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
DAC	Data Acquisition
EMA	Experimental Modal Analysis
FPGA	Field Programmable Gate Array
FRF	Frequency Response Function
MEMS	Micro-Electro-Mechanical-Systems
MT	Machine Tools
LC	Load Cell
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].

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[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 summarizes some key aspects of measurement instruments in the frame of this thesis [5].

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]

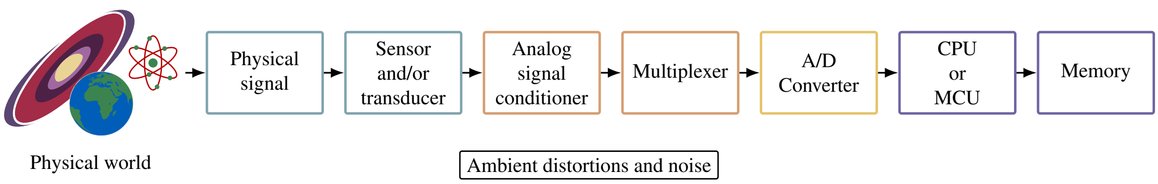


Figure 2.1: *Digital measurement instrument*

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 for 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, capacitative 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 the duration of the signal capture different methods of force measurement are applied.

- 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 interaction of a current-carrying coil and magnetic
- Distributing the force on a specific area to generate pressure 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 capacitative 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

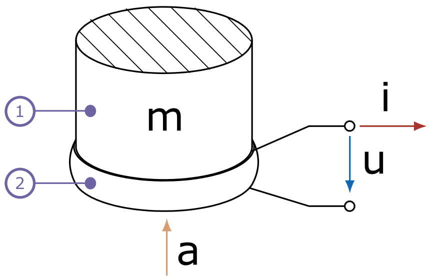


Figure 2.2: Function principle of a piezoelectric accelerometer

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. Namely in LCs and accelerometers, where the piezoelectric charge is converted into a current or voltage signal.

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

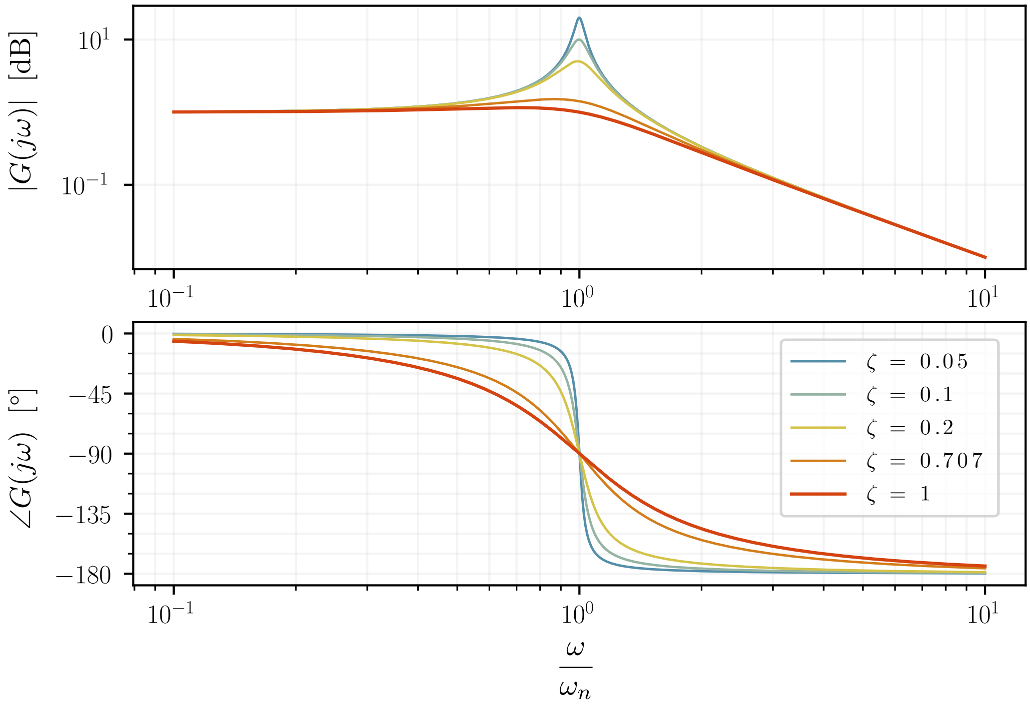
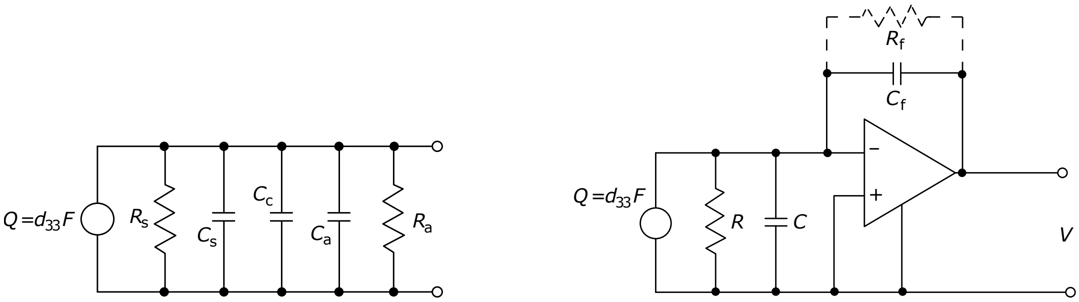


