Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

innovative composite structures

Development of a Low-Cost Modal Analysis System

subtitle

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Master Thesis

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Abstract

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Entwicklung eines Low-cost-Modalanalyse-Systems

Bachelor- / Masterarbeit

Problemstellung

Mit zunehmender Verbreitung von simulationsgestützer Entwicklung wird auch der Bedarf nach Methoden zur Modellverfikation in der Industrie grösser. Die experimentelle Modalanylse (EMA) ist ein mächtiges Werkzeug zur Validierung von Simulationsmodellen von Werkzeugmaschinen. Dabei wird die Struktur mittels Impulshammer angeregt und die Antwort mit Beschleunigungssensoren gemessen. Kommerziell erhältliche EMA-Systeme kosten jedoch schnell über 50‘000 CHF und sind daher für die breite Anwendung nicht geeignet. Für die Modellvalidierung sind jedoch die Auflösung und die Abtastrate des Messsystems häufig weniger kritisch, was den Einsatz von günstigeren Komponenten zulassen würde.
Mit den heute erhältlichen MEMS-Beschleunigungssensoren (wie sie in jedem Smartphone verbaut werden) und Mikrocontroller-Plattformen (wie Arduino) ergibt sich die Möglichkeit, ein einfaches EMA-System aus sehr günstigen Komponenten zu entwickeln.

Aufgabenstellung

Auf Basis von günstigen Sensoren und Mikrokontrollern, sowie freier open-source Software, soll ein preiswertes Messsystem zur Validierung von Simulationsmodellen entwickelt werden.

Arbeitspakete:

- Festlegen der Anforderungen an das Messsystem
- Auswahl der Komponenten
- Entwicklung der Software zum Auslesen der Sensoren (Arduino)
- Evaluation der Auswertesoftware (open-source)
- Vergleich mit einem komerziellen EMA-System
- Präsentation der Ergebnisse und Diskussion

Aufteilung der Arbeit: 70% Entwicklung/Programmierung, 20% Messen, 10% Bericht

Anforderungen: Erfahrung mit Programmierung; optimalerweise im Bereich Mikrokontroller (Arduino).

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Contents

List of Abbreviations

AMP	Amplifier
ADC	Analog to Digital Converter
ASCII	American Standard Code For Information Interchange
CPU	Central Processing Unit
DAC	Data Acquisition
EMA	Experimental Modal Analysis
FIFO	First In, First Out
FPGA	Field Programmable Gate Array
FRF	Frequency Response Function
MCU	Microcontroller Unit
MEMS	Micro-Electro-Mechanical-Systems
MT	Machine Tools
LC	Load Cell
LPF	Low Pass Filter
IN-AMP	Instrumentation Amplifier
PCB	Printed Circuit Board
IC	Integrated Circuit
RS	Recommended Standard
SPI	Serial Peripheral Interface
USB	Universal Serial Bus
WLAN	Wireless Local Area Network

1

Introduction

1.1 Motivation

The Experimental Modal Analysis (EMA) is a powerful tool for evaluating dynamic models of structures. Despite its extensive usage in the aerospace industry, in many other engineering fields the benefits of EMA are overshadowed by the initial investment and the operator costs of an EMA system. Progress in Micro-Electro-Mechanical-Systems (MEMS) enables a different branch of sensors to be used for EMA.

1.2 Related Work

In the field of civil engineering bridges and skyscrapers require continuous vibration signal logging for structural health monitoring. This leads to an increased interest in driving down the cost of accelerometer based monitoring systems. Bla bli and blu have developed low-cost MEMS systems for structural health monitoring of civil structures. Bli, bla and blu have expanded on this idea by interfacing the system via a Wireless Local Area Network (WLAN) protocol. Somebody developed an modal test system, which uses piezo load cells that are typically used to tune musical instruments as response sensors. Waltham and Kotlicki implemented a piezo load cell that is designed to trigger barbeque lighters in a modal impact hammer [4].

Names o
neers dev
cost syst

Names o
neers tha
wlan syst

Engineer
strument

[1]

1.3 Overview

We will first give background information bla bla bla. * EMA * EMA system ** Components ** Filter **

2

State of the Art

2.1 Measurement

The process of measurement is the comparison of data from the physical world in the frame of an agreed standard. It is carried out by using an instrument.

This section brings to light some key aspects of measurement instruments and components, used in the frame of this thesis. As a result some sections of [5] are summarized.

2.1.1 Measurement and Instrumentation

Measurement instruments translate signals from the physical world into an agreed upon standard. These standardized signals can be compared, altered and stored. The original data acquired from the physical signal is usually in analog form. This is then converted to digital before it is passed on. The signal chain of a typical digital measurement instrument is shown in Figure 2.1.

[5]

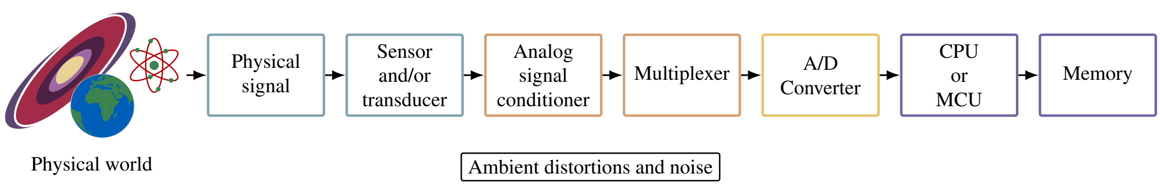


Figure 2.1: *Digital measurement instrument*

2.1.2 Sensors and Transducers

A device that responds to a changing phenomenon is called sensor. If we need to transfer the energy from one to another, we use a device called transducer. If one compares sensors and transducers based on the energy input and output, one identifies three types:

- In *modifiers* a specific energy form is not converted but modified. Hence they use the same form of energy as input and output.
- *Self-generators* give out electric signals from non-electric inputs without the need of additional energy.
- *Modulators* in contrast give out electric signals from non-electric inputs, but require an additional energy input.

As part of this we focus on self-generating piezoelectric sensors, capacitive modulators that convert mechanical deformation in a static electric field into an electric current, as well as strain gauge based modulators.

2.1.3 Load Cells

A force measurement sensor that converts a force into an electrical signal is called Load Cell (LC). The basis of force measurement results from the physical behavior of a body under external forces. Depending on the bandwidth and magnitude of the signal, as well as the duration of the signal capture, different methods of force measurement are applied in various designs. The methods in brief are:

- Balancing the unknown force against a standard mass through a system of levers
- Measuring the acceleration of a known mass
- Equalizing it to a magnetic force generated by the interaction of a current-carrying coil and a magnet
- Distributing the force on a specific area and then measuring the pressure
- Converting the applied force into the deformation of an elastic element

Furthermore, these methods yield numerous of designs of measuring equipment. Each of which addressing two main problems. First, the physical and geometrical constrains by the application of the device and second, the means by which the force can be converted into an electrical signal.

LCs in EMA equipment designs typically use piezoelectric sensors because of their high bandwidth in compact designs and their capability to detect small deflections.

