

CZECH TECHNICAL UNIVERSITY IN PRAGUE  
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

FACULTY OF ELECTRICAL ENGINEERING  
DEPARTMENT OF MICROELECTRONICS

FAKULTA ELEKTROTECHNICKÁ  
KATEDRA MIKROELEKTRONIKY



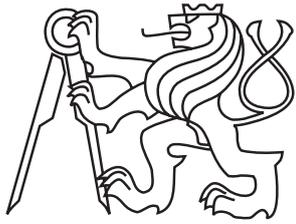
MEASUREMENT OF CHANGING MECHANICAL  
PROPERTIES OF CARBON COMPOSITE ON  
NANOSATELLITE MINICUBE MISSION QB50

MASTER'S THESIS  
DIPLOMOVÁ PRÁCE

2015

Bc. ONDŘEJ NENTVICH





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NANOSATELLITE MINICUBE MISSION QB50

MĚŘENÍ ZMĚN MECHANICKÝCH VLASTNOSTÍ UHLÍKOVÉHO KOMPOZITU NA  
NANOSATELITU MINICUBE MISE QB50

MASTER'S THESIS  
DIPLOMOVÁ PRÁCE

AUTHOR  
AUTOR PRÁCE

Bc. ONDŘEJ NENTVICH

SUPERVISOR  
VEDOUCÍ PRÁCE

Ing. LADISLAV SIEGER, CSc.

Prague

2015



## ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: **Bc. NENTVICH Ondřej**

Studijní program: Komunikace, multimédia a elektronika  
Obor: Elektronika

Název tématu: **Měření změn mechanických vlastností uhlíkového kompozitu na nanosatelitu miniCube mise QB50**

### ***Pokyny pro vypracování:***

- 1) Prostudujte problematiku vyhodnocení útlumu exponenciálně tlumeného signálu vznikajícího kmitáním uhlíkového kompozitu
- 2) Navrhněte algoritmus vyhodnocení útlumu měřeného signálu
- 3) Prostudujte vhodné způsoby excitace uhlíkového kompozitu a snímání jeho kmitů
- 4) Navrhněte systém pro měření změn mechanických vlastností uhlíkového kompozitu v závislosti na změně teploty
- 5) Relizujte vhodné zapojení z 3) a 4) pro Payload nanosatelitu miniCube mise QB50
- 6) Realizujte měření pod systémem RTOS
- 7) Ověřte a zhodnoťte funkčnost systému

### ***Seznam odborné literatury:***

- [1] JAN, J. Číslicová filtrace, analýza a restaurace signálů. 2nd ed. Brno: VUTIUM, 2002. 427 p. ISBN 80-214-2911-9
- [3] TŮMA, J. Zpracování signálů získaných z mechanických systémů užitím FFT. Praha: Sdělovací technika, 2000. 168 p. ISBN 80-901936-1-7
- [3] HANA, P., INNEMAN, A., DANIEL, V., et al. Mechanical properties of Carbon Fiber 3 Composites for applications in space. Proc. SPIE 9442, Optics and Measurement Conference 2014, 2015, , no. 1, DOI: 10.1117/12.2175925

Vedoucí: **Ing. Ladislav Sieger, CSc.**

Platnost zadání: 31. 8. 2016

L.S.

prof. Ing. Miroslav Husák, CSc.  
vedoucí katedry

prof. Ing. Pavel Ripka, CSc.  
děkan

V Praze dne 16. 2. 2015



## Master's Thesis Assignment

Student: **Bc. NENTVICH Ondřej**

Study program: Communication, Multimedia and Electronics  
Focused: Electronics

### Topic:

Measurement of changing mechanical properties of carbon composite on nanosatellite miniCube mission QB50

### Instructions:

- 1) Study the problematic of evaluating the attenuation of exponentially attenuated signal generated by oscillations of carbon composite.
- 2) Implement an algorithm to evaluate the attenuation of the measured signal.
- 3) Study the suitable methods of excitation of the carbon composite and sensing its oscillations.
- 4) Design a system for measurement of mechanical changes of the carbon composite in dependence on the temperature change.
- 5) Implement a suitable wiring from 3) and 4) for the Payload of nanosatellite miniCube mission QB50.
- 6) Implement the measurement under the RTOS system.
- 7) Check and evaluate the functionality of the system.