Figure 2.3: *Bode plots of second order system describing the dynamic behavior of seismic accelerometers*

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]*

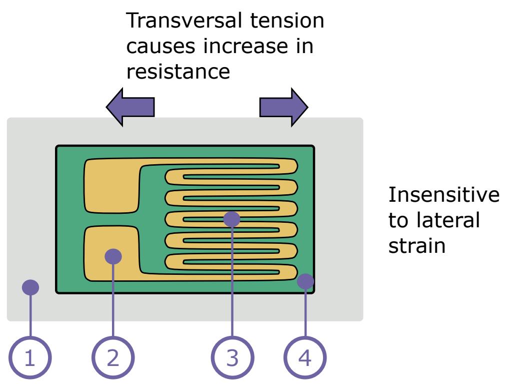
2.1.6 Strain Gauge Load Cells

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

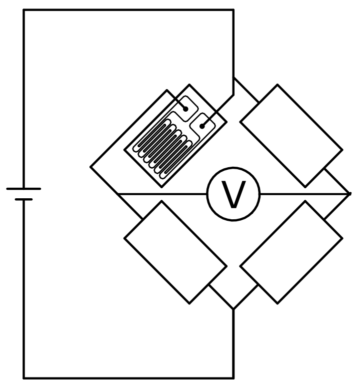
The probe is loaded in a controlled manner in its elastic region. Deformations are captured by a strain gauge at a suitable location. The probe deformation is directly determined by the force acting on the probe because of Hooke's law.

The strain gauges themselves each use a specific length gauge wire in order to reach a resistance of typically $120\,\Omega$. The wire is bonded between two thin sheets in coiled up form as can be seen in Figure 2.5a. 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, 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 increasing the wire's resistance.

In order to measure deformations one needs to take environmental infulences into consideration. It is well known that resistance is subsceptable to variations in temperature.



(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 Capacitative Accelerometers

To understand the working principle of capacitative accelerometers. We first consider the displacement 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 capacitative 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 distance3 of the plates in m
A is the effective area of the plates in m^2

In variable area displacement sensors, the 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 capacitative displacement sensors are setup in capacitative 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.

