}{\left(\frac{R_1}{R_2} + 1\right)\left(\frac{R_4}{R_3} + 1\right)} V_{in}$$
(12)



- From Eq. (12), it is noted that V_{out} is zero (balanced) if the ratio R1:R2 is equal to the ratio R3:R4.
- □ In case of 1-Strain gage system,



To balance the bridge circuit, calibration needs to be made for the zero-strain condition.



Selection of Strain Gage



Strain Limit : Max. 5% of Gage Length(>3.2mm) Min. 3% of Gage Length(<3.2mm)



- □ Factors to be considered
 - Best combination of gage and adhesive
 - Test duration
 - □ Strain range required: Based on the numerical model
 - Operating temperature
 - □ Gage length & width
 - Number of gages in gage pattern
 - Arrangement of gages in gage pattern
 - Grid resistance
 - Strain sensitive alloy
 - Carrier material
 - Solder tab type
 - Configuration of solder tap





Steady-State Response Analysis



- Complex Frequency Response Function of a SDOF system
 - It is typically simpler to consider the frequency response function (FRF) in the complex domain
 - **Consider the E.O.M of** $m\ddot{u} + c\dot{u} + ku = p(t)$ ------ (15)

$$\begin{split} m\ddot{u}_{R} + c\dot{u}_{R} + ku_{R} &= p_{0}\cos\Omega t \\ + \left(m\ddot{u}_{I} + c\dot{u}_{I} + ku_{I} = p_{0}\sin\Omega t\right) \times i \end{split} \tag{16}$$
$$\begin{split} m\ddot{\overline{u}} + c\dot{\overline{u}} + k\overline{u} &= p_{0}e^{i\Omega t} \end{aligned} \tag{17}$$

□ Then, the general response takes the form

 $\overline{u}(t) = \overline{U}e^{i\Omega t} = u_R + iu_I \quad (18)$ where $\overline{U} = Ue^{-i\alpha}$ is complex amplitude

If the input takes a cos(Ωt) form, the response is a real part of u(t). If the input takes a sin(Ωt) form, then the response is an imaginary part of u(t).

Steady-State Response Analysis



Substituting Eq. (18) into the E.O.M, Eq. (15), $\dot{\overline{u}}(t) = i\Omega \overline{U}e^{i\Omega t}$ $\ddot{\overline{u}}(t) = -\Omega^2 \overline{U} e^{i\Omega t}$ $-m\Omega^{2}\overline{U}e^{i\Omega t}+i\Omega c\overline{U}e^{i\Omega t}+k\overline{U}e^{i\Omega t}=p_{0}e^{i\Omega t}$ $(-m\Omega^2 + i\Omega c + k)\overline{U}e^{i\Omega t} = p_0 e^{i\Omega t}$ (19) $\overline{U} = \frac{P_0}{k - m\Omega^2 + i\Omega c} \qquad \text{setting} \quad U_0 = \frac{P_0}{k}$ $\overline{H}_{0}(\Omega) = \frac{\overline{U}}{U_{0}} = \frac{1}{\left(1 - \frac{m}{k}\Omega^{2}\right) + i\frac{c\Omega}{k}} \quad \text{using} \quad c = \zeta c_{cr} = \zeta 2\sqrt{mk}$ $=\frac{1}{\left(1-\frac{\Omega^{2}}{\omega_{n}^{2}}\right)+i2\zeta\frac{\Omega}{\omega}} \quad \text{setting } r=\frac{\Omega}{\omega_{n}} \quad \dots \dots \quad (20)$



□ Therefore, the complex frequency response function is as follows

$$U = Ue^{-i\alpha} \longrightarrow \overline{U}_{0} = \frac{\overline{U}}{U_{0}} = \frac{1}{(1 - r^{2}) + i(2\zeta r)}$$
(21)

The complex FRF contains both magnitude and phase angle information of the steady state response of structures.

