Instrumentation (ch. 4 in Lecture notes)

- Measurement systems – short introduction
- Measurement using strain gauges
- Calibration
- Data acquisition
- Different types of transducers

Physical process

Instrumentation and data acquisition

Measurement result (numbers)
The old resistance measurement system

Transducer = weights, wheels and string
Data acquisition = writing down total weight
The new resistance measurement system

Data acquisition and signal conditioning system

Transducer based on strain gauges
Measurement systems

Transducers

Amplifier

Filter

A/D

Analog signals

+- 10 mV

+- 10V DC

Digital signals

NTNU
Strain gauges
Wheatstone bridge

- $\Delta R$ is change of resistance due to elongation of the strain gauge
- $R$ is known, variable resistances in the amplifier
- $V_{\text{in}}$ is excitation – a known, constant voltage source
- $V_{g}$ is signal
Wheatstone bridge

- Constant voltage (can also be current) is supplied between A and C
- The measured voltage (or current) between B and G depends on the difference between the resistances $R_1$-$R_4$
- One or more of the resistances $R_1$-$R_4$ are strain gauges
- If all resistances are strain gauges, it is a *full bridge circuit*
- If only one resistance is a strain gauge it is a *quarter bridge circuit*
Force transducer with two strain gauges, using a Wheatstone half bridge
Calibration

- How to relate an output Voltage from the amplifier to the physical quantity of interest

Known load → Adjust calibration factor → Known measurement value

In a measurement:
Measurement value = transducer output · amplification · calibration factor

In a calibration:
Calibration factor = Known load / (transducer output · amplification)
What is the calibration factor dependent on?

- Type of strain gauges used (sensitivity)
- Shape of sensor and placement of strain gauges
- Excitation voltage
- Amplification factor (gain)

This means that one shall preferably calibrate the sensor with the same amplifier and same settings as will be used in the experiment.
Zero level measurement

• The measurement is made relative to a known reference level
  – Typically, the signal from the unloaded transducer is set as zero reference

• Two options:
  – Balancing the measurement bridge by adjusting the variable resistances in the amplifier
    • Tare/Zero adjust function in the amplifier
  – First making a measurement of the transducer in the reference condition (typically unloaded), and then subtract this measured value from all subsequent measurements
    • This is usually taken care of by the measurement software (Catman)

• In hydrodynamic model tests, we usually use both options in each experiment
Amplifiers

- Many different types:
  - DC
  - AC
  - Charge amplifier (for piezo-electric sensors)
  - Conductive wave probe amplifier
- Provides the sensor with driving current ($V_{in}$)
- Amplifies the sensor output from mV to (usually) ±10V
- Tare/zero adjust function (bridge balancing)
  - Adjusting the resistances $R_1$, $R_2$, $R_3$, $R_4$ in the Wheatstone bridge to get zero $V_G$ in unloaded condition
A/D converters

- Conversion of analog ±10V DC signal to digital
- Typically 12 to 20 bits resolution
- Typically 8 to several hundred channels
- Each brand and model requires a designated driver in the computer, and often a custom data acquisition software
- Labview works with National Instruments (NI) A/D converters, but also other brands provides drivers for Labview
- Catman is designed to work only with HBM amplifiers
A/D conversion – sampling of data

- The continuous analog signal is *sampled* at regular *intervals* - *the sampling interval* \( h \) [s]
  - The analog value at a certain instant is sensed and recorded
- The analog signal is thus represented by a number of discrete – digital – values (numbers)
- The quality of the digital representation of the signal depends on:
  - The sampling frequency \( f = 1/h \) [Hz]
  - The accuracy of the number representing the analog value
    - The accuracy means the number of bits representing the number
    - 8 bit means only \( 2^8 = 256 \) different values are possible for the number representing the analog value => poor accuracy
    - 20 bit means \( 2^{20} = 1048576 \) different values => good accuracy
  - The measurement *range* vs. the *range* of values in the experiment
  - High sampling frequency and high accuracy both means large amounts of data being recorded => large data files!
    - The reason not to use high sampling frequency is mainly to reduce file size
Sampling frequency

Nyquist frequency $f_c$

$$f_c = \frac{1}{2 \cdot h}$$

Means:
- You need at least two samples per wave period to properly represent the wave in the digitized data.
- You should have more samples per period to have good representation …
- Less than two samples per wave period will give “false signals” (downfolding)
Effect of folding