### References:

- [1] JAN, J. Číslíková filtrace, analýza a restaurace signálů. 2nd ed. Brno: VUTIUM, 2002. 427 p. ISBN 80-214-2911-9
- [2] TŮMA, J. Zpracování signálů získaných z mechanických systémů užitím FFT. Praha: Sdělovací technika, 2000. 168 p. ISBN 80-901936-1-7
- [3] HANA, P., INNEMAN, A., DANIEL, V., et al. Mechanical properties of Carbon Fiber 3 Composites for applications in space. Proc. SPIE 9442, Optics and Measurement Conference 2014, 2015, , no. 1, DOI: 10.1117/12.2175925

Supervisor: **Ing. Ladislav Sieger, CSc.**

Assignment validity: 31. 8. 2016

L.S.

prof. Ing. Miroslav Husák, CSc.  
Head of department

prof. Ing. Pavel Ripka, CSc.  
Dean

In Prague, 16. 2. 2015



## ABSTRACT

This master's thesis talking about measurement of mechanical changes of carbon fibre material. The board is one of the part nanosatellite VZLUsat-1 and one of experiments on board. Microcontroller processing sampling of signal, calculates Fast Fourier Transform and attenuation of signal. All measurements of the probe VZLUsat-1 will be launched during mission QB50.

## KEYWORDS

QB50, CubeSat, Space, FFT, Composite, Carbon, VZLUSAT1, Sampling, Research

## ANOTACE

Tato diplomová práce pojednává o měření mechanických vlastností uhlíkového kompozitu. Měřicí deska je jednou z mnoha dalších na nanosatelitu VZLUsat-1 a jednou z experimentů. Mikrokontrolér zpracovává navzorkovaný signál, spočítá rychlou Fourierovu transformaci a útlum signálu. Veškerá měření na sondě VZLUsat-1 budou vypuštěna během mise QB50.

## KLÍČOVÁ SLOVA

QB50, CubeSat, Vesmír, FFT, Kompozit, Carbon, VZLUSAT1, Vzorkování, Výzkum

NENTVICH, Ondřej. *Measurement of changing mechanical properties of carbon composite on nanosatellite miniCube mission QB50*: master's thesis. Prague: Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Microelectronics, 2015. 75 p. Supervised by Ing. Ladislav Sieger, CSc.



## ACKNOWLEDGEMENT

I would like to express thanks to the mentor *Mr. Ing. Ladislav Sieger, CSc.* for many useful advices, comments and patience during works on nanosatellite, this master's thesis and also to my colleagues who support me.

Also I would like to express huge gratitude to *Mr. Kazuo Yana, Ph.D.* from Hosei University in Tokyo, Japan, who provided me experiences about signal processing during summer internship in 2014.

## DECLARATION

I declare that I have written my master's thesis on the theme of "Measurement of changing mechanical properties of carbon composite on nanosatellite miniCube mission QB50" independently, under the guidance of the master's thesis supervisor and using the technical literature and other sources of information which are all quoted in the thesis and detailed in the list of literature at the end of the thesis.

As the author of the master's thesis I furthermore declare that, as regards the creation of this master's thesis, I have not infringed any copyright. In particular, I have not unlawfully encroached on anyone's personal and/or ownership rights and I am fully aware of the consequences in the case of breaking Regulation § 11 and the following of the Copyright Act No 121/2000 Sb., and of the rights related to intellectual property right and changes in some Acts (Intellectual Property Act) and formulated in later regulations, inclusive of the possible consequences resulting from the provisions of Criminal Act No 40/2009 Sb., Section 2, Head VI, Part 4.