$$\overline{H}_{0}(\Omega) = \frac{1 - r^{2}}{(1 - r^{2})^{2} + (2\zeta r)^{2}} + i \frac{-2\zeta r}{(1 - r^{2})^{2} + (2\zeta r)^{2}}$$
(22)
Real part Imaginary part

$$H_{0}(r) = |\overline{H}_{0}(\Omega)| = \frac{1}{\sqrt{(1 - r^{2})^{2} + (2\zeta r)^{2}}}$$
(magnitude)------ (23)

$$\tan \alpha(r) = \frac{2\zeta r}{1 - r^{2}}$$
(phase angle) ----- (24)

$$|\overline{A} = A_{R} + iA_{r}| \\A = \sqrt{A_{R}^{2} + A_{r}^{2}} \\\alpha = \tan^{-1}\left(\frac{A_{r}}{A_{R}}\right)$$



Plotting the magnitude and phase angle of the complex FRF of displacement output per unit force input



- Eq. (21) is the complex FRF of *displacement* output per unit force input. It is also called as *receptance FRF*.
- Then, the *mobility* FRF (i.e. *velocity* output per unit force input) $\overline{H}_{v/p}(\Omega) = i\Omega \frac{1/k}{(1-r^2)+i(2\zeta r)} \quad \text{since} \quad v(t) = i\Omega U e^{i\Omega t} \quad \dots \quad (25)$
- Then, the accelerance FRF (i.e. acceleration output per unit force input)

$$\overline{H}_{a/p}(\Omega) = -\Omega^2 \frac{1/k}{(1-r^2) + i(2\zeta r)} \quad \text{since} \quad a(t) = -\Omega^2 U e^{i\Omega t} \quad \dots \quad (26)$$



 Plotting the magnitude and phase angle of the mobility and accelerance FRFs



Mobility FRF and Phase Angle

Accelerance FRF and Phase Angle



- Modeling Methods of Damping
 - **Ο** Viscous damping factor (ζ)
 - $\Box Structural damping factor (\gamma)$
 - **Damping capacity (** ψ)
- The structural damping is defined as dissipated energy per radian of the cyclic vibration

$$\gamma = 2\xi = \frac{\psi}{2\pi} \tag{27}$$

- The structural damping is proportional to displacement but 180 degree out of phase with the velocity of a harmonically oscillating system.
- Introducing the structural damping to a SDOF system

$$m\ddot{\vec{u}} + k(1+i\gamma)\overline{u} = p_0 e^{i\Omega t}$$
(28)

Assuming a solution of the form,

$$\overline{u} = \overline{U}e^{i\Omega t}$$
⁽²⁹⁾





 $\hfill\square$ Then the complex amplitude $\ensuremath{\overline{U}}$

$$\overline{U} = \frac{P_0}{\left(k - m\Omega^2\right) + i(k\gamma)} \tag{30}$$

□ Then, the complex FRF for a SDOF system with structural damping

$$\overline{H}_{0}(r) = \frac{\overline{U}}{U_{0}} = \frac{1}{(1 - r^{2}) + i(\gamma)}$$

$$H_{0}(r) = |\overline{H}_{0}(r)| = \frac{1}{\sqrt{(1 - r^{2})^{2} + (\gamma)^{2}}}$$

$$\tan \alpha = \frac{\gamma}{1 - r^{2}}$$
(31)
(32)



 Steady-state response of a cantilevered beam with structural damping using 3D finite element model

where

 $[K] = \int_{V} \mathbf{B}^{T} \mathbf{D} \mathbf{B} dV; [M] = \int_{V} \rho \mathbf{N}^{T} \mathbf{N} dV \quad \dots \qquad (39)$

• At resonance frequency $(\Omega = \omega_i)$, the vibrating deflection shape will take the same shape as the mode shape.



