Spring 2009

CE 281: Experimental Systems

Instructor:	Henri Gavin, 162 Hudson Hall, `henri.gavin@duke.edu`
Class Time:	Mo, We, Fr 1:30-2:15
Classroom:	211 Teer
Lab:	Room 053 Hudson Annex
Texts:	All readings are on the web.
URL:	`http://www.duke.edu/~hpgavin/ce281/`
Prerequisite:	Senior or graduate standing in engineering or the physical sciences
Computers:	Many assignments will require computations using MATLAB. Students are responsible for familiarizing themselves with MATLAB.
Grading:	Homework: 20%; Labs: 30%; Midterm: 20%; Project: 30%

Course Objectives:
To deepen an understanding of dynamic processes in solid mechanics, structural dynamics and viscoelasticity by coupling mathematical models to the observation and interpretation of physical measurements. Precise instrumentation and digital data acquisition solutions are emphasized. The dynamics of accelerometers, strain gages, electro-magnetic shakers, and servo-hydraulic systems are described in detail. Applications are taken from the fields of viscoelasticity, structural dynamics, and control.

Lectures will cover:

1. overview of linear systems analysis
2. measurement of voltage and current, electronics, op-amps and filters
3. random and systematic measurement error: sources and propagation
4. linear and constrained non-linear least-squares, parameter uncertainty
5. scaling and similitude for static and dynamic modeling
6. strain gages, induction motors, piezo-electrics and other types of sensing and actuation
7. plane-stress photo-elasticity
8. viscometry and visco-elastic solids and fluids
9. digital filters, the FFT and time-frequency distributions
10. auto-correlation, power spectral estimation, frequency response function
11. parameter estimation for linear systems: FRF and RLS approaches
12. actuation systems: modeling, identification, and control

and will be applied to in-class demonstration experiments, including:

1. integrated circuits for instrumentation and signal conditioning
2. strain gage tranducers for sensing load and displacement
3. photo-elasticity and visco-elasticity, creep, relaxation, and hysteresis
4. free and forced vibration of a lightly damped linear structure
5. chaotic dynamics of a pre-buckled cantilever
6. in-elastic dynamics of a structural frame

and individual term projects.

CE 281: EXPERIMENTAL SYSTEMS
OUTLINE, READINGS, REFERENCES, AND LABS

1. **Math review and overview of linear systems:**

   Input-output models, impulse response function, convolution, Fourier transform, Laplace transform, transfer functions, state variables, parallel, series, feedback connections, coupled electrical/structural/hydraulic systems, `damp`, `expm`, `bode`, `lsim`
   reading: [25]:98-103 [26]: 6,7,11
   references: [14] [30] [43] [44] [49]

2. **Introduction to electronic laboratory tools:**

   input and output impedence, digital volt meters, oscilloscopes, power supplies, function generators.
   reading: [22]:A.1-A.4,A.7,9.8 [25]:106-108 [74]:37-38
   references: [39]:1,A [51] [56] [78]:1.3

3. **Analog signal conditioning:**

   amplification: operational amplifiers (op-amps); instrumentation amplifiers; input and output impedance; slew rate; common mode rejection ratio.

   filtering: *RC* networks, magnitude and phase relations; active (Salen-Key) *RC* filters; anti-alias filtering.

   summation, integration and differentiation, bias, drift, and noise.
   reading: [22]:9.1-9.2 [25]:111,113,153 [74]:80,82
   references: [4]:7 [13] [19] [23] [28] [39]:4.00–4.12,5.00–5.08 [42] [45] [52] [54] [59]
   lab: scope, DMM, function generator, power supplies, model, design, proto-type, and test (i) an instrumentation amplifier, (ii) a non-inverting amplifier, (iii) a low pass filter, (iv) an integrator, and (v) a differentiator.

4. **Quantification and propagation of measurement error:**

   accuracy and precision of measured quantities; statistical description of data; Student-t confidence limits; Chauvenet's Criterion for out-lying data.
   reading: [25]:228,152 [74]:1,4-5 & Hand-outs
   references: [1] [4]:3 [5] [7] [10] [15] [17] [18]:6.10 [68] [78]:1.4,2

5. **Linear and non-linear least squares:**

   dependent and independent parameters; non-linear models and linear least squares problems; orthogonal polynomials; data covariance and parameter covariance; condition number, regularization, and singular value decomposition; Nelder-Mead simplex, Gauss-Newton, Levenberg-Marquardt, sequential quadratic programming, and the Matlab optimization toolbox.
   reading: Matlab optimization toolbox reference & Hand-outs
   references: [3] [9] [20] [38] [47] [55] [60]

6. **Similitude and scale modeling:**

   principle of dimensional homogeneity; the Buckingham-Π theorem; geometric, kinematic and dynamic similitude;
   reading: [25]:231 & Hand-outs
   references: [53] [71] [77] [80]

7. **Transducers (sensors and actuators):**

   strain gauges and Wheatstone bridges; piezo-electric sensors; linear variable differential transformers (LVDT); electro-magnetic sensors (velocity); micro-machined silicon accelerometers; electro-magnetic actuators; piezo-electric actuators; hydraulic actuators; dynamic models for sensors and actuators.
   reading: [25]:151.1 [74]:3,6.1-6.4,16-17,22-24,99 [22]:8.4-8.5,10 Strain Gage Tech Notes & Hand-outs
   references: [4]:5,6,11.19,12,13.4-13.6,17,E [8] [11] [12][18]:6,7 [31][32] [37] [50][57][62][64][70] [78]:3,4.3
   lab: Ω-transducer and load-cell: analysis, instrumentation and calibration (Labs 1,2,3). Apply IC instrumentation to your Ω-transducer or load-cell.