In Prague,

July 30, 2015

.....  
author's signature



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# List of Acronyms

**ACK**

Acknowledge

**ADC**

Analog to Digital Converter

**CMOS**

Complementary

Metal-Oxide-Semiconductor

**CSP**

CubeSat Space Protocol

**CubeSat**

Small standard nanosatellite  
of dimensions 10x10x10 cm  
per unit

**DFT**

Discrete Fourier Transform

**DiF**

Decimation in frequency

**DiT**

Decimation in time

**DK**

Data Keeper

**DSP**

Digital Signal Processing

**EEPROM**

Type of non-volatiles memory

**EPS**

Electrical Power System

**etc.**

etcetera

**FEM**

Finite element method

**FFT**

Fast Fourier Transform

**FIPEX**

Flux- $\Phi$ -Probe Experiment

**FIR**

Finite impulse response

**Flash**

Type of non-volatiles memory

**FRAM**

Type of non-volatiles memory

**FreeRTOS**

Free Real Time Operating  
System

**FW**

Firmware

**HK**

House keeping

**HM**

Health Monitoring

**HW**

Hardware

**I/O**

Input/Output

**I<sup>2</sup>C**

Inter-Integrated Circuit

**INMS**

Ion-Neutral Mass  
Spectrometer

**LCD**

Liquid crystal display

**LED**

Light emitting diode

**LHC**

Large Hadron Collider

**m-NLP**

multi-Needle Langmuir Probe

**MCU**

Microcontroller

**MOSFET**

Metal Oxide Semiconductor  
Field Effect Transistor

**NACK**

No Acknowledge

**OBC**

On Board Computer

**PC**

Personal computer

**ppm**

points per million

**QB50**

Missions of nanosatellites  
CubeSats

**RAM**

Type of volatiles memory

**SCL**

Serial clock

**SD**

Secure digital

**SDA**

Serial data

**SPI**

Serial Peripheral Interface

**SRAM**

Type of volatiles memory

**USART**

Universal synchronous and  
asynchronous serial receiver  
and transmitter

**vs.**

versus

**VZLUsat-1**

Marking of nanosatellite from  
institution VZLÚ

**VZLÚ**

Výzkumný a zkušební letecký  
ústav, a.s. – Aerospace  
Research and Test  
Establishment



## List of Symbols

$A$	Cross sectional area ( $\text{m}^2$ )	$\omega_n$	Angular frequencies of natural oscillations ( $\text{rad} \cdot \text{s}^{-1}$ )
$E$	Elastic Modulus (Pa)	$\rho$	Material Density ( $\text{kg} \cdot \text{m}^{-3}$ )
$F_d$	Damping force (N)	$b$	Cantilever width (m)
$F_i$	Inertial force (N)	$c_0$	Velocity of longitudinal waves ( $\text{m} \cdot \text{s}^{-1}$ )
$F_r$	Reverse force (N)	$f_{\text{dec}}$	Decimated frequency (Hz)
$J$	Quadratic torque-section ( $\text{m}^4$ )	$f_{\text{max}}$	Maximal frequency (Hz)
$N$	Number points of signal (-)	$f_s$	Sampling frequency (Hz)
$N$	Number of point least square method (-)	$h$	Cantilever height (m)
$\beta_n$	Own root of frequency equation	$j$	Quadratic sectional radius (m)
$\delta$	Attenuation of system ( $\text{s}^{-1}$ )	$k$	Number points of moving averages (-)
$\lambda$	Wavelength (m)	$k$	Directive of line (-)
$\omega$	Angular frequency ( $\text{rad} \cdot \text{s}^{-1}$ )	$k$	Spring constant ( $\text{N} \cdot \text{m}^{-1}$ )
$\omega_0$	Angular frequency of natural oscillations ( $\text{rad} \cdot \text{s}^{-1}$ )	$l$	Cantilever length (m)
		$m$	Mass (kg)

$q$	Offset of line (dB)
$v$	Velocity of propagation ( $\text{m} \cdot \text{s}^{-1}$ )
$x$	Point of signal (mV)
$x$	Deviation (m)
$x_i$	Time point in least square method (s)
$y_i$	Amplitude point in least square method (dB)



# 1 Introduction

This master's thesis is generally talking about mission QB50, small nanosatellites called CubeSat. Main part of the thesis is measuring mechanical changes of carbon fibre material in time. It seems to be quite easy task, but there are many aspects which could happened and all dangerous states that must be prevented. So here is a reason to test all climatic conditions, mainly in vacuum and operation temperatures on orbit.

The probe also has many other measurements such as X-Ray measurement of the Sun called Medipix, evaporation measurement, verifying quality of the carbon fibre shielding and some other measurements. For example issue of evaporation is detailed and described in the thesis *Measurement of evaporation and evaluation of changes of the mechanical properties of carbon composite on nanosatellite miniCube mission QB50* [1] of my colleague Bc. Martin Urban. Or the issue with radiation shielding has in charge my other colleague Bc. Veronika Stehlíková and it is more detailed in her thesis *Radiation resistance measurement on nanosatellite miniCube mission QB50* [2].

Tested carbon fibre material could be used on a new satellites in future and it should replace old and heavy tungsten shielding. It would lead to decrease in weight of the whole satellite and launch cost.

The device for measuring mechanical changes in time consists of excitation coil which attracts cantilever with glued permalloy circle. It causes vibrations of the beam and produce mechanically damped oscillations which are measured by piezo-electric element. Piezo transforms mechanical oscillations into electrical. Then Microcontroller samples them and evaluate them. Process of evaluation consists of calculation of Fast Fourier Transform (FFT) and attenuation of the signal. Results of the measurement are frequencies, one is mechanical resonance of the beam, the other frequencies are resonances of whole satellite and the last measured parameter is attenuation of beam for additionally specifying of the model using Finite element method (FEM).

Measurement board runs under Free Real Time Operating System (FreeRTOS) and communicates with the probe through CubeSat Space Protocol (CSP) via Inter-Integrated Circuit (I<sup>2</sup>C) interface.