4 Problem Statement

Problem Statement



A carbon steel cantilever beam is prepared for a resonant vibration test under harmonic base excitation. The first natural frequency is determined by a ABAQUS 3D finite element (FE) model. A strain gage is installed at the highest stress location in order to measure strains. Using an accelerometer installed on the shaker armature, the base excitation amplitudes are also measured. Structural damping factor is defined in the ABAQUS 3D FE model. Through direct steady-state response analyses of the 3D finite element model, estimate the structural damping factor by matching computed strains with measured strains



 Frequency Response Function (FRF) is for measured output strain per unit input force.



Thus, strain values are in $\pi/2$ out of phase with the base excitation. And at a resonant frequency, complex strain output becomes pure imaginary number as seen in Eq. (22)

Procedures



- 1) Perform a sweep sine test. Run the provided NI-LabVIEW VI program in order to plot the frequency response function/phase angle and identify the experimental first natural frequency of the specimen. For details on the sweep sine test, please refer to Lecture note 4.
- 2) Perform the eigenvalue analysis using the provided 3D ABAQUS FE model to identify the numerical first natural frequency.
- 3) In most cases, the accurate density could be simply obtained. Thus, identify Young's modulus of the 3D FE model that gives the first natural frequency best matching with the experimentally obtained value. In this step, "trial and error" is required.
- 4) Shake the test specimen at the identified first natural frequency. Run the provided NI-LabVIEW VI program. The NI-LabVIEW VI program will save filtered accelerations and strains in ASCII files (*.lvm). Max amplitudes of the strains and the base accelerations are readable from the front panel.

Procedures



- 5) Increase the excitation voltage to the shaker in order to increase the level of strains from approximately 300 με to 900 με(Caution !: Please do not exceed 2000 με (micro strain) which is close to the yielding point of steel material.). Read max amplitudes of the strain and base acceleration at 10 or more different strain levels.
- 6) Convert the base acceleration amplitudes to the base displacement amplitudes by dividing it by $(2\pi f_n)^2$.
- 7) Observe the steady state response of the test specimen. Describe the steady state response at each strain level.
- 8) After the lab test, make a table that lists pairs of measured strain amplitudes, acceleration amplitudes and computed displacement amplitudes. Make two plots of strain vs. base acceleration amplitudes and strain vs. base displacement amplitudes.
- 9) Input each base displacement amplitude as a loading to the input file (See the following) of the 3D FE model and Run ABAQUS steady state dynamic analyses. By "trial and error" method, determine the structural damping factor that gives strains best matching with the experimentally obtained strains at the same location. Repeat this identification process for each strain amplitude.