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

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

$$\tag{2.10}$$

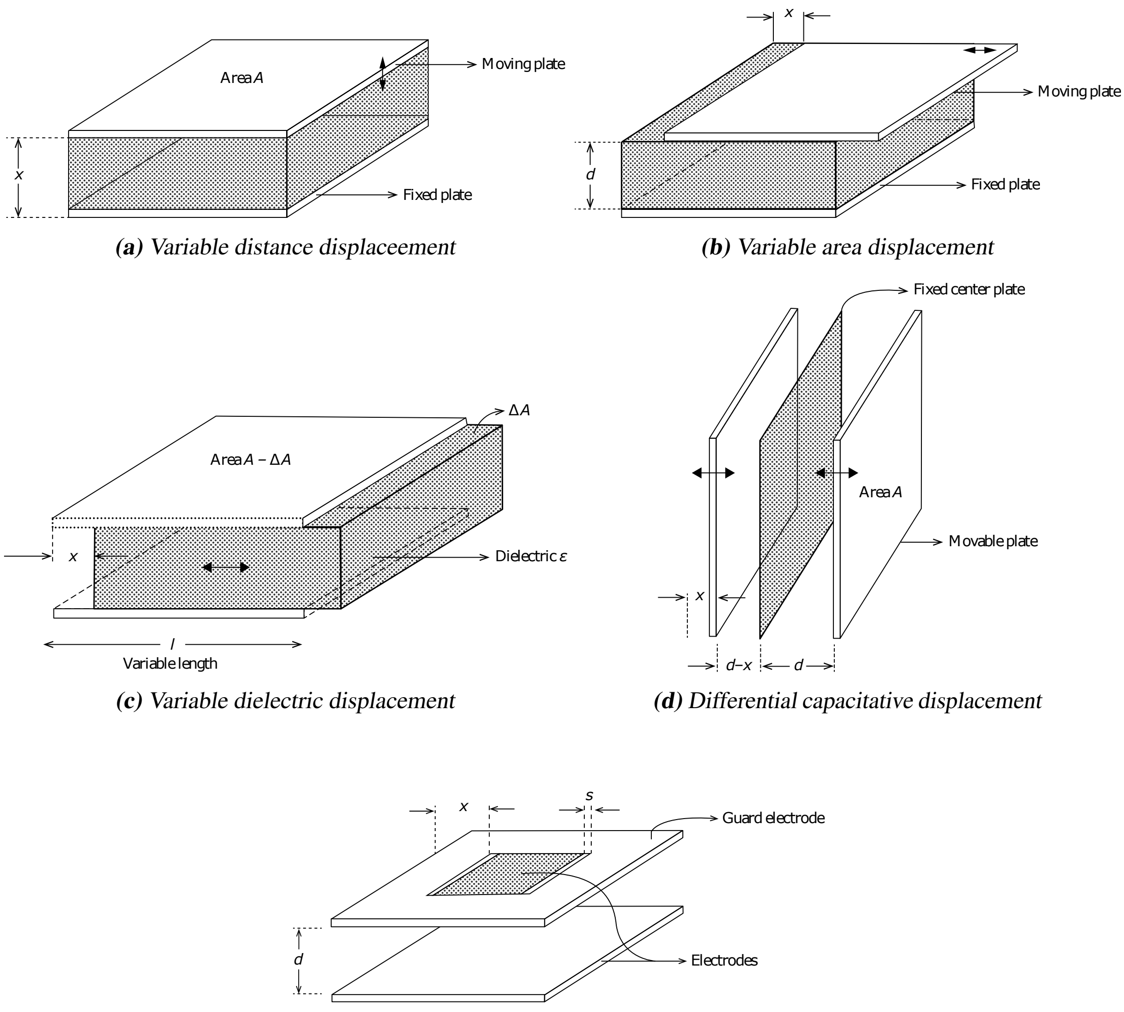
Giving approximately

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

Capacitive Accelerometers

2.2 Experimental Modal Analysis

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



(a) Variable distance displaceement

(b) Variable area displacement

(c) Variable dielectric displacement

(d) Differential capacitative displacement

(e) IC smart capacitative displacement

Figure 2.6: *Capacitative displacement sensors [5]*

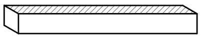
Vibration

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

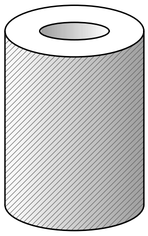
- Internally generated forces
- Unbalances
- External loads
- Ambient excitations

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

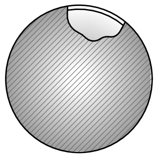
Resonant vibration arises when one or more of the natural modes of vibration, inherent properties of the structure under investigation, is excited. Resonant vibration typically amplifies the vibration response to a level that exceeds deflection, stress and strain caused by static loading.



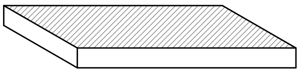
(a) *Vertical stress, longitudinal particle displacement*



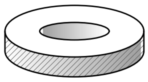
(d) *Lateral stress, lateral particle displacement*



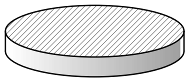
(g) *Vertical stress, radial particle displacement*



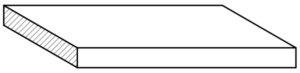
(b) *Vertical stress, lateral particle displacement*



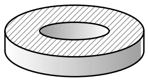
(e) *Radial particle displacement*



(h) *Radial particle displacement*

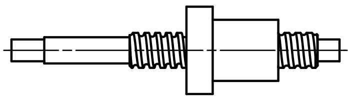


(c) *Vertical stress, lateral particle displacement*

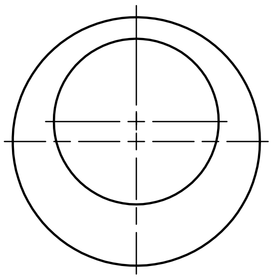


(f) *Radial particle displacement*

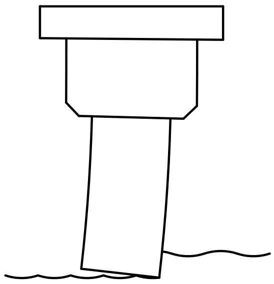
(i) *Radial particle displacement*



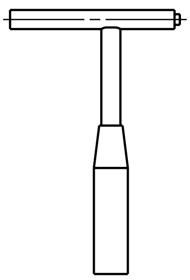
(a) *Axis Motion*



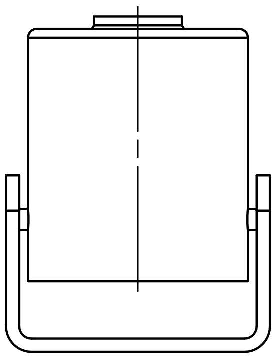
(b) *Imbalance*



(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.*

Modes

Modes ore 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).
- 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]