2.1.4 Accelerometers

Accelerometers are sensors that convert acceleration into an electrical signal. In order to measure a physical phenomenon we use seismic masses that act on the sensor structure based on their inertia properties. In strain gauge based accelerometers the structure translates the inertia force into a deformation, where capacitive sensor structures may use deformations or relative motions of separate components in an electric field. In piezoelectric accelerometers the seismic mass deforms a piezoelectric material. Figure 2.2

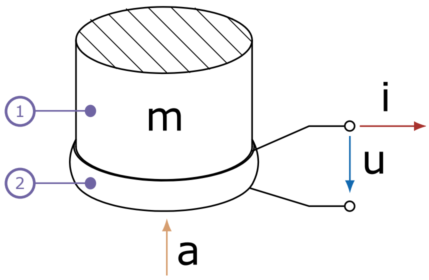


***Figure 2.2:** Function principle of a piezoelectric accelerometer*

a	:	Acceleration
m	:	Mass
i	:	Induced Current
u	:	Induced voltage
1	:	Seismic mass
2	:	Piezoelectric material

***Table 2.1:** Legend to Figure 2.2*

In seismic accelerometers the base of the arrangement is motion. When describing the one dimensional case, one can express non-stationary random vibrations acting on the accelerometer as

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} = c\frac{\mathrm{d}z}{\mathrm{d}t} + kz = mg\cos(\theta) - m\frac{\mathrm{d}^2 x_1}{\mathrm{d}t^2} \tag{2.1}$$

where

m is the seismic mass
$z = x_2 - x_1$ is the relative motion between the mass and the base
x_1 is the displacement of the base
x_2 is the displacement of the mass
θ is the angle between sense axis and gravity

The second-order system expressed in Laplace transform thus takes the form

$$G(s) = \frac{X(s)}{F(s)}\frac{K}{s^2/\omega_n^2 + 2\zeta s/\omega_n + 1} \tag{2.2}$$

where

s is the Laplace operator
$K = 1/k$ is the static sensitivity
$\omega_n = \sqrt{k/m}$ is the undamped frequency in $\mathrm{rad/s}$
$\zeta = c/2\sqrt{km}$ is the damping ratio

It is obvious that the performance of accelerometers depends on their static sensitivity, the natural frequency and the damping ratio. We want the accelerometer to have an linear transfer function in the range of operation. But namely the damping ratio can distort a measurement when operating an accelerometer near its eigenfrequency, see Figure 2.3.

2.1.5 Piezoelectric Sensors

Some materials develop electric charge proportional to directly applied mechanical stress. The same materials show the converse effect. A proportional strain of the material will occur to an applied electric field.

The first phenomenon has found its application in a variety of self-generating sensors that output electrical signals – amely in LCs and accelerometers, where the piezoelectric charge is converted into a current or voltage signal.

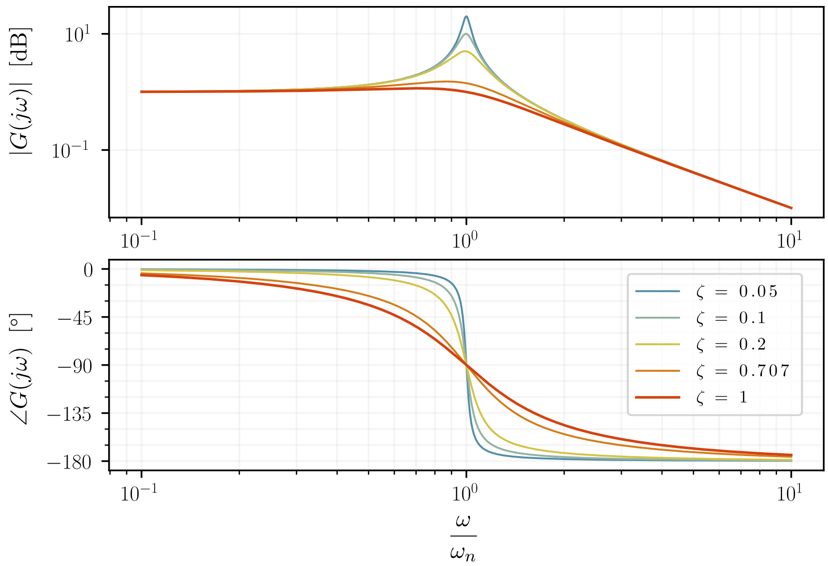
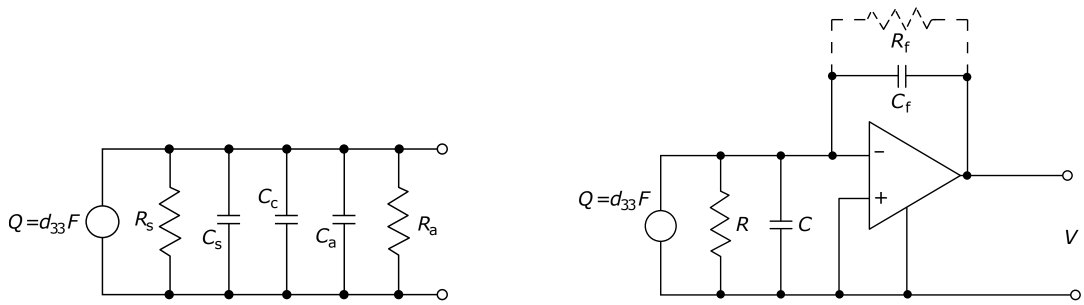


Figure 2.3: *Bode plots of second order system describing the dynamic behavior of seismic accelerometers*

Piezoelectric sensors are designed to exploit the piezoelectric effect of the material in one axis. Additionally, we use amplifier circuits so that the weak current or voltage, induced due to the piezoelectric charge, is elevated to amplitudes that are in the range of operation of standard electronic components. These circuits require additional energy. Commercially available LCs therefore require supplied energy – see Figure 2.4.



(a) *Piezoelectric sensor connected to a voltage amplifier*

(b) *Strain gauge in Wheatstone bridge circuit*

Figure 2.4: *Piezoelectric sensors connected to amplifier circuits [5]*

2.1.6 Strain Gauge Load Cells

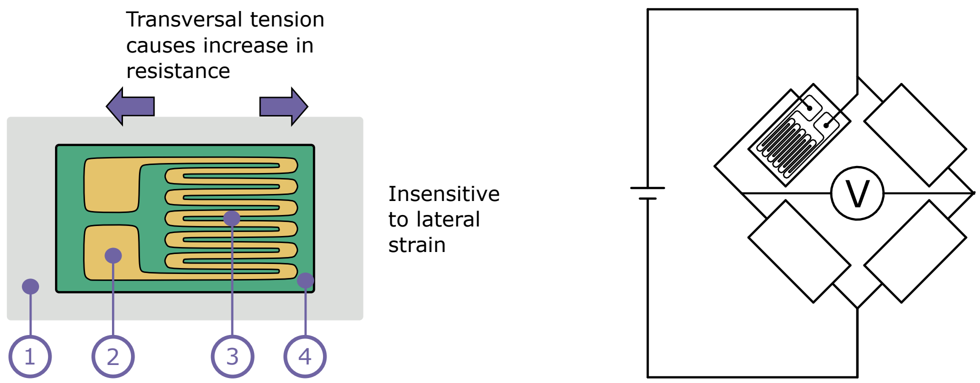
In strain gauge LCs the elastic properties of a material probe is exploited.

The probe is loaded in a controlled manner in its elastic region. Deformations are captured by a strain gauge at a suitable location. The probe deformation is directly determined by the force acting on the probe because of Hooke's law.

The strain gauges themselves each use a specific length gauge wire in order to reach a resistance of typically 120 Ω. The wire is bonded between two thin sheets in coiled up form as can be seen in Figure **??**.

The sheets act as insulating carrier and can be easily deformed with the intent of passing the load to the wire grid. The gauge is attached to the probe structure by a wax or a resin. The intent is that deformations in transversal direction of the strain gauge act on all coils simultaneously, changing their resistance. By using small sized strain gauges with respect to the probe, the mechanical and thermal properties of the strain gauge become negligible small. As an example, we assume the probe expands. Then a strain gauge on its surface experiences tension. The coils in the grid are therefore stretched and as a result of the generalized Hook's law the coil cross sections decrease. Both the strain in axial direction of the coil and the decreased coil cross sections increase the wire's resistance.