8. **Photoelasticity:**

   strain-optic law; linear polarizers, circular polarizers, and quarter wave plates; isoclinics and isochromatics; visco-elasticity, creep, relaxation, and calibration.
   reading: [74]:60 Photo Stress Tech Notes
   references: [18]:10-15
   lab: Stresses in a thick visco-elastic ring under diametric compression.

9. **Digitization:**

   discretization and quantization of signals; properties of analog-to-digital converters; noise levels in PC-based digitization systems; register-level programming; Nyquist frequency, aliasing.
   reading: [74]:85 [25]:121 [22]:9
   references: [2] [12] [18]:8 [21] [35] [34]:8.3 [66] [73]

10. **Scaling and smoothing of data:**

    sensor sensitivity; system calibration; smoothing of digitization noise; de-trending of data; numerical integration and differentiation; finite difference, trapezoidal, Simpson, Tick, Runge-Kutta.
    reading: [25]:111,134 [22]:4
    references: [18]:7.5 [34]:3 [60]:16.1 [78]:1.3,A
    lab: visco-elasticity, creep, relaxation, and hysteresis (Labs 8,9,10)

11. **Digital signal processing:**

    digital filters; fast Fourier transform methods; leakage and resolution; power spectrum estimation, windowing and averaging; Hilbert transforms, Kramer-Leadbetter envelopes, time-frequency distributions, Choi-Williams kernels.
    reading: [26]:14,21 [22]:D & Hand-outs
    references: [16] [34]:9.1-9.6 [40] [58] [60]:12,13.0-13.6 [61] [63] [72] [82]
    lab: power spectral densities of lightly damped linear systems; estimation of damping. (Labs 16,17,18)

12. **Modeling of data (non-parametric identification):**

    auto-correlation, cross-correlation and power spectra; H_1, H_2, H_v estimates for frequency response functions; coherence functions; curve-fitting frequency response functions; Auto-regressive, moving-average (ARMA) models.
    reading: [25]:230 & Hand-outs
    references: [5] [18]:16 [35] [33] [69] [78]:A
    lab: chaotic dynamics of a pre-buckled cantilever (lab ..)

13. **Modeling of dynamic systems (parametric identification):**

    static and dynamic models; interactions between test specimens, sensors, and test hardware; identification of mechanisms and estimation of parameters; Least Mean Squares (LMS) and Recursive Least Squares (RLS); parameter estimation from curve-fitting; non-linear dynamic systems and identification; models for hysteresis, chatter, dynamic buckling.
    reading: [22]:11 & Hand-outs
    references: [18]:13.2.6 [27] [36]:2 [41] [48] [67] [69] [79]:appendix [77]:5
    lab: inelastic dynamics

14. **Individual Projects:**

    identification of project topic; preliminary analysis incorporating equilibrium, continuity, and material characteristics; development of experimental hardware; sensor calibration; data collection; parameter estimation and error analysis; oral presentation and written report.

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VENDORS AND SUPPLIERS

Alligator Technologies	`www.alligatortech.com`	signal conditioning
Analog Devices	`www.analogdevices.com`	integrated circuits
BLH	`www.blh.de`	strain gages
Burr-Brown	`www.burr-brown.com`	integrated circuits
Brüel & Kjaer	`www.bkhome.com`	test and measurement
DSP Technology	`www.dspt.com`	digital signal processing
Interface	`www.interfaceforce.com`	force transducers
Keithley	`www.keithley.com`	test instruments
Kinemetrics	`www.kinemetrics.com`	seismic sensors
Lucas-Schaevitz	`www.schaevitz.com`	displacement sensors
Measurement Computing	`www.measurementcomputing.com`	data-acquisition hard/soft-ware
Measurements Group	`www.measurementsgroup.com`	strain gages and photo-elasticity
Midori America	`www.midoriamerica.com`	displacement and rotation
National Instruments	`www.natinst.com`	data-acquisition software
Moog	`www.moog.com`	servo-valves
Omega	`www.omega.com`	pressure and temperature sensors
Peak to Peak Power	`www.peaktopeakpower.com`	power supplies
Quanser Consulting	`www.quanser.com`	digital signal processing
Schenck Pegasus	`www.schenckpegasuscorp.com`	servo-valves
Sensotec	`www.sensotec.com`	force and pressure sensors
Silicon Designs	`www.silicondesigns.com`	acceleration sensors
Tektronix	`www.tektronix.com`	test and measurement
Trans-Tek	`www.transtekinc.com`	displacement, velocity, and rotation