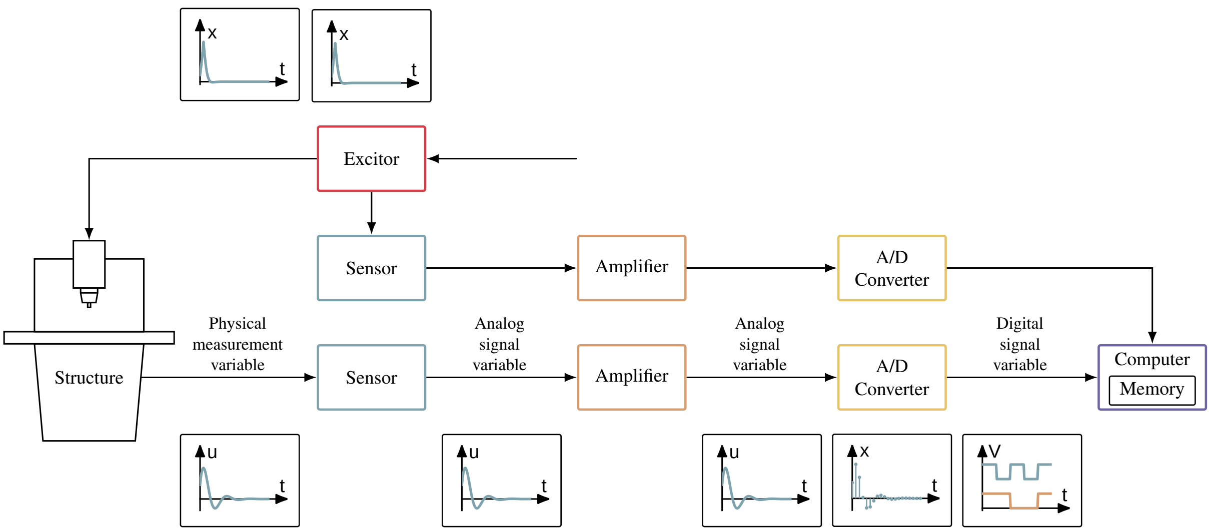


Figure 2.9: *FRF measurement setup*

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.

cite elect books

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 other electronic components. Ideally no loss or noise is introduced in wires but inductances occur due to the conductors 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