In order to measure deformations one needs to take environmental influences into consideration. It is well known that resistance is susceptible to variations in temperature. Placing the strain gauge in a wheatstone bridge, with resistors, that change their resistance in the same manner as the strain gauge will reduce the influence of temperature significantly – see Figure 2.5b.



(a) Strain gauge on structure, with (1) Structure, (2) Metal Pad, (3) Grid and (4) Carrier

(b) Strain gauge in Wheatstone bridge circuit

Figure 2.5: *Strain Guage*

2.1.7 Capacitive Accelerometers

To understand the working principle of capacitive accelerometers, we first consider the displacement sensors.

Capacitive Displacement Sensors

The basic sensing element of a displacement sensor typically consists of two parallel electrodes with capacitance C.

$$C = f(d, A, \varepsilon) \tag{2.3}$$

With variable distance, dielectric material or area and with the measurement of the capacitance, we can then deduce the plate displacement in normal and parallel direction to the plates depending on the method used. See Figure 2.6

In variable displacement sensors, the distance between two capacitive plates is inversely proportional to the capacitance.

$$C(x) = \frac{\varepsilon A}{x} = \frac{\varepsilon_r \varepsilon_0 A}{x} \tag{2.4}$$

where

ε is dielectric constant or permittivity
ε_r is the relative dielectric constant (in air and vacuum $\varepsilon_r \approx 1$)
ε_0 is $8.854\,188\,\mathrm{F/m}$, the dielectric constant of vacuum
x is the distance of the plates in m
A is the effective area of the plates in m^2

In variable area displacement sensors, the capacitance is proportional to the reduction of area due to the movement of the plate.

$$C(x) = \frac{\varepsilon_r \varepsilon_0 (A - wx)}{d} \tag{2.5}$$

where

ε_2 is the permittivity of the displacing material (e.g. liquid)
w is the width
wx is the reduction in the area due to movement of the plate
d is the distance of the plates in m

In variable dielectric sensors, the capacitance depends on the ratio of each permittivity in the electric field.

$$C(x) = \varepsilon_0 w[\varepsilon_2 l - (\varepsilon_2 - \varepsilon_1)x] \tag{2.6}$$
$$\tag{2.7}$$

where

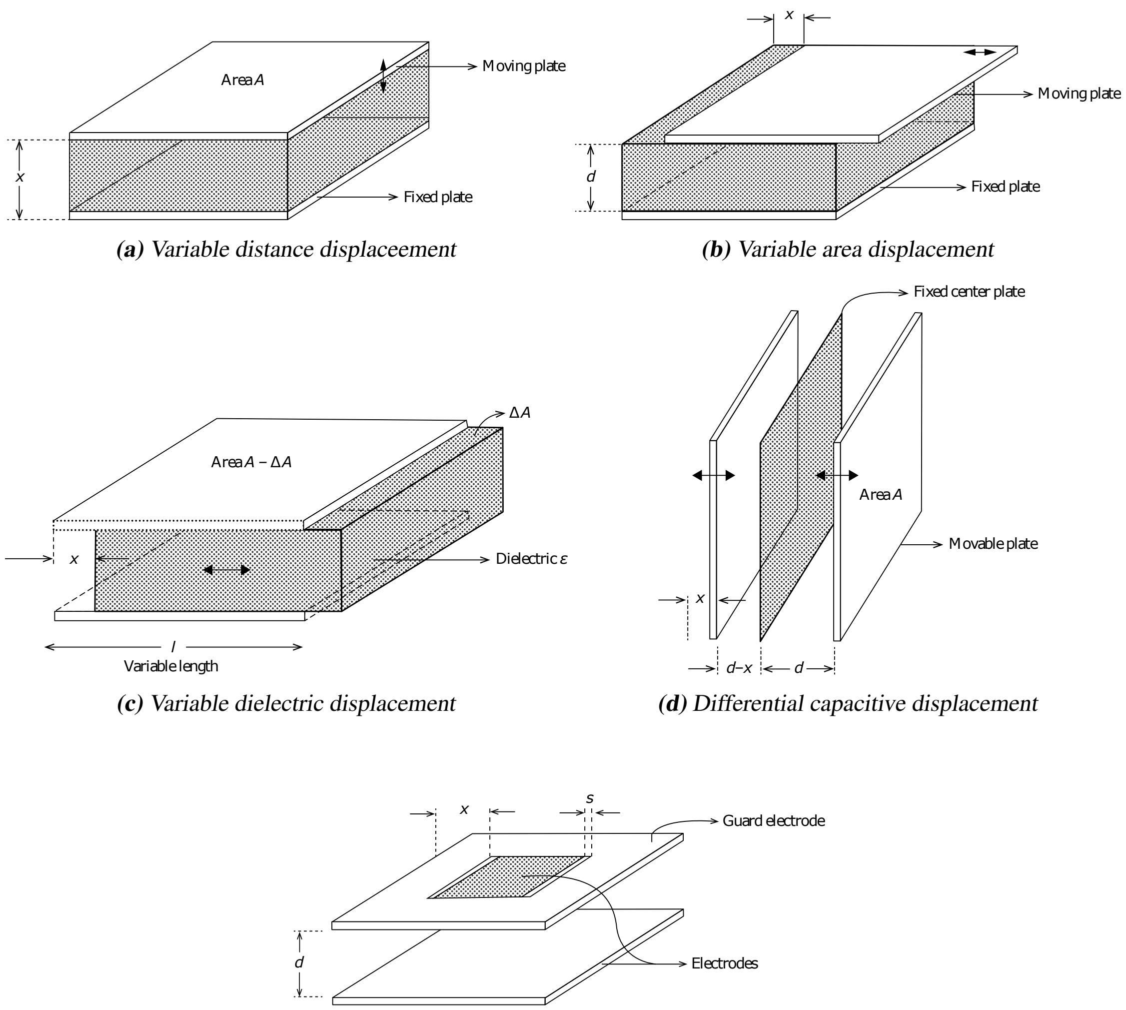
x is the displacement normal to the plates direction
ε_1 is the relative permittivity of the dielectric material
ε_2 is the permittivity of the displacing material (e.g. liquid)

Differential capacitive displacement sensors are setup in capacitive arrangements that aim to eliminate nonlinearities. Different variations of these types of sensors exist. For example we can allow the outer plates to move and fix the middle one or we can reverse this setup. But the range is equal to twice the separation in both cases.

$$2\delta C = C_1 - C_2 = \frac{\varepsilon_r \varepsilon_0 lw}{d - \delta d} - \frac{\varepsilon_r \varepsilon_0 lw}{d + \delta d} = \frac{2\varepsilon_r \varepsilon_0 lwd}{d^2 + \delta d^2} \tag{2.8}$$
$$C_1 + C_2 = \frac{\varepsilon_r \varepsilon_0 lw}{d - \delta d} + \frac{\varepsilon_r \varepsilon_0 lw}{d + \delta d} = \frac{2\varepsilon_r \varepsilon_0 lwd}{d^2 + \delta d^2} \tag{2.9}$$
$$\tag{2.10}$$