- To avoid folding:
  - Make sure $f_c$ is high enough that all frequencies are correctly recorded

  or

  - Apply analogue low-pass filtering of the signal, removing all signal components at frequency above $f_c$ before the signal is sampled
Filters – to remove parts of the signal

Amplitude vs. Frequency

- **Low pass filter**: Removes high frequency part of signal (noise)
- **High pass filter**: Removes low frequency part of signal (mean value)
- **Band pass filter**: Retains only signals in a certain frequency band

Amplifier
Filter
A/D

Analog signals
Digital signals

+- 10V DC

Transducers
Filtering – low pass filter

Asymmetric filtering (used in real-time)

Symmetric filtering (can only be used after the test)

Real time filters always introduce a phase shift – a delay
Data acquisition without filtering

- It is OK to do data acquisition without filtering as long as there is virtually no signal above half the sampling frequency
  - so there is no noise that is folded down into the frequency range of interest
- Requires high sampling frequency
  - (>100 Hz, depending on noise sources)
- Requires knowledge of noise in unfiltered signal
  - Spectral analysis, use of oscilloscope

- Unfiltered data acquisition eliminates the filter as error source, and eliminates the problem of phase shift due to filtering
  - Drawbacks:
    - Must have good control of high-frequency noise
    - Large sampling frequency means large data files
Selection of filter and sampling frequency

- The problem with high sampling frequency is that result files become large
  - Double the sampling frequency means double the file size
  - This is less of a problem for measurement of low-frequency phenomena (ship motions etc.)
- Low-pass filter should be set just high enough to let the most high-frequency signal of interest to pass unmodified
- Sampling frequency should then be set to at least twice the low-pass filter cut-off frequency, preferably 5-10 times this value
  - 20 Hz Low-Pass filter $\rightarrow$ minimum: 40 Hz sampling
    recommended: 200 Hz sampling
Data acquisition software

• Communicates with the A/D converter
• Conversion from ±10V DC to physical units
• Records the time series
• Common post-processing capabilities:
  – Graphical presentation of time series
  – Calculation of simple statistical properties (average, st.dev.)
  – Zero measurement and correction for measured zero level
  – Storage to various file format
Data Acquisition with digital amplifiers

Transducer (strain gauge)

Analog mV/V signal

MGC+ amplifier

Digital signal in Physical units

PC computer

Data acquisition software
Collecting data
Statistical analysis
Presentation
Storage to various file format

Change of resistance due to elongation

Strain gauge excitation (amplification)
Bridge balancing
Analog to digital conversion
Zero correction (tare)
Filtering and signal conditioning
Conversion to physical units
Length of records
- of irregular wave tests and other randomly varying phenomena

• The statistical accuracy is improved with increasing length of record. The required duration depends on:
  – The period of the most low frequent phenomena which occur in the tests
  – The system damping
  – The required standard deviation of the quantities determined by the statistical analysis

• Rule of thumb: 100 times the period of most low frequent phenomena of interest
Length of records
- Typical full scale record lengths:

- Wave frequency response: 15-20 minutes
- Slow-drift forces and motions: 3-5 hours (ideally ~10 hours)
- Slamming ??
- Capsize ??

- To study and quantify very rarely occurring events, special techniques must be applied!
Transducer principles
- for strain and displacement measurements

• Resistive transducers
  – Change of resistance due to strain – strain gauges
• Inductive transducers
• Capacitance transducers
Inductive transducers

- Measures linear displacement (of the core)
- Needs A/C excitation
- Used also in force measurements in combination with a spring or membrane
Force measurement instruments:

Dynamometers

- 1-6 force components can be measured
- Strain gauge based sensors are most common
- One multi-component dynamometer might be made of several one, two or three component transducers
- Many different designs are available
- Custom designs are common
- Special dynamometers for special purposes like:
  - Propeller thrust and torque
  - Rudder stock forces
Propeller dynamometer for measurement of thrust and torque
Three-component force dynamometer
6 component dynamometer
Pressure Measurements
- Transducer principles

Inductive

Strain gauge

Piezo-electric
Pressure Measurements
- Requirements

- Stability is required for velocity measurements
  - Strain gauge or inductive

- Dynamic response (rise time and resonance frequency) is important for slamming and sloshing measurements
  - Piezo-electric
  - Strain gauge
Position measurements