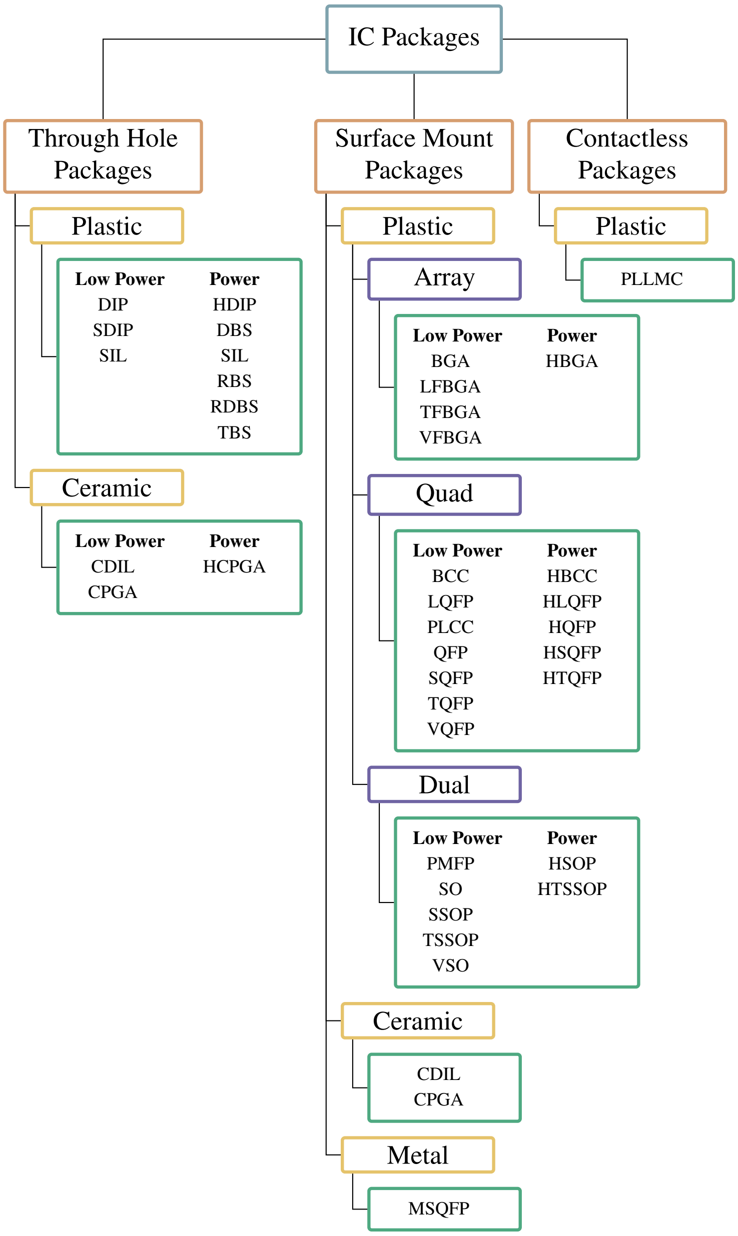


Figure 2.10: *Flowchart of IC packages*

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

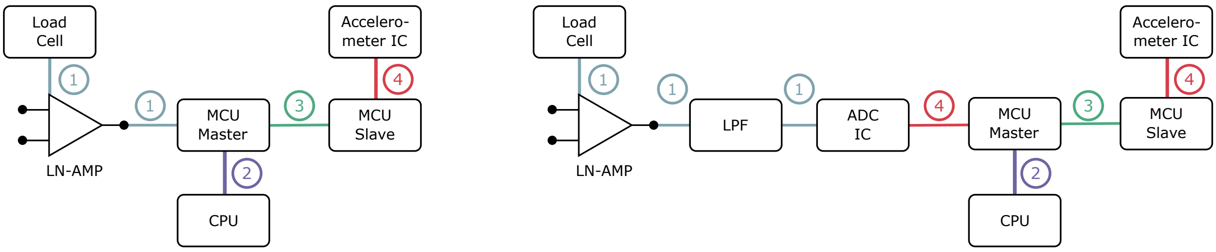
3.1.3 Filtering

4

Data Acquisition and Software

4.1 Data acquistion

The data acquisition 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 it to a computer that serves as visualization and analysis tool.



(a) Without signal conditioning

(b) With signal conditioning and external ADC

Figure 4.1: *Data Acquisition (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 Dataflow

multiple accelerometers, master requests for data in slave buffer cyclic, changes slave, limits of arduino library,

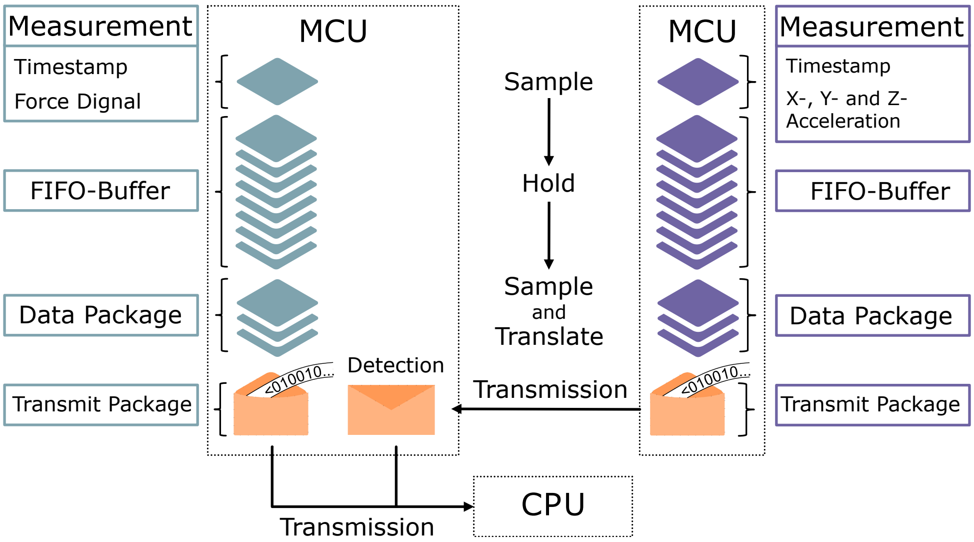


Figure 4.2: *Data flow between two MCU's and the CPU*

4.1.2 Interfaces

Standard interfaces, determined by senor ic MCU com based uart length -> differential transmission using the rs-485 protocol, introduces slave master com, only one slave can speak at a time

4.1.3 Components

mcus arduino due, tinsy, higher resolution stm32

rs-485 converter

adcs

instrumentation amplifiers

MCU communication protocol

The communication protocol between microcontrollers and between microcontroller and computer was developed for this project.