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```
**
**
** STEP: Step-3
**
*Step, name=Step-3, perturbation
*Steady State Dynamics, direct, interval=EIGENFREQUENCY, friction damping=N0
0., 300., 10, 3.
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Displacement/Rotation
*Boundary, load case=1
_PickedSet745, 3, 3, 0.049091763E-3
*Boundary, load case=2
_PickedSet745, 3, 3
```

··· From "*Model.inp*" ABAQUS input file

10) Make plots of the displacement amplitudes vs. the identified structural damping factor; the strain amplitudes vs. the identified structural damping factor

5 Test Setup and Equipment

Test Setup and Procedures (1)

- □ Step1 Turn on the power supply.
- Step2 Generate excitation signals in NI-LabVIEW and send them through the analog output board (NI-PXI 6733).
- □ Step3 Under the vibration excitation, proceed the test.

- Drawing of specimen
 - Young's modulus: 2.015E11 (Pa)
 - Poisson ratio: 0.29
 - Material: Carbon Steel

Unit:inch

Unit: inch

Test Equipment

- □ Agilent 33250A (For function generator based test)
- Amplifier (California AP2000 2000W)
- Power Supply (MPJA 14604PS)
- NI-PXI 8105 Controller
- □ NI-PXI 6733 (For NI analog out signal generator based test)
- □ 68-Pin Connector Block (SCB68)
- □ ICP type Dytran triaxial accelerometer (3093B1)
- □ Strain gage WK-06-062AP-350, Vishay Micro-Measurement
- Two one-channel AnyLoggers (Korea Maintenance Co., LTD): One is AnyLoggerS-V/ICP and the other AnyLoggerS-B.
- LDS V408 Electrodynamic shaker
- Agilent 33250A waveform generator
- NI-LabVIEW 8.6

Agilent Function Generator(33250A)

- □ Single-channel pulse generator
- □ 50 MHz, 10 V from 50 Ohm into 50 Ohm
- Triggerable / PLL operation selectable
- Pulse / burst modes selectable
- Variable transition times
- BNC outputs, single-ended
- Dropout and glitch free timing change
- Frequency Range: 1 mHz 50 MHz
- □ Variable Delay Range: 20 ns 999.5 s
- Period RMS jitter: 0.00 s 999.5 s
- □ Width Range: 10 ns to 9.995 s
- Amplitude Range: 100 mV 20.0 V (depends on selected impedance (all other values for 50 ? source impedance into 50 ? load))
- □ Transition Time Range (10/90): 5.00 ns 200 ms
- □ Source Impedance: 50 ? or 1 k?

Amplifier(California AP2000 2000W)

- □ 320 watts RMS x 2 at 4 ohms
- 480 watts RMS x 2 at 2 ohms
- 960 watts RMS x 1 bridged output at 4 ohms
- □ 4-ohm stable in bridged mode
- Stereo or bridged mono output
- Tri-way capable (Tri-Way Crossover required)
- Dual power supply for stability at high volumes
- Fuse rating: 25A x 4
- Requires 4-gauge power and ground leads and a 100-amp fuse
- Wiring and hardware not included with amplifier
- Variable low-pass filters (50-250 Hz, 12 dB/octave)
- □ Variable bass boost (0-12 dB) at 45 Hz
- □ Variable subsonic filter (20-50 Hz)
- Preamp-level inputs (speaker-level to preamplevel adapter included)
- Preamp outputs
- Wired bass level remote control
- □ 24-1/4"W x 2"H x 10-1/4"D

Power Supply(MPJA 14604PS)

- □ Input voltage : 110-127 AC
- Output voltage : 0-30 DC
- Current : 0-10 A
- □ Voltage regulation
 - CV 1X10⁻⁴+3mV
 - □ CC □ 2X10⁻³+6mA
- Load regulation
 - □ CV□5X10⁻⁴+3mV
 - □ CC □5X10⁻⁴+6mA
- Ripple & node
 - CV<1.5mVrms
 - CC <10mArms
- Protection : current limiting
- □ Voltage indication accuracy : 1%+1d
- □ Current indication accuracy : 1%+1d
- □ Ambient temperature : 0 ~40C
- □ Humidity: <90%

NI-PXI 8105 Controller

- Intel Core Duo Processor T2500(2.0 GHz dual core)
- 512 MB (1 x 512 MB DIMM) dual channel 667 MHz DDR2 RAM standard,4 GB (2 x 2 GB DIMMs) maximum
- □ Integrated I/O
 - □ 10/100/1000BASE-TX Ethernet
 - 4 Hi-Speed USB ports
 - ExpressCard/34 slot