• Mechanical connection:
  – Inductive transducers
  – Wire-over-potentiometer
  – Wire with spring and force measurement

• Without mechanical connection:
  – Optical and video systems
  – Acoustic systems
  – Gyro, accelerometers, Inertial Measurement Units (IMU)
Mechanical position measurements

- Axial force transducer
- Spring
- Wire connected to model
- Potentiometer
  Measuring rotation
- Wire connected to model
- Ship model
Optical position measurement

- Remote sensing, non-intrusive measurement
- Using CCD video cameras
- Each camera gives position of the marker in 2-D
- Combination of 2-D position from two cameras gives position in 3-D by triangulation
- Use of three markers on one model gives position in 6 DoF by triangulation
- Calibration is needed for the system to determine:
  - Camera positions and alignment
- The relative positions of the markers on the model must be known to the system
Optical position measurement principle
Velocity measurements

- **Intrusive measurement** (probe at point of measurement)
  - Pitot and prandtl tubes for axial or total velocity measurement
  - Three and five hole pitot tubes for 2 and 3-D velocity measurement
  - Various flow meter devices

- **Non-intrusive measurement** (no probe at point of measurement)
  - Laser Doppler Anemometry (LDA or LDV)
    - Measures velocity in a single point at each time instance
  - Particle Image Velocimetry
    - Measures flow field (2-D) in one instant
Prandtl (pitot-static) tube

\[ \Delta P = \frac{1}{2} \cdot \rho \cdot V^2 \]

\[ V = \sqrt{2 \cdot \Delta P / \rho} \]
Pitot tube

- Smaller size than Prandtl tube
- Less accurate, due to sensitivity to static pressure

\[ P_{tot} = P_{dyn} + P_{stat} = \frac{1}{2} \cdot \rho \cdot V^2 + \rho \cdot g \cdot h - \rho \cdot g \cdot z \]
Prandtl tube rake for propeller wake measurements

Axial wake shown as color contours
Propeller disk indicated by dashed line
Five-hole pitot tube

Radial wake component
(Horizontal)

Tangential wake component
(Vertical)

VIEW FROM SIDE
PCS
VIEW FROM THE FRONT
VIEW FROM ABOVE

$\alpha = 20\, \text{degrees}$

Axial wake shown as color contours
Radial and tangential wake shown as vectors
Propeller disk indicated by dashed line
Particle Image Velocimetry (PIV)

- Velocity distribution in a plane is found from the movement of particles in a short time interval.
- High-speed video is used to capture images.
- A sheet of laser light is used to illuminate the particles in the water.
- Finding the velocity by comparing the two pictures is not trivial.
- ”Seeding” the water with suitable particles is another practical challenge.
3-D Particle Image Velocimetry (PIV)

- Like 2-D PIV, except that two cameras are looking at the particles from different angles
- You obtain 3-D velocity vectors in a plane
Laser Doppler Velocimetry (LDV or LDA)

- Point measurement – must move the probe to measure at different locations
- Calibration free
- Give 3-D flow velocity – also time history ⇒ can measure turbulence intensity

Photo courtesy of Marin, the Netherlands
Practical arrangement for stereo LDV and PIV
Applications of velocity measurement systems

• Pitot and Prandtl tubes:
  – Intrusive measurement of velocity at a single (or few) points
  – Cheap, simple and reasonably accurate average

• LDA/LDV
  – Very accurate, very high resolution point measurements, useful for turbulence measurements
  – Non-intrusive
  – Doesn’t require calibration
  – Costly and time consuming

• PIV
  – Measurement of flow fields
  – Non-intrusive
  – Tedious calibration required for each new test set-up
  – Very costly and time consuming
Wave probes

Conductive wires

Measurement of resistance,
Conversion to +-10V DC

Water will short-circuit between the wires

Wave probe amp.
wave probe
output
10V DC
+-

+-
0 0
Relative wave measurements

(a) Capacitance strips ahead of model
(b) Flush capacitance strips
(c) Resistance wires
Acoustic wave probes

- **Working principle:**
  A sound pulse is emitted, and the time it takes the reflected sound to reach the probe is used to calculate the distance to the water

- **Benefits:**
  - Works also at high forward speeds
  - Non-intrusive
  - Calibration free

- **Drawbacks:**
  - More costly
  - Steep waves in combination with smooth surface (no ripples) causes drop-outs, when no reflected sound reach the probe