4.2 Software

arduino

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

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

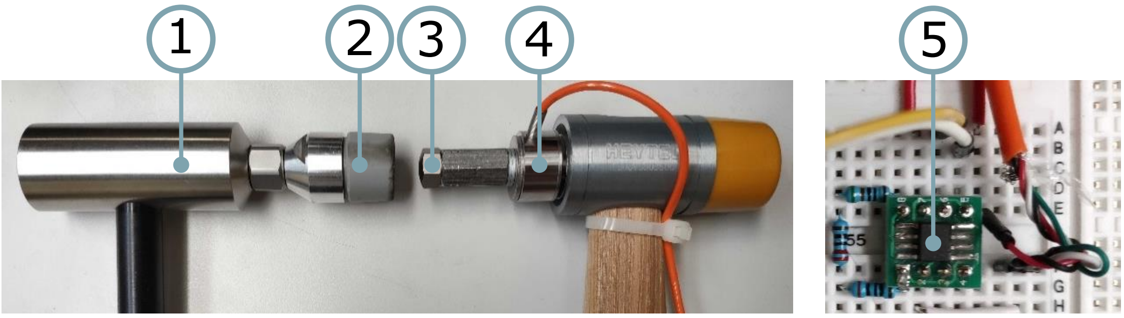
Table 4.2: *Protocol used to communicate between two MCU's and between MCU and computer*

5

Test Setups

5.0.1 Hammer-Hammer Test

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



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

Figure 5.1: *Protocol used to communicate between two MCU's and between MCU and computer*

5.0.2 Andromeda FRF measurement

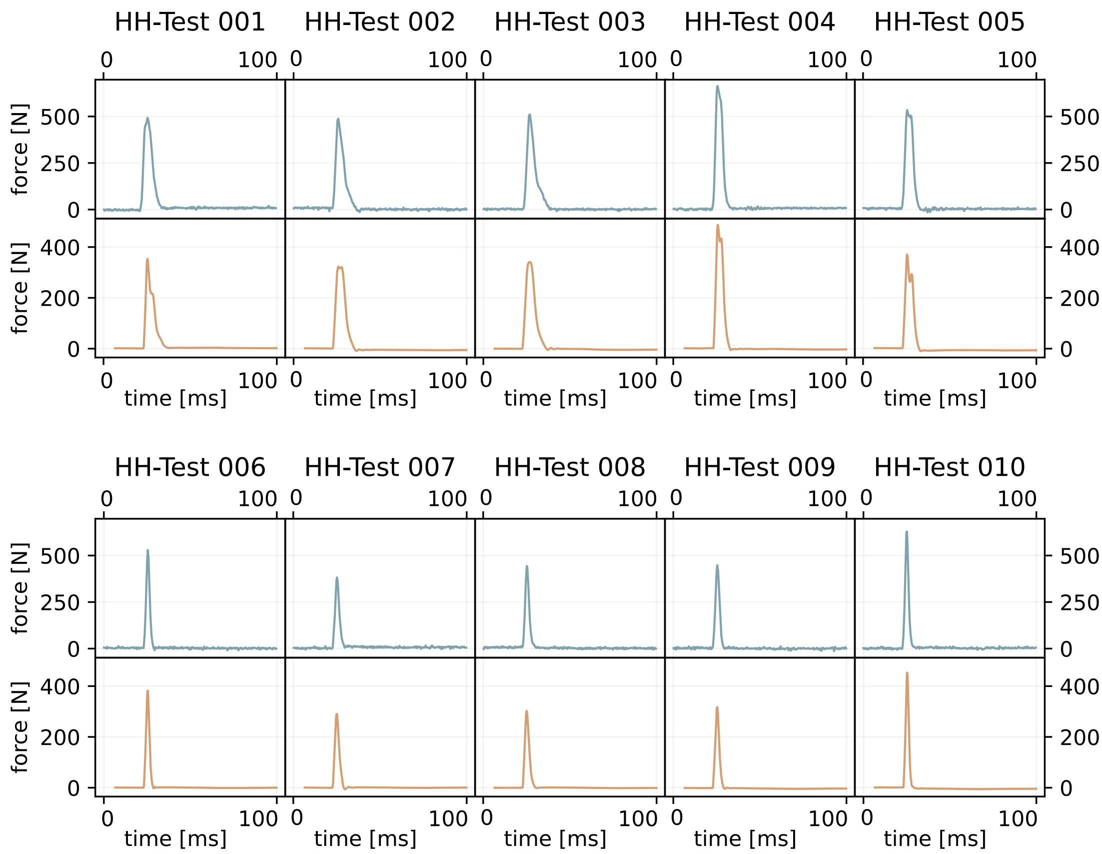


Figure 5.2: *The HH-Test recordings of the reference hammer (orange) and the evaluated impact hammer system (turquoise). Note that the evaluated signal values are normalized so that the maxima are equal to the reference system.*