 - DVI-I video connector
 - GPIB (IEEE 488) controller
 - RS232 serial port
 - □ IEEE 1284 ECP/EPP parallel port
 - Integrated hard drive
- Internal PXI trigger bus routing
- Watchdog timer Software
- □ Hard drive-based recovery image PXI System

PXI 6733 High-Speed Analog Output

- 8 high-speed digital I/O lines; two 24-bit counters; digital triggering
- Onbard or external update clock PXI trigger bus for synchronization with DAQ motion, and vision products
- NI DAQmx driver with configuration utility to simplify configuration and measurement
- □ Superior integration:LabVIEW, LabVIEW Real-Time, LabWindows ™/CVI, and Measurement Studio for VB
- □ 1MS/s, 16-Bit, 8 Channels

68-Pin Connector Block (SCB68)

- □ Number of channels : 8 differential, 16 single-ended
- Accuracy $: \pm 1.0^{\circ}$ C over a 0° to 110° C range
- Output : 10 mV/°C
- □ I/O connectors One 68-pin male SCSI connector
- Temperature : 0° to 70° C
- Relative humidity : 5% to 90% non-condensing
- Temperature : -55° to 125° C
- Relative humidity : 5% to 90% non-condensing

Model 3030B4 Dytran Uniaxial Accelerometer

Specification	Value	Uint
Weight	6.8	Grams
Size(Hex X Height)	0.375 x 0.67	mm
Connector	Top Mounted 10-32 Micro Coax	
Mounting Provision	Integral Stud, 10-32 (UNF-2A)	
Sensitivity	10	mV/G
Ranges	+ /-500	G
Frequency Range	2 to 10000	Hz
Linearity	1	% F.S.
Equivalent Electrical Noise	0.0036	G, RMS
Temp. Range	-60 ~ +250	۴F
Supply Current Range	2 to 20	mA
Voltage Range	+18 to +30	Volts
Output impedance	100	OHMS

Strain Gage			
Specification	Value	Uint	
Part Number	WK-06-062AP-350		
Resistance	350±0.3%	Ohms	
Strain Range	±1.5%		
Temp. Range	-452 to +550	°F	
WK	Fully encapsulated K-alloy gages with high-endurance leadwires		

actual size

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AnyloggerS-V/ICP for acceleration transmitter AnyLoggerS-B for strain transmitter

Specification

Contents	AnyloggerS-V/ICP	AnyLoggerS-B	
Support Num. of Channel	1	1	
Input Voltage Range	-5 ~ 5V	0 ~ 3V	
Gain	1,2,5,10,20,50,100	50,100,250,500,1000,2500,5000	
Programmable	10~1000Hz (10,20,50,100,200,500,1000)	10 ~ 1000Hz	
Lower Pass Filter		10,20,50,100,200,500,1000	
Prog. Offset	0 ~ 5V(12Bit)	0 ~ 3.3V(12Bit)	
Max Sampling Rate	1000Hz	1000Hz	
Exciting Voltage	24V(Only ICP Type)	3.3V±0.5%	
Connector	BNC Connector	4Pin Circular Connector	
SIM Usage	No	Yes	
Power Consumption (w/o sensor)	150mA	100mA(w/o SIM)	
Internal Battery	Li-ion Rechargable 1500mAh x 2EA(Serial)	Li-ion Rechargable1500mAh x 2EA(Serial)	
Ext. Power Requirement	5V	5V	
Operation Temperature	-10 ~ 80°C	-10 ~ 80°C	
Sync. Accuracy	< 10ms	< 10ms	
Dimension	800 x 973 x 353 800 x 883 x 353		
Weight	210g 210g		
ADC Resolution	Differential 16Bit Differential 16Bit		
Measurement Accuracy	F.S. 0.1%	F.S. 0.1%	
Sensor Connectability	Voltage or ICP source	Bridge type sensor	
Signal Ripple	Depends on Gain	Depends on Gain	
Communication	Bluetooth v1.2 class1 18dBm(w/o ant.)	Bluetooth v1.2 class1 18dBm(w/o ant.)	
Radio Frequency Range	2.402 ~ 2.480GHz	2.402 ~ 2.480GHz	
Transmission Method	smission Method FHSS(freq. Hopping Spread Spectrum) FHSS		
Modulation Method	GFSK(Gaussian-filtered Freq. Shift Keying)	GFSK	
Approvals	MIC, FCC, CE MIC, FCC, CE		

V408 LDS Shaker			
Specifications	Value	Unit	
Armature diameter	38	mm	
Sine force peak	98	Ν	
Armature resonance freq.	9000	Hz	
Useful frequency range	5 to 9000	Hz	
Mass of armature	0.2	kg	
Max. Acceleration Sine Peak	981	m/sec ²	
System Velocity Sine Peak	1.52	m/sec	
System Displacement Continuous Peak-to-Peak	14	mm	
Usable Frequency Range	5 - 9,000	Hz	

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Agilent 33205A			