## 2 Mission QB50

Main idea of the mission QB50 is that anybody could build their own probe especially Universities with quite low-cost start and required equipment. Basic cost for Hardware (HW) is in range 50-100 thousands Euro. Name QB50 is derived from number of CubeSats.

Generally 50 CubeSats are carried out on orbit. These probes are from whole the world. One of them is Czech nanosatellite VZLUsat-1 which is the first probe that will be launched during mission QB50.

Each satellite is normalized to units which must be observed. Basic idea of the mission QB50 is discovering the least explored lower thermosphere – measuring or research in these altitudes about 200-380 km.

Launch is scheduled on February 1, 2016 from Alcantara launch site in Brazil by rocket Cyclone-4 [3].

### 2.1 One CubeSat unit

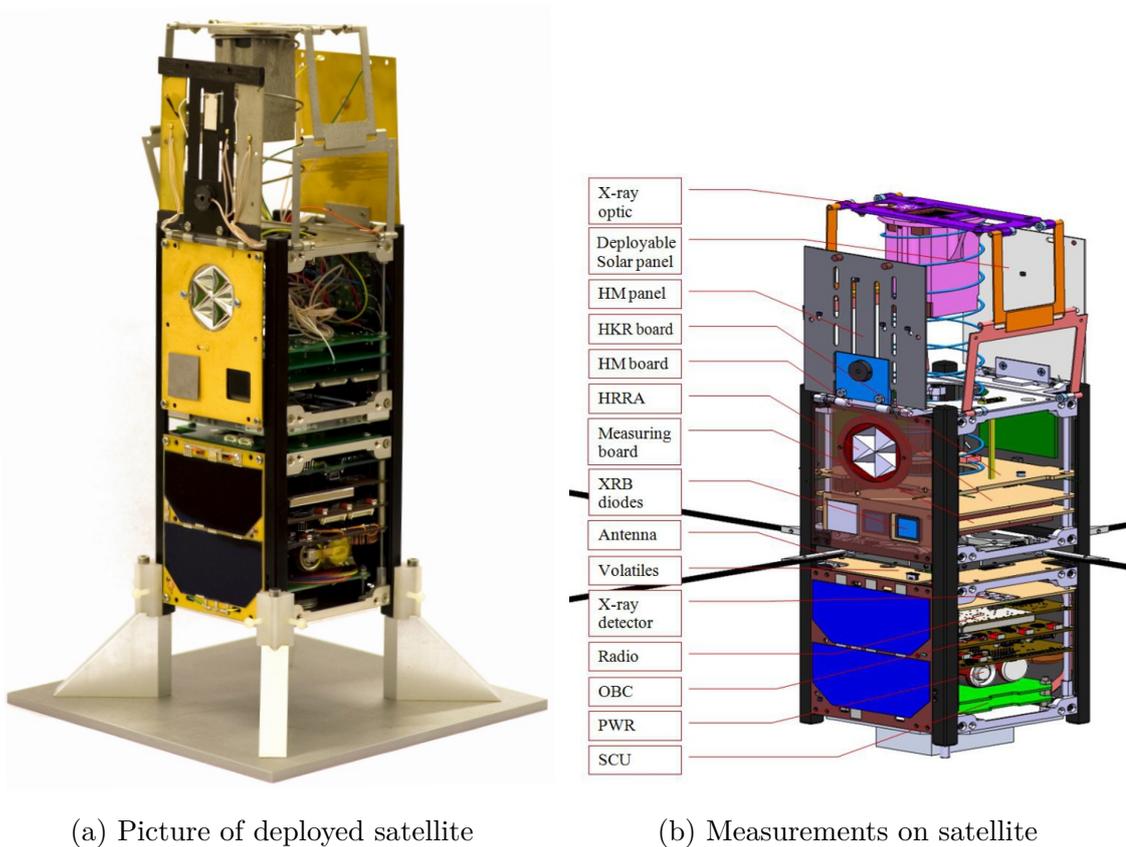
One unit of the probe has these parameters [3]:

- **Dimensions**  $10 \times 10 \times 10$  cm per unit
- **Weight** up to 1 kg per unit
- **Units** up to 3 units in row ( $30 \times 10 \times 10$  cm), during this mission

Advantages of CubeSats are that existing standardised HW boards like On Board Computer (OBC), Electrical Power System (EPS) board, solar panels, radio board, etc. are qualified for these missions and use in space environment. It is only necessary to implement communication with other boards [4].