Giving approximately

$$\frac{\delta C}{C} = \frac{\delta d}{d} \tag{2.11}$$



(a) *Variable distance displaceement*

(b) *Variable area displacement*

(c) *Variable dielectric displacement*

(d) *Differential capacitive displacement*

(e) *IC smart capacitive displacement*

Figure 2.6: *Capacitive displacement sensors [5]*

Capacitive Accelerometers

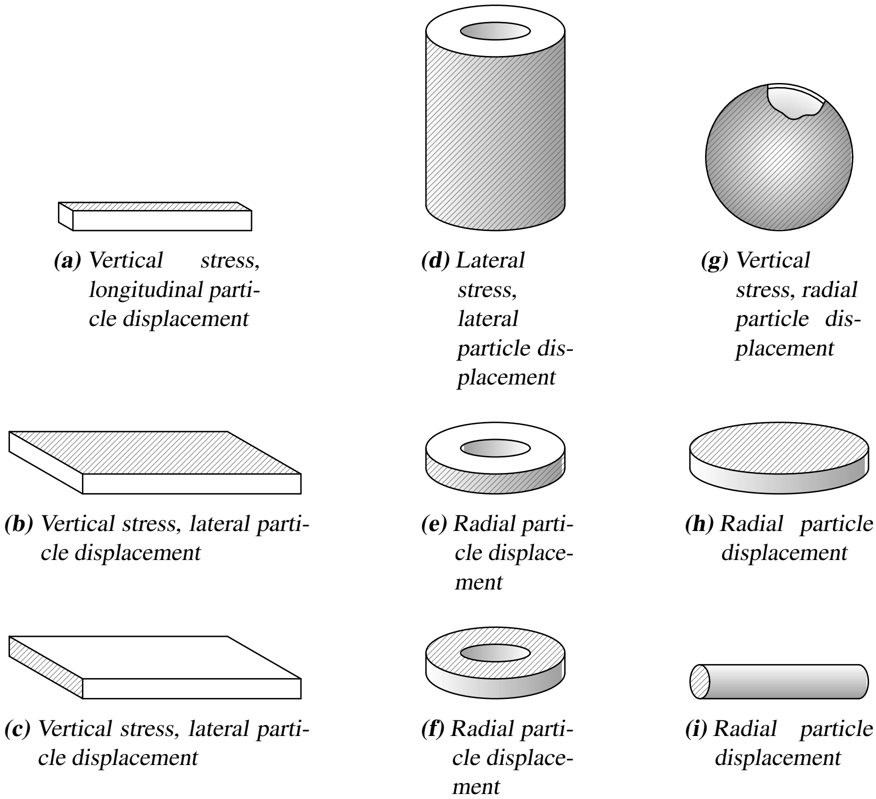
2.2 Experimental Modal Analysis

EMA is a powerful tool to detect vibration related problems of mechanical structures. We use modes to characterize resonant vibrations of the system [3]

Vibration

In every vibration one can observe a combination of two different types of vibrations. The forced and the resonant ones. Forced vibrations in a structure are caused by

- Internally generated forces
- Unbalances
- External loads



(a) Vertical stress, longitudinal particle displacement

(d) Lateral stress, lateral particle displacement

(g) Vertical stress, radial particle displacement

(b) Vertical stress, lateral particle displacement

(e) Radial particle displacement

(h) Radial particle displacement

(c) Vertical stress, lateral particle displacement

(f) Radial particle displacement

(i) Radial particle displacement

Figure 2.7: *Piezoelectric designs, where electrodes are placed on the shaded areas*

- Ambient excitations

Common examples of vibration sources in Machine Tools (MT) are displayed in Figure 2.8.

Resonant vibration arises when one or more of the natural modes of vibration, inherent properties of the structure under investigation, is excited. Resonant vibration typically amplifies the vibration response to a level that exceeds deflection, stress and strain caused by static loading.

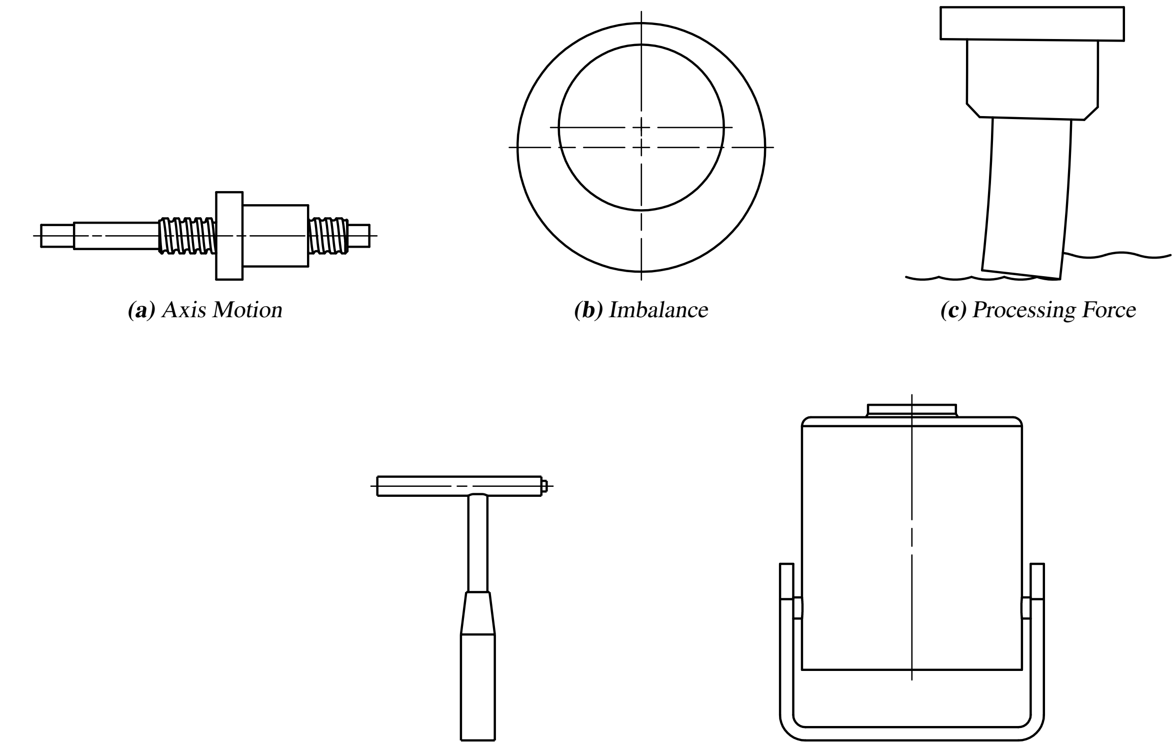
Modes

Modes or resonances are properties that are inherent to a structure.

2.2.1 Frequency Response Measurement

In a EMA one needs to determine the Frequency Response Function (FRF) from input to output. To achieve this we measure the so called response or output function of the structure under investigation. The measurement instrument for this task uses a signal chain in form of 2.9.

- The sensor on the structure translates the physical value (acceleration, velocity or position) into an electrical voltage or current, the analog signal variable.
- The amplifier amplifies the typically low power signal to fit it to the input range of the Analog to Digital Converter (ADC).



(a) Axis Motion *(b) Imbalance* *(c) Processing Force*

(d) Impact Hammer *(e) Modal Shaker*

Figure 2.8: *Sources of forced vibration. Note that (a), (b) and (c) occur during MT operation, while (d) and (e) are devices that are explicitly used for EMA to introduce vibrations into the structure of investigation.*

- The ADC samples and quantizes the analog signal. It is then converted into a digital signal, in which the quantity is expressed in form of a binary code.
- The discrete time signal is then stored on the computer memory.