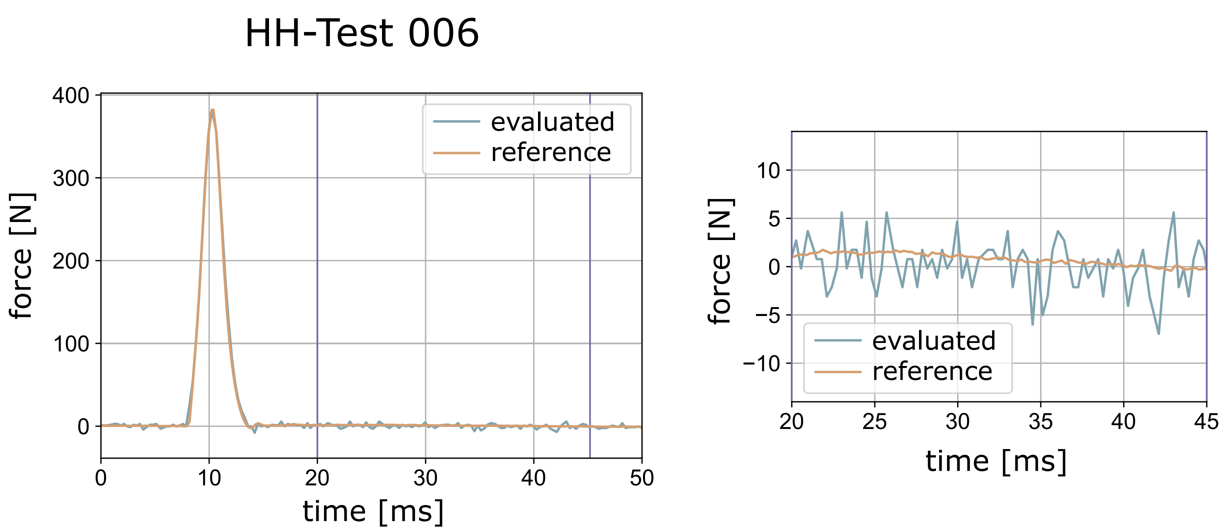


Figure 5.3: *The HH-Test recordings of the reference hammer (orange) and the evaluated impact hammer system (turquoise). Note that the evaluated signal values are normalized so that the maxima are equal to the reference system.*