### 3 CubeSat VZLUsat-1



**Fig. 3.1:** Nanosatellite VZLUsat-1

One of the Czech nanosatellites is VZLUsat-1 shown in Fig. 3.1a. Výzkumný a zkušební letecký ústav, a.s. – Aerospace Research and Test Establishment (VZLÚ) is supervisor and main coordinator of project and it has whole team participating on the probe. The team involves some universities and companies such as *Czech Technical University in Prague, University of West Bohemia, Rigaku Innovative Technologies Europe, TTS, 5M, IST, ...*

Probe VZLUsat-1 consists of many experiments as is shown in Fig. 3.1b. One of them is X-Ray camera called Medipix with Lobster Eye (X-Ray) optics with focal length approx. 20 cm. It takes pictures of the Sun and measures X-ray intensity in range 5-20 keV. The important thing is measuring of temperature. Satellite

have many PT1000 temperature sensors connected to the one common board called *Measure Board*. Another measurement is HM system which consists of measuring mechanical changes in time, radiation shielding and evaporation from the carbon fibre on the probe. The goal is to verify properties of carbon fibre material in space.

Dimensions of the probe in packed state are  $20 \times 10 \times 10$  cm and when VZLUsat-1 will be dropped out from launcher with other satellites then it deploys solar panels, Lobster Eye optics and HM panel. Dimensions will change to approx.  $30 \times 10 \times 10$  cm. Unpacked state is in the picture Fig. 3.1a.

## 3.1 Parts of Probe

Each member of the team is responsible for specific part of scientific experiment on board. The most important parts are on the followings pages. Almost all boards are connected through main 80 pins connector which contains power, reserved data signals and also user defined pins which could be used for any purpose.

### 3.1.1 X-Ray Optics and Medipix

Probe VZLUsat-1 has X-Ray optics with focal length approx. 20 cm and should be looking into the Sun. This state will happened twice a year because of static orientation of probe. For detection of the right orientation there are three sensors, two in UV spectrum and one in IR spectrum. Main reason why probe has two UV diodes is that one is sensitive in maximum radius approx.  $80^\circ$ , second one has radius reduced to approx.  $15^\circ$  by a small tube. The first one is looking for sources of UV radiation, mainly from the Sun in wide angle and the second one has narrower angle for more precise determination of Sun position. When both sensors have strong enough UV signal then Medipix will start up, which then take a picture of the Sun.

Medipix is CMOS silicon detector originally developed as low energy (1 – 20 keV) X-Ray detector for Large Hadron Collider (LHC) in *CERN*. Board with this chip assembled on the probe was used as medical equipment for scanning soft tissues with high resolution. For this mission Medipix/Timepix is used for detection X-Rays from the Sun [5].

### ■ 3.1.2 Radio

Radio is one of the most important boards on every satellite. It provides communication between Earth and downloading results or uploading configurations. Transmission frequency is in radio-amateur free band at 436 MHz with communication speed 9 600 Baud.

University of West Bohemia is responsible for communication with the sat. They will download data and upload configurations to the probe. And also process some data from it. Communication board which will be launched, is already tested with antenna and radio board and works fine on the ground in 10 km distance [6].

### ■ 3.1.3 Scientific Unit

Every nanosatellite should have one of three scientific units:

**Tab. 3.1:** Scientific units [3]

Type	Description
<i>INMS</i>	Ion-Neutral Mass Spectrometer
<i>FIPEX</i>	Flux- $\Phi$ -Probe Experiment
<i>m-NLP</i>	multi-Needle Langmuir Probe

All scientific units are equipped with a thermometer such as Thermistor, Thermocouple, ...

VZLUsat-1 has FIPEX as scientific unit. The unit measures behaviour of atmospheric oxygen at lower thermosphere. It is important for exploring erosion on surfaces of spaceships during contact of atomic oxygen with surface of probes [3, 7].

### ■ 3.1.4 Volatiles Board

Volatiles board is assembled with humidity sensors which are looking for residual humidity or evaporation from the whole probe, mainly from carbon-fibre materials. It has three types of sensors, two from *IST* company labeled HYT271 and HYT939, both in two of each. Third type is HAL2 in three pieces from *TTS* company. It is not only sensitive to humidity, but a little to other gases. All sensors are connected to the board with a driver called PicoCap which is converting capacitance into ratio compared to the reference capacitance. All HYT sensors and PicoCap communicate

via I<sup>2</sup>C bus connected directly to the OBC. Everything about humidity sensors and measuring evaporation is described in detail in thesis of my colleague Martin Urban in [1].

### ■ 3.1.5 Radiation Shielding Measurement

The goal of this experiment is to verify quality of radiation shielding of Carbon-fibre composite using three same XRB diodes. One is looking into the space, second is covered by this material and third is shielded by composite and by tungsten sheet.