[2]

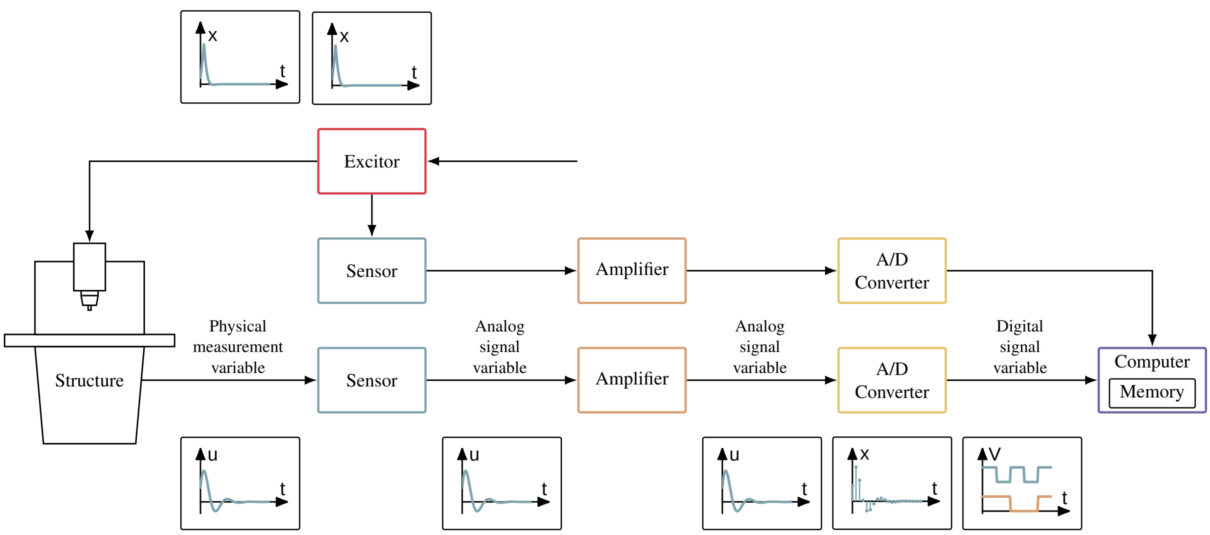


Figure 2.9: *FRF measurement setup*

2.3 Electronic Components

This section serves as an introduction to the function of selected electronic components and circuits. It does not give a complete overview of the state of the art. For more background on electronics may be consulted.

c hand-

Electronic components are divided into two main types; passive and active ones. Where active components are allowed to generate, amplify or oscillate an electrical signal, passive components can only absorb, dissipate or store electric energy.

2.3.1 Passive Components

Because of the increase in digital processing, the number of passive components has decreased drastically in modern electronic circuits. This, in addition to the trend of using more complex devices in favour to multiple simple passive components, has led to a great variety of passive components which are designed with emphasis on reliability.

Wires

Wires connect several electronic components. Ideally no loss or noise is introduced in wires but inductances occur due to the conductor's shape and material properties as well as electric fields, that are either self induced or present due to ambient conditions.

Depending on the mechanical requirements for the wire, it can either be designed with a solid core or a stranded wire core. A wire consisting of multiple smaller diameter conductors shows better flexibility but reduced current-carrying capacity at the same wire diameter. This is because of the smaller overall conductor cross-section of a stranded wire and, when transmitting high frequency signals, a greater power dissipation due to the more prevalent skin effect. Furthermore the simplicity of solid core wires makes them more resistant to corrosion and more suitable to be used in harsh environments.

Braided or foil shielding wires are usually used to shield other wires from ambient fields. Shaped as a tube they enclose one or multiple wires acting as a Faraday cage.

Resistors

Resistors are loads that reduce the current flow and set the voltage levels within a circuit. There are many different types of resistors.

2.3.2 Active Components

2.3.3 Integrated Circuits

2.3.4 Circuits

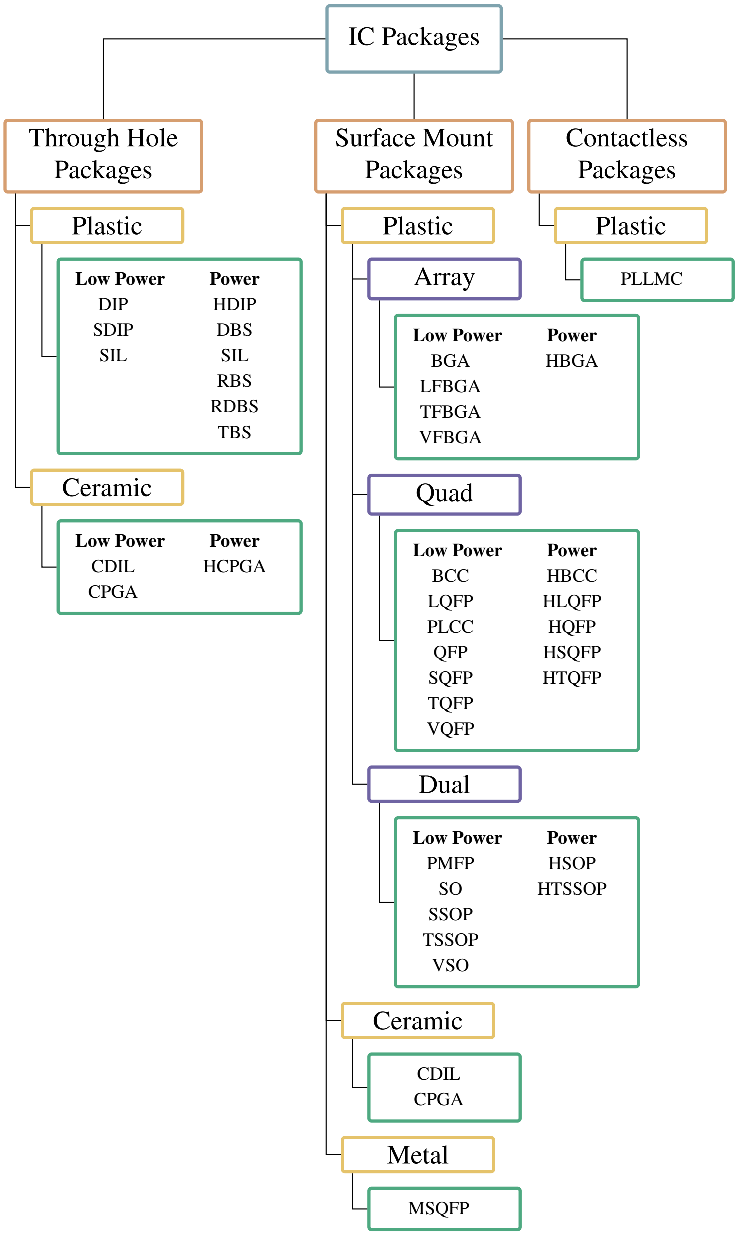


Figure 2.10: *Flowchart of IC packages*

3

Signal Conditioning and Processing

In an ideal world, the signal output of a sensor would correlate to the measurand exactly. In real systems this is not the case because of a variety of reasons. In low-frequency applications, the most important ones are:

- The voltage or current rating at a sensors output is not perfectly linear with respect to the measurand. Often the output is pseudo-linear in a limited range of values and deviates from the trajectory for values outside of this range.
- Noise and shifts introduced through the inherent impedances of analog components lead to deviations from the voltage or current rating of the sensor as well as deviations of these ratings with respect to the measurand itself.
- The quantization process causes the captured value space to have a finite resolution.
- Analogue signals can only be digitized with a finite sampling rate. A discrete set of data points is captured instead of a continuous signal.

The field of signal processing includes analysing, modifying and synthesizing signals. Most prominently, in data acquisition system we convert analog signals to digital ones that can be further processed without the parasitic effects of the analog realm. On the opposite side when addressing these parasitic effects one needs to apply signal conditioning. In other words, before every processing step of an analog signal we need to consider signal conditioning. When dealing with digital signals, no signal conditioning is required.