General Specification			
Dowor cupply	100-240 V, 50-60 Hz		
Power supply	100-127 V, 50-400 Hz		
Power consumption	140 VA		
Operating temp.	0°C to 55°C		
Storage temp.	-30°C to 70°C		
Interface	IEEE-488 and RS-232 std.		
Language	SCPI-1997, IEEE-488.2		
Dimonsions (M/vHvD)	Bench top 254 x 104 x 374 mm		
Dimensions (WXHXD)	Rack mount 213 x 89 x 348 mm		
Weight	4.6 kg		
Vibration and shock	MIL-T-28800E, Type III,		
Acoustic noise	40 dBA		
Calibration interval	1 year		

For detailed service guide and specifications, visit the link below http://cp.literature.agilent.com/litweb/pdf/33250-90011.pdf

□ LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language that uses icons instead of lines of text to create applications.

□ In contrast to text-based programming languages, where instructions determine the order of program execution, LabVIEW uses dataflow programming, where the flow of data through the nodes on the block diagram determines the execution order of the VIs and functions. VIs, or virtual instrument, are LabVIEW programs that imitate physical instruments.

6 Installation of Strain Gage

1. Degrease the gage area using solvent Such as CSM degreaser or GC-6 Isopropyl Alcohol

Prepare 320-grit silicon-carbide paper And M-Prep Conditioner A

2. Wet M-Prep Conditioner A on the gage area using cotton tipped stick

- Abrade the wetted surface with 320 grit silicon-carbide paper
- Dry wiping the area using gauze sponge

3. Apply a liberal amount of M-Prep Neutralizer 5A with a cotton-tipped applicator

Dry the surface with a slow wiping using gauze sponge Note : Wipe one direction

Installation of Strain Gage

Step 4

Installation Tape

M-Bond 200 Catalyst C

M-Bond 200

Soldering Iron

4. Using a ball-point pen, make a mark for alignment purpose

Place the gage (bonding side up) on the the sticky side of tape. Position the center of the gage on the mark on the specimen.
Attach the gage/tape assembly on the specimen.

5. Carefully lift the gage/tape assembly at a shallow angle, bring the gage up with the tape as shown in the above. Apply M-Bond 200 Catalyst-C to the bonding surface of the strain gage and allow the catalyst to dry at least 60 sec at normal condition

6. Apply one drop of M-bond 200 adhesive

Immediately press using thumb at least several minutes.

7. Carefully remove the installation tape And apply protective coating.

8. Do soldering to wire the strain gage.

Users Manual NI-LabVIEW VI Program

Users Manual of LabVIEW VI Prog. (1) Km MARTENARE Co. LTD

- 2) Set Path The original raw strain and acceleration data will be saved in the chosen files. Users need to make empty data files in the folder or use current data files prior to the test.
- 3) Set Bridge Type- for strain gage
- 4) Sampling Rate Default 1KHz
- 5) Gage Factor- Set the Gage Factor based on the Strain Gage Spec.
- 6) Set GAIN 46.45 for calibration.
- 7) Set Vex- 3.33 V
- 8) Set Sensitivity Enter the sensitivity of the acceleration sensor in the unit of V/g
- 9) Set files- Create files where measured and computed data will be saved and link them to this panel by choosing them.
- 10) Set Filter Type Bandpass
- 11) Set Filter Order
- 12) Set Low Cutoff Freq
- 13) Set High Cutoff Freq
- 14) Run- When the specimen is under sweep since test, click "Run" botton

Users Manual of LabVIEW VI Prog. (2) Km 한국유지관리(주)

- 15) Stop click "Stop".
- Check FRF- determine the first natural frequency.

Excite the specimen at its first natural frequency, varying the excitation level.

17) Read Data – read strain and acceleration amplitudes for each excitation level.