Evaluation of shielding quality is comparing all three diodes together. First serves reference for maximal intensity of radiation, middle diode real intensity of radiation and third is measuring background. This issue is described in more detail in thesis of my colleague Veronika Stehlíková in [2].

### ■ 3.1.6 HM System

Health Monitoring system contains two parts. One is mechanical part with beam made of carbon-fibre composite and six thermometers PT1000. Thermometers measure heat transmission from one surface to another and how good reflectivity of thermal radiation surface layers of Nickel or Gold is. Also HM panel measures aging of carbon-fibre material using excitation of beam and measure its oscillations by piezo. Whole signal is sampled by ADC in MCU. Microcontroller is on the HM board which is the second part of Health Monitoring system. Evaluation of signal is done by FFT and results are resonant frequencies of beam and of the probe. This issue is described in more detail on followings pages of this thesis.

### ■ 3.1.7 On Board Computer

On Board Computer is synonymous for heart of probe. Board is in charge of many functions, but primary is operating other boards, their requirements and reply to them. Besides that, it communicates with ground segment and organizing further actions on the deck.

### ■ 3.1.8 Electronic Power System

Power system consists of solar panels which generate electric energy and power board which transforms and stabilizes voltage at defined value (5 V or 3.3 V). Board has two backup lithium batteries when probe is in solar shade. This board is autonomous and when power goes under critical value, it cuts off all systems included OBC and then it waits for power.

### ■ 3.1.9 Stabilising system

It is necessary to stabilize probe to its defined state. Small nanosatellites does not have rockets for stabilization, but it has six coils – two in each dimension. Coils are excited by electric pulses and create the force necessary to stabilize the probe according to magnetic field of Earth.

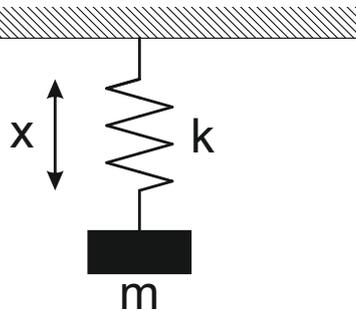


## 4 Mechanical Changes Measurement

Main part of this thesis is about measuring mechanical changes. Here, on a few pages in this chapter, is described theory about measurement of mechanical changes – equations how to compute natural frequencies in the elementary case as a string, or for the real model of a cantilever with one fixed side. It is also described how to get the natural frequencies from sampled signal – by using FFT. It is supposed that the cantilever produces damped oscillations with exponential envelope and signal is then analysed by linear regression. All these processes are discussed on the following pages.

### 4.1 Damped Oscillations

Damped oscillator is in the illustration Fig. 4.1 with spring which is represented by Spring constant ( $k$ ), weight at the end by Mass ( $m$ ) and deviation by  $x$ .



**Fig. 4.1:** Picture of elementary damped oscillator

These oscillations could be described using following equation (4.1).

$$F_f + F_d + F_r = 0 \quad (4.1)$$

where

$$F_f = m \frac{d^2x}{dt^2} \quad (4.2)$$

$$F_d = b \frac{dx}{dt} \quad (4.3)$$

$$F_r = kx \quad (4.4)$$

and meaning Inertial force ( $F_i$ ), Damping force ( $F_d$ ), Reverse force ( $F_r$ ).

When equations (4.2 – 4.4) are put into (4.1), it gets differential equation of second order (4.5).

$$m \frac{d^2x}{dt^2} + b \frac{dx}{dt} + kx = 0 \quad (4.5)$$

Solving it, gets equation for damped oscillations

$$x(t) = x_0 e^{-\delta t} \sin \left( t \sqrt{\omega_0^2 - \delta^2} \right) \quad (4.6)$$

If it is known that  $\omega = \sqrt{\omega_0^2 - \delta^2}$ , formula (4.6) could be rewritten into the form for damped sine oscillations (4.7).

$$x(t) = x_0 e^{-\delta t} \sin(\omega t) \quad (4.7)$$

where  $\delta$  is Attenuation of system,  $\omega$  is Angular frequency and  $x$  is Deviation.