3.1 Signal Conditioning

3.1.1 Excitation

3.1.2 Amplification

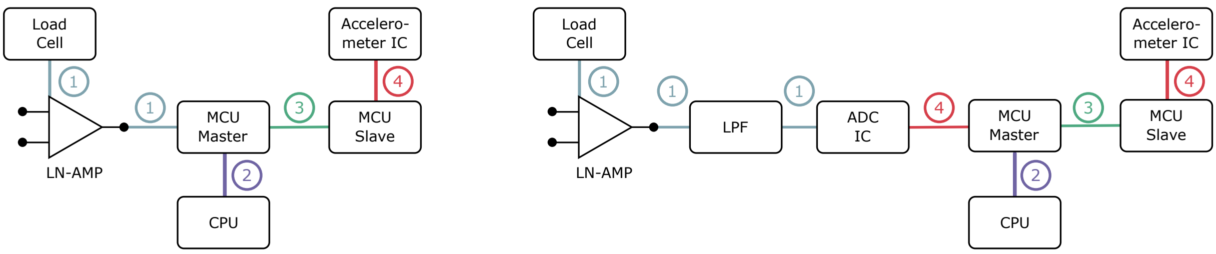
3.1.3 Filtering

4

Data Acquisition and Software

4.1 Data acquistion

The Data Acquisition (DAC) system developed in this thesis is an open source Arduino based system consisting of multiple microcontrollers. All signal channels are transmitted to a central microcontroller before passing to a computer that serves as visualization and analysis tool.



(a) *Without signal conditioning* ***(b)*** *With signal conditioning and external ADC*

Figure 4.1: *DAC-system building blocks*

Interfaces
1 : Analog Signal
2 : Universal Serial Bus (USB)
3 : Recommended Standard (RS)-485
4 : Serial Peripheral Interface (SPI)

Table 4.1: *Legend to Figure 4.1*

4.1.1 Building Blocks

Building blocks are the main components used in the DAC signal chain. Additional components that are required to enable the stable operation of the building blocks are not listed.

Because the of accelerometer Integrated Circuit (IC) output interfaces it is not possible to connect all sensors directly to one Microcontroller Unit (MCU) that acts as a DAC. We need to transform the signal to a different interface. A low-cost and versatile method to achieve this, is to use a MCU for each accelerometer IC. These read the sensor IC registers and communicate to the MCU master. The master, on the other hand, acts as a passthrough and transmits the data to the Central Processing Unit (CPU). In the setup used, it also reads out the LC signal. Table 4.2 lists the MCUs used during this thesis. Other components can be found in Appendix A.

The analog signal output of the LC needs to be amplified to match the input range of the ADC. To gain the maximum resolution, this depends on the expected input range. To get a higher value resolution than offered by the MCU embedded ADC one can set in an external ADC IC upstream to the MCU. Additionally, we use a Low Pass Filter (LPF) in Figure 4.1b. The LPF is needed to cut off high frequency components of the signal that occur particularly in sharp impulse signals. This design choice may lead to problems because it is not standard procedure in the development a measurement instrument. Typically, components in the analog signal chain are chosen, based on the frequency bandwidth of the input signal. This means, the cut-off frequency of the LPF is set well above the signal's bandwidth. But because we use low-cost components in our system, the bandwidth is limited to half the sampling rate of the slowest sensor. According to the Nyquist frequency theorem, the cut-off frequency then needs to be reduced to half the sampling frequency, potentially reducing the output magnitude of higher frequency components of the signal.

Name	Core	ADC-Resolution / bit	Operating Voltage / V	Clock Speed / MHz	Flash Memory / kByte	SRAM / kByte
Arduino Due	AT91SAM3 ARM Cortex	12	3.3	84	512	96
Teensy 3.2	MK20DX256VLH Cortex-M4	13 (16 bit-values)	3.3	72	256	64
Robotdyn Blackpill	STM32F103C8 Cortex-M3	12	72	64	20	

Table 4.2: *List of MCUs used in this work*

4.1.2 Interfaces

The interfaces are the connections and protocols between the different building blocks of the DAC system. The interfaces are chosen based on the sensors used and the expected data rate at the required cable length between each section. I.e.:

- Between the analog LC and the external ADC in Figure 4.1b and the MCU integrated ADC in Figure 4.1a respectively the signal transmission is analog.
- The register of the accelerometer IC is accessed via SPI
- The communication between MCUs is rooted in RS-485 differential transmission to accommodate

for signal transmission over cable lengths greater than $10\,\mathrm{m}$ and uses a specialized protocol to keep data packages as small as possible.

- Between the MCU and the CPU USB transmits data using the serial class of the Arduino software.

Data rates and package sizes are critical when sampling at high frequencies.

With RS-485 data can be transmitted over distances of no less than $100\,\mathrm{km}$ at a data rate of $1\,\mathrm{kbit/s}$. At $1200\,\mathrm{m}$ cable length we can reach data rates of around $100\,\mathrm{kbit/s}$. In our range of application, i.e. a few tens of m, we can expect data rates of $1\,\mathrm{Mbit/s}$, thus representing the bottle neck in the digital data chain. If we then transmit $80\,\mathrm{bit}$ acceleration measurements (see Figure 4.2) at $1.6\,\mathrm{kHz}$ we stay below this expected limit by a safety factor of more than 10. The arduino the serial package parses all data as human readable code, specifically American Standard Code For Information Interchange (ASCII). In this format every digit of integer values is passed as $8\,\mathrm{bit}$-value. Which means that a $32\,\mathrm{bit}$ timestamp and every single axis acceleration are passed as ten $8\,\mathrm{bit}$-values and six $8\,\mathrm{bit}$-values respectively. This increases the size of an accelerometer package to $624\,\mathrm{bit}$, which in turn reduces the safety factor to approximately 1. It is clear that one cannot use human readable code to transmit the data and guarantee stability at the required sampling rate.

MCU communication protocol

The communication protocol for MCU to MCU and MCU to computer was developed for this project.

<[(reg) (#bytes) (data)]>

<[/]>	:	Start-/End-bytes, represented as ASCII
(reg)	:	Registry/Address of the transmission
(#Bytes)	:	Number of bytes in transmission
(data)	:	Data to transmit

Table 4.3: *Protocol used to communicate between two MCU's and between MCU and computer*

4.1.3 Dataflow

All MCUs operate sequentially. The dataflow in MCU must be sequential. For this reason during a measurement all data is passed to a central MCU, where it is streamlined to the pc. The central MCU or master cycles through all connected MCU performing a data request, hold and receive action. As soon as a slave MCU gets a request, it transmits a data package from its buffer. The master now receiving the data package will throughput the signal to the CPU, where it is stored. By the end of this process the master will jump to the next slave.

All measurements consist of a $32\,\mathrm{bit}$-timestamp and the measured values and are pushed into a First In, First Out (FIFO) buffer in the flash memory of the MCU, directly connected to the sensor. Bundled data packages are then pulled from the buffer and translated into the transmission code as defined in Table 5.2. In Figure 4.2 the data flow is represented by a system that is using only one slave MCU, displayed in violet.

Measurements are packaged due to the time the master requires to change the communication to another slave. During these switches no data is transmitted eventually bottlenecking the data rate of the system.