Users Manual of LabVIEW VI Prog. (3) KM 한국유지관리(주)

 한국유지관리(주)

 KOREA MAINTENANCE Co., LTD

- Two-stack sequences were used for the front panel
- Users should set correct IP address and port number following the Anylogger manual.
- All original raw data is saved into the designated path - The saved data will be read from the second stack for final conversion and storing
- The raw data is converted into voltage by multiplying factors:
 - □ For strains: **3.3/2¹⁶**
 - □ For acceleration: **10/2**¹⁶
- Voltage values are converted to physical values based on the sensitivity provided
- Data in physical units is displayed in the front panel

First Stack of Block Diagram of VI Program

Users Manual of LabVIEW VI Prog. (4) Km 한국유지관리(주)

- In the second stack, all the original raw data is calibrated in the identical way as shown in the first stack.
- Finally, the calibrated data is stored in the designated files.

Second Stack of Block Diagram of VI Program

8 Experimental Test Results

Abaqus Simulation

- The first natural frequency identified from the sweep sine test was 77.8 Hz.
- As increasing the shaker excitation voltage, 10 pairs of strain vs. acceleration amplitudes were measured and plotted as follows

 As expected, a linear relationship between strains and displacements was observed.

Experimental Test Results (2)

- Using the provided 3D FE model, structural damping factors were identified for each base excitation and strain level.
- □ As the strain level increases, the damping factor also increased.

Acc. Amplitude 0-pk (g)	Displacement (mm)	Strain Amplitude(με)	Damping Factor	3D FE Strain(με)
1.1958	0.049091763	328.249	0.037536727	328.252
1.65443	0.067920124	423.9	0.040022439	423.908
2.1386	0.087796992	511.512	0.042874646	511.523
2.32156	0.095308139	572.011	0.041621419	571.999
2.6529	0.108910802	629.951	0.043186307	629.959
3.07585	0.126274375	668.09	0.047213664	668114
3.50647	0.143952829	715.458	0.050261912	715.478
3.85242	0.158155284	772.928	0.051116379	772.934
4.07135	0.167143124	838.773	0.049768711	838.968
4.26971	0.175286494	874.53	0.050071069	874.533

9 Homework and Project

For harmonic motion, the structural damping force can be represented by the complex form

$$\bar{f}_d = -i\gamma k\bar{u}$$

or by the real form

$$f_d = -\gamma k \dot{u} \frac{|u|}{|\dot{u}|} = -\gamma k |u| \operatorname{sgn}(\dot{u})$$

(a) Sketch f_d vs u for one cycle of harmonic motion

$$u = -U\cos(\Omega t - \alpha)$$

(b) Determine an expression for the work (W_D) done per cycle.

(c) Determine an expression for $\rm C_{eq}.~$ Note that the equivalent viscous damping coefficient is defined by

$$c_{eq} = -\frac{W_D}{\pi \Omega U^2}$$

- Following the procedures explained in this lecture note, conduct the experiment and write a report.
 - Write a full report using the instructions provided in class. Organize your report into sections (e.g. Introduction, Procedures, Results, Discussion, Summary, References). Write concisely and clearly.
 - Include the following: (1) A schematic diagram and descriptions of specifications of the test equipment. (2) Plots of the frequency response function and phase angle recorded by NI-LabVIEW VI program during the experiment. (3) Natural frequencies and mode shapes from 3D FE analyses. (4) Tables of strain amplitudes, acceleration amplitudes, and converted displacement amplitudes measured from experiments. (5) Identified structural damping factor and (6) Observation of varying damping factors and explanations for damping changes that depend on the strain level.

 Roy R. Craig, Jr. and Andrew J. Kurdila, "Fundamentals of Structural Dynamics", 2nd Ed. Wiley