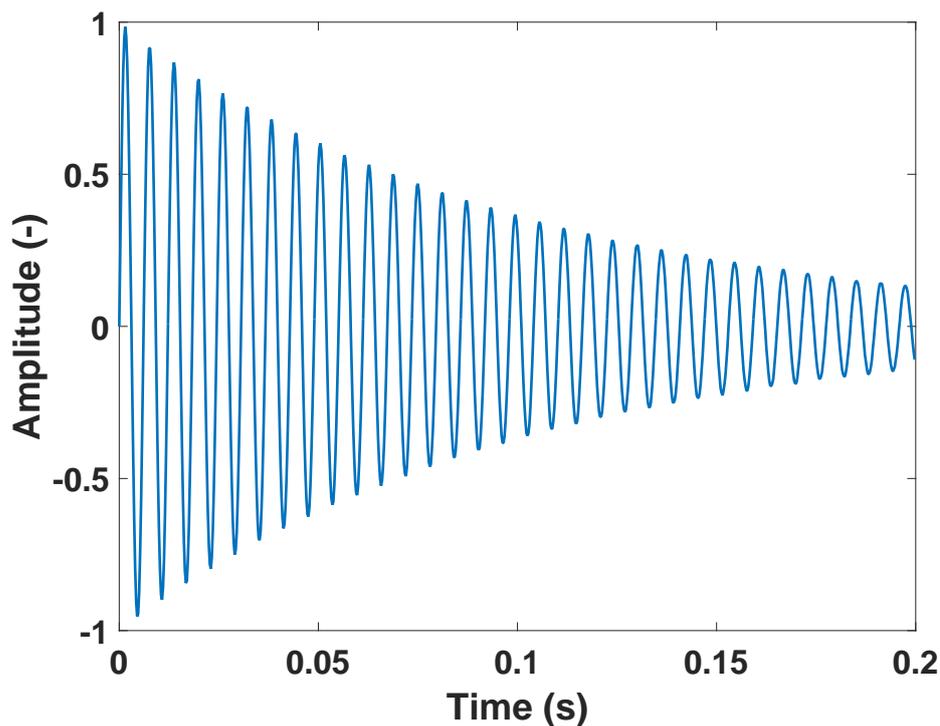


Fig. 4.2: Simulated damped signal

## 4.2 Elementary Oscillator

Elementary oscillator could be described on simplified example as a string. In this case the following equation (4.8) for examination Young's modulus of elasticity is applied.

$$v = \sqrt{\frac{E}{\rho}} \quad (4.8)$$

where Velocity of propagation ( $v$ ) is defined as  $v = \lambda f$ ,  $\lambda$  is Wavelength,  $E$  is Elastic Modulus,  $\rho$  is Material Density.

In this case it is possible to determine that  $\lambda = 4L$ , where  $L$  is part of string length illustrated in Fig. 4.3.

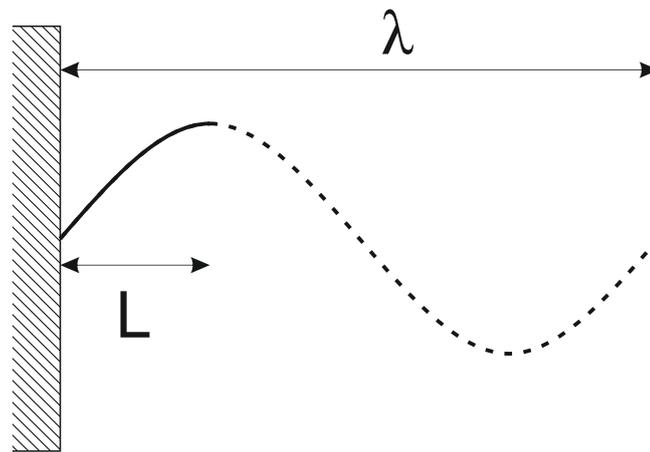


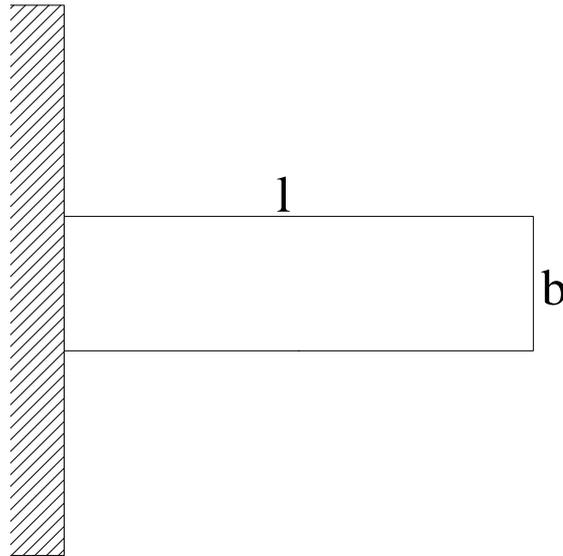
Fig. 4.3: Length of string  $L$  vs. wavelength  $\lambda$

## 4.3 Cantilever Oscillations

For our purpose to approximate to the real situation which is in the simplest case cantilever with one fixed side and one freely hanged, as is in the picture Fig. 4.4.