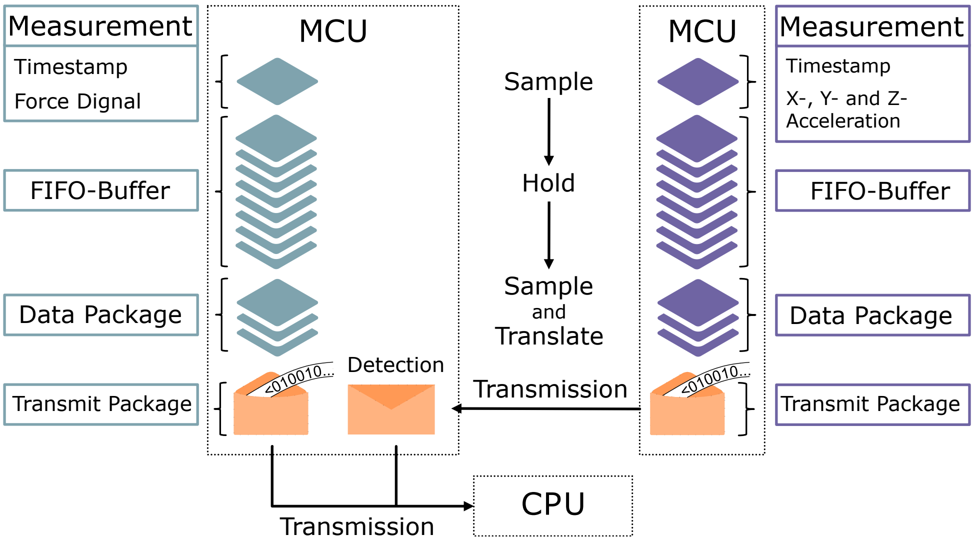


Figure 4.2: *Data flow between two MCUs and the CPU*

4.2 Software

The software developed during this project is split into the Arduino software running on the MCUs and a python based tool to receive and visualize the data via USB.

For the instrument to work, some functions are required, while other desired functions are tools that simplify the workflow during measurements and facilitate bug fixes in the software.

The requirements to the software tools are:

m1 Read out accelerometer and LC data at the maximum sample speed of the accelerometer IC.

m2 Synchronize measurements timestamps

m3 Initialize measurement by hammer impulse

The desired software tools are:

w1 Continuous real time output of measurement data

w2 Cache clearing

5

Test Setups

5.0.1 Hammer-Hammer Test

The hammer tips of the reference system and the experimental system are hit against eachother.

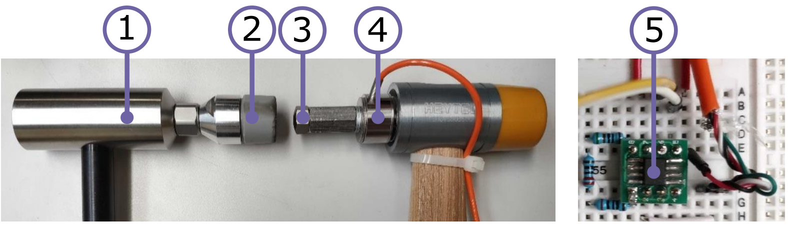


Figure 5.1: *Hammer-Hammer test components*

1	:	Piezo + AMP
2	:	Soft Tip
3	:	Tip 34CrMo4
4	:	LC DYMH-103
5	:	IN-AMP AD627

Table 5.1: *Legend to Figure 5.1*

5.0.2 Andromeda FRF measurement

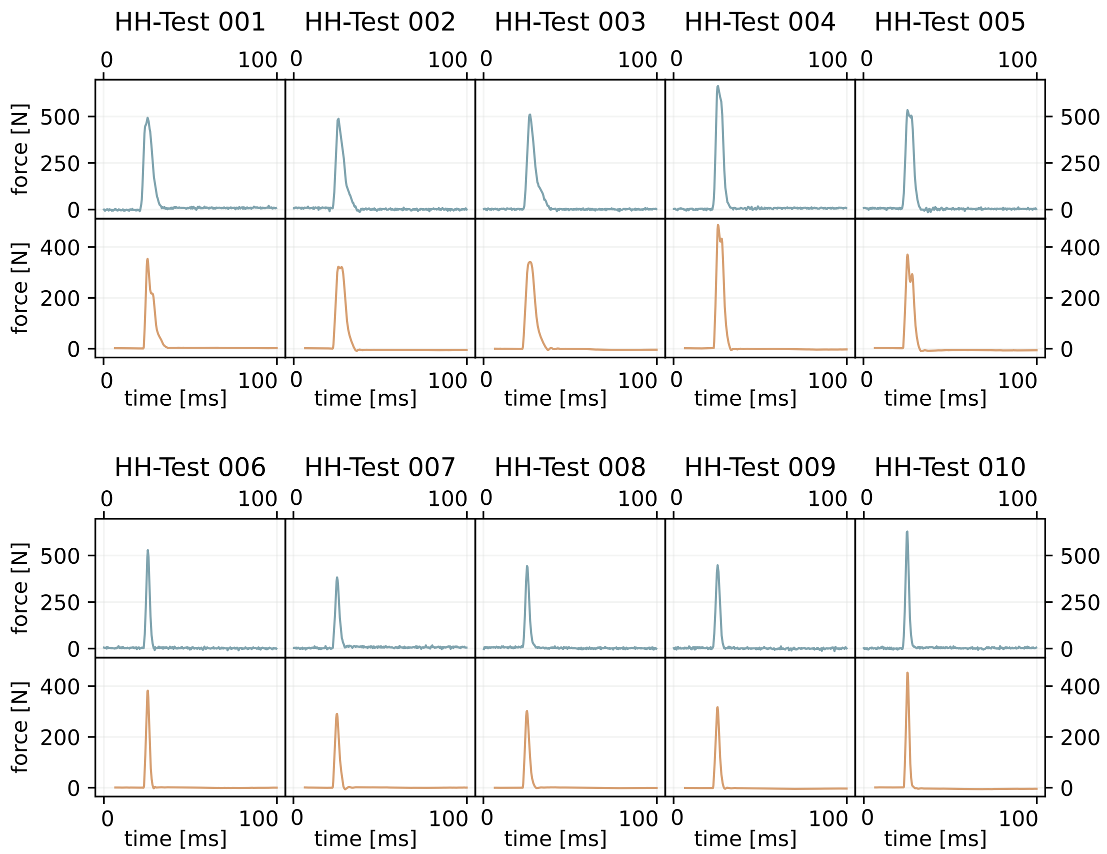


Figure 5.2: *The HH-Test recordings of the reference hammer (orange) and the evaluated impact hammer system (turquoise). Note that the evaluated signal values are normalized so that the maxima are equal to the reference system.*

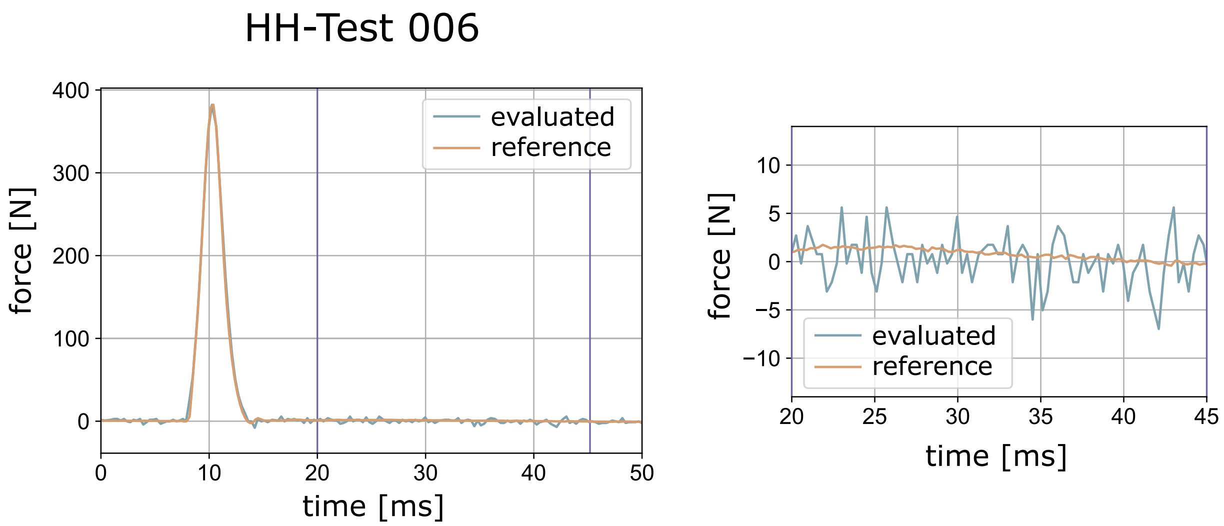


Figure 5.3: *The HH-Test recordings of the reference hammer (orange) and the evaluated impact hammer system (turquoise). Note that the evaluated signal values are normalized so that the maxima are equal to the reference system.*