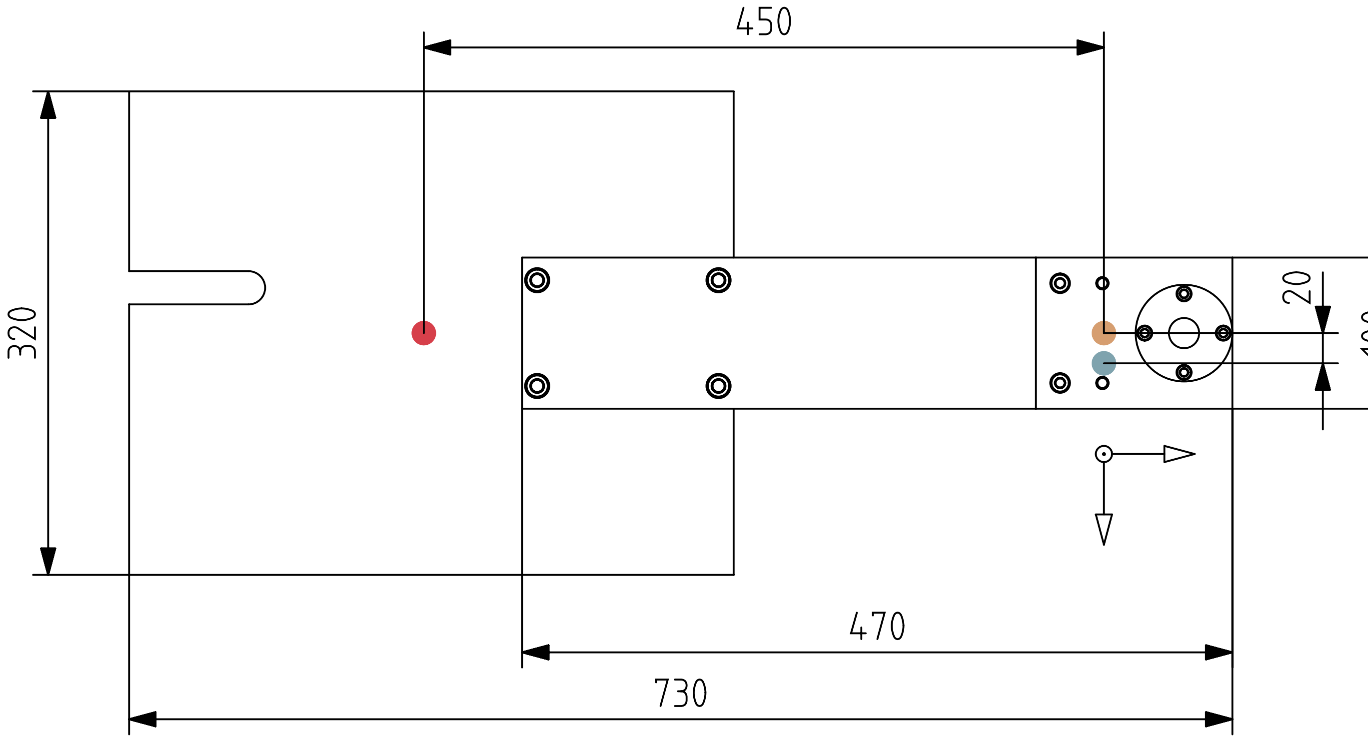


Figure 5.4: *Andromeda*

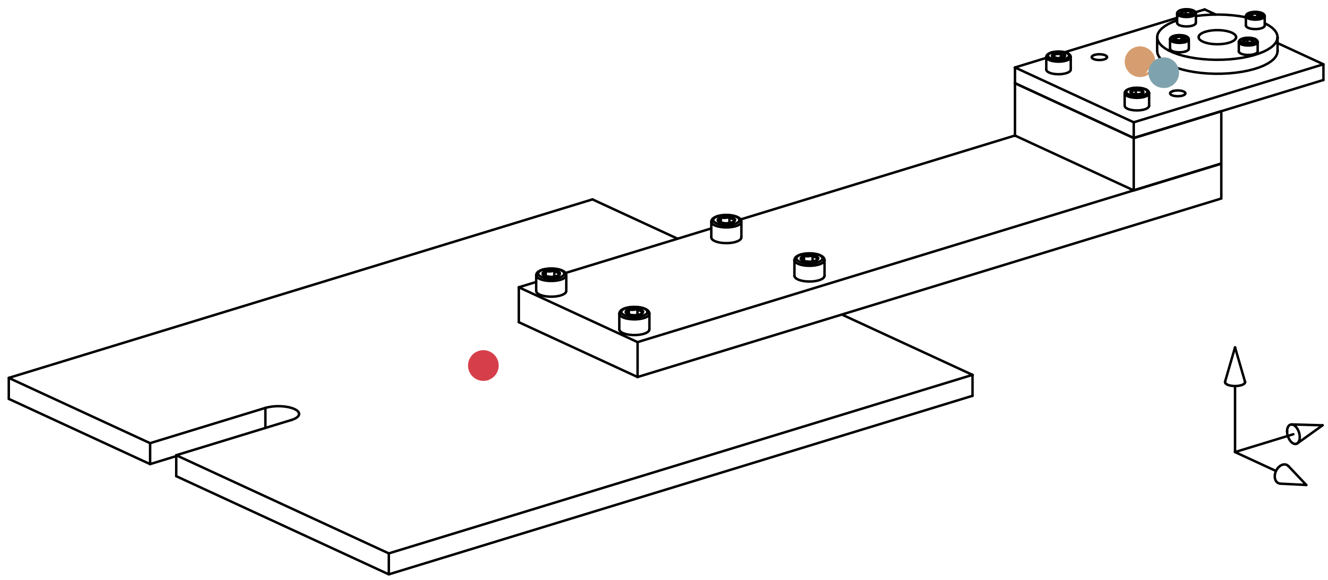


Figure 5.5: *Andromeda*

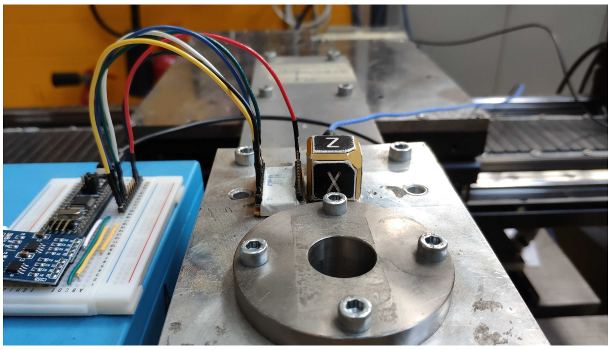


Figure 5.6: *Andromeda*

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 Integrated Circuit (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

List of Figures

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Bibliography

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