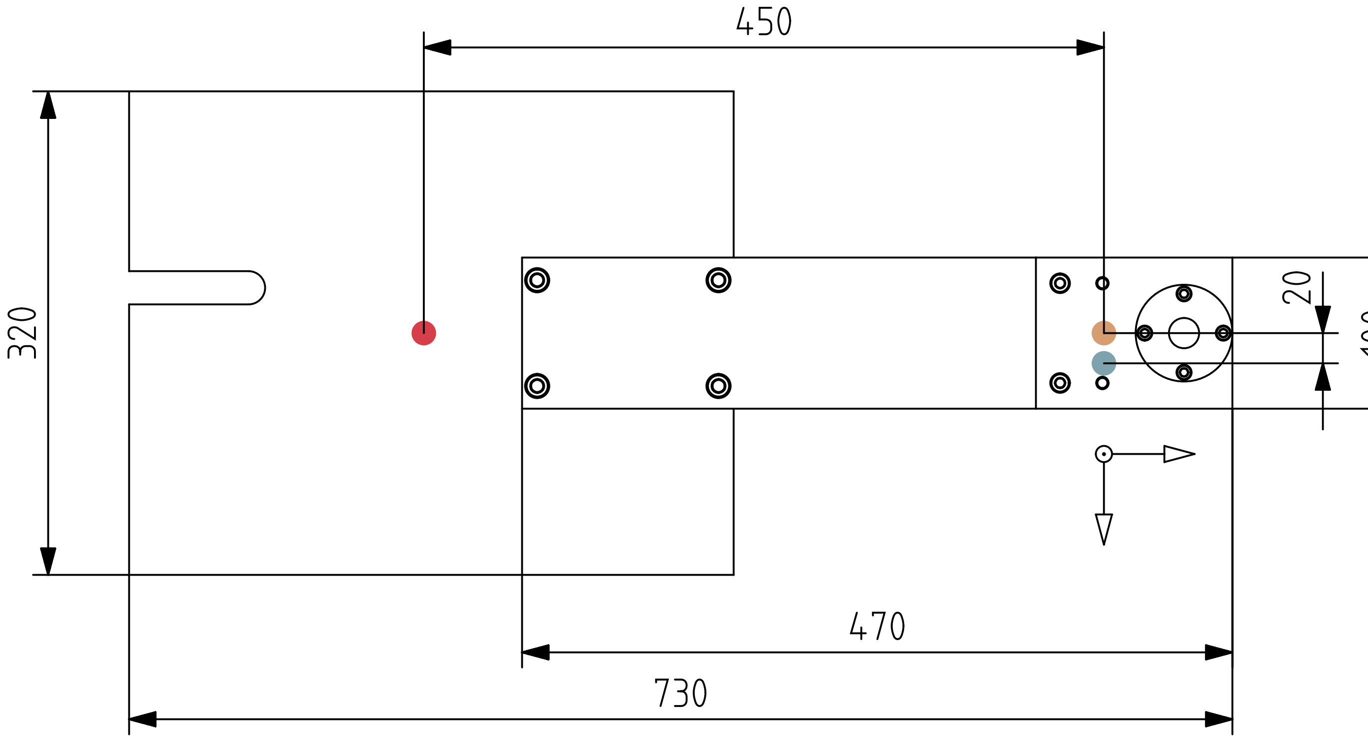


Figure 5.4: *Andromeda*

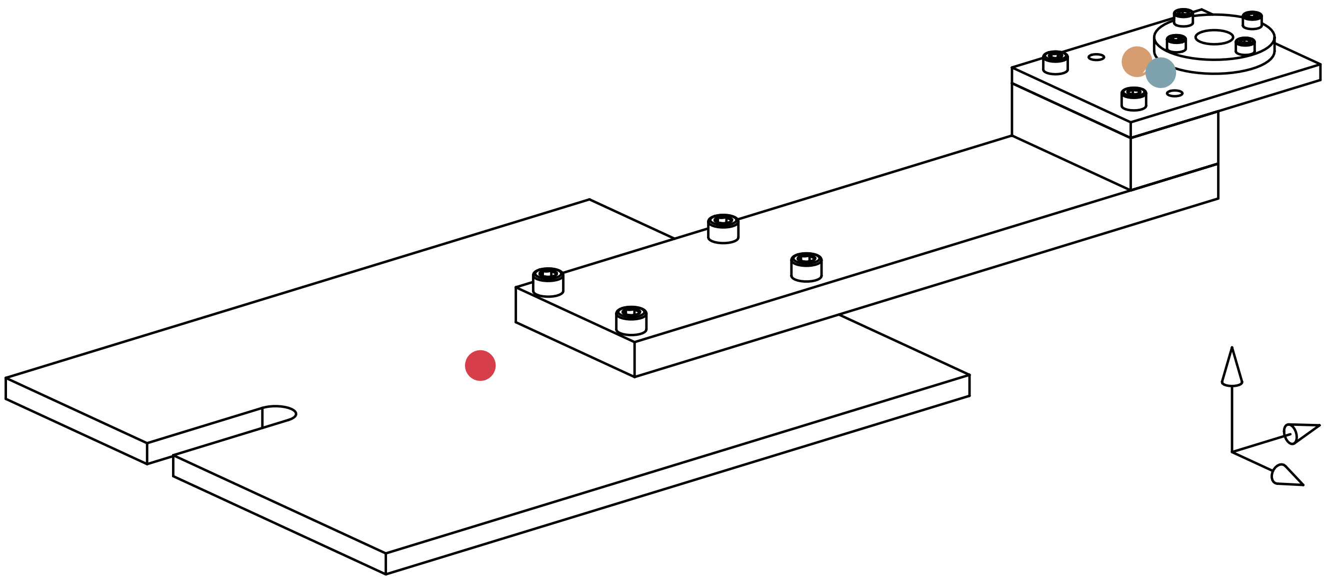


Figure 5.5: *Andromeda*

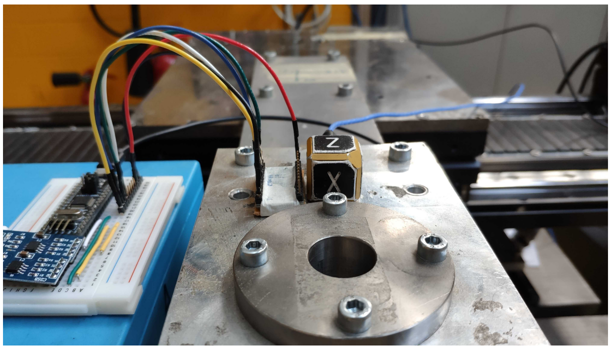


Figure 5.6: *Andromeda*

6

Results and Discussion

In this chapter we summarize the results of this work.

6.1 Hammer-Hammer Test

6.2 Hammer-Surface Test

6.3 Impulse hammer

First section bla bla bla.

7

Conclusion and Future Work

7.1 Conclusion

In this thesis

- A low-cost capacitive accelerometer IC has been used to measure the output signal of an EMA measurement setup
- An impulse hammer using a strain gauge load cell has been developed using low-cost components.
- Different conditioning filter circuits have been studied and tested for the impulse hammer signal
- An Arduino communication protocol has been developed

7.2 Future Work

multichannelling industrialization Printed Circuit Board (PCB) Field Programmable Gate Array (FPGA)

A

Appendix

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List of Figures

List of Tables

Bibliography

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