Natural frequencies of cantilever are described by a few equations. In the first step it is needed to find own roots of frequency equation of the cantilever (4.9).

$$\cosh(\beta_n l) \cdot \cos(\beta_n l) + 1 = 0 \quad (4.9)$$



**Fig. 4.4:** Picture of the Cantilever

This equation can be solved only by numeric method and its four first roots are:

$$\begin{aligned}\beta_1 l &= 1.875 & \beta_2 l &= 4.694 \\ \beta_3 l &= 7.855 & \beta_4 l &= 10.996\end{aligned}$$

where  $\beta_n$  is Own root of frequency equation,  $l$  is Cantilever length [8].

Natural frequencies are computed using following equation (4.10). For this formula it is required to know computed roots and some other parameters, all necessities are in Tab. 4.1 and put into equation (4.11).

$$\Omega_n = \frac{(\beta_n l)^2}{l^2} c_0 j \quad (4.10)$$

$$\Omega_n = \frac{(\beta_n l)^2}{l^2} \sqrt{\frac{E}{\rho}} \sqrt{\frac{J}{A}} = \quad (4.11)$$

$$= \frac{(\beta_n l)^2}{l^2} \sqrt{\frac{E}{\rho}} \sqrt{\frac{h^2}{12}} \quad (4.12)$$

where  $j$  is Quadratic sectional radius,  $c_0$  is Velocity of longitudinal waves,  $J$  is Quadratic torque-section and  $A$  is Cross sectional area.

Conversion between angular speed and frequency is in following equation (4.13).

$$f = \frac{\Omega_n}{2\pi} \quad (4.13)$$

**Tab. 4.1:** Cantilever Parameters

Symbol	Description
$l$	Cantilever length
$b$	Cantilever width
$h$	Cantilever height
$E$	Elastic Modulus
$\rho$	Material Density

Investigated parameter is Young's modulus of elasticity  $E$  and it is verified using formula (4.11). From this point of view, it is a prerequisite that the other parameters do not change according to Tab. 4.1.

Properties of cantilever could be also simulated using FEM. This issue was simulated by Petr Hána from Technical University of Liberec using FEM and results of this method were almost the same as using equation (4.11) [8–10].

For verifying natural frequencies, it is needed to get oscillations from the beam. Signal measurement could be performed by two methods. One is by accelerometer and another one is by piezoelectric plate.

## 4.4 Measuring by Accelerometer

Accelerometers are usually small and lightweight, about a few grams. One disadvantage is that they must be placed into position with the highest variation of signal – for the highest acceleration. That location is at the end of the cantilever. It is not recommended for this purpose because the weight of the plate is about a few grams and accelerometer with wires would cause bigger attenuation and frequency change. Results of measured cantilever would be changed – there would be a big deviation from theoretical results [10].

## 4.5 Measuring by Piezo

Another method how to measure oscillations is by piezoelectric plate. Here are some requirements for placing it for higher sensitivity and it is the place with the mechanical stress of the measured material and that position is at a fixed end of

cantilever. When piezo is stressed, it produces electrical voltage which is measured, it corresponds to mechanical oscillations in this case [10].

## 4.6 How to Excite the Cantilever

Here is another issue and it is how to excite the cantilever. One of the possibilities is to tap it by finger, but it is not suitable for autonomous measurement or in space. There are some other possibilities and one of them is to mechanically tighten the cantilever and then let it go. This situation is not reliable from my point of view. There should be a precise mechanism.

There is another method and it is electrical excitation of beam. At the opposite side of the cantilever is a fixed coil which attracts the beam by electric pulse to the coil. The question is how to attract it. One possibility is a glued permanent magnet. Permanent magnet has some problems. It is quite heavy and it will affect the measurement. So there is a material called permalloy which is a material with high permeability. It is able to conduct magnetic flux and pull itself closer to the coil – minimize energy state.

Permalloy is the most suitable for this experiment if it is as small as possible to not affect the measurement and frequency spectrum of the cantilever. It reckons with small deviation in frequency caused by permalloy.

## 4.7 HM Panel

When all these necessities are put together, it leads to creating a sample of a panel with the cantilever. The panel is called HM panel. Final version is in the picture Fig. 4.5. In the drawing position of the coil is shown and there is a permalloy under it. Dimensions of the cantilever are  $13\text{ mm} \times 67\text{ mm} \times 1\text{ mm}$ .

Additional parameters of carbon-fibre composite are Young's modulus which is  $E = 34\text{ GPa}$  and material density  $\rho = 1700\text{ kg} \cdot \text{m}^{-3}$ .

## 4.8 Measured Parameters

One of the most important parameters of the material is Young's modulus. Additional parameter is an attenuation of oscillations during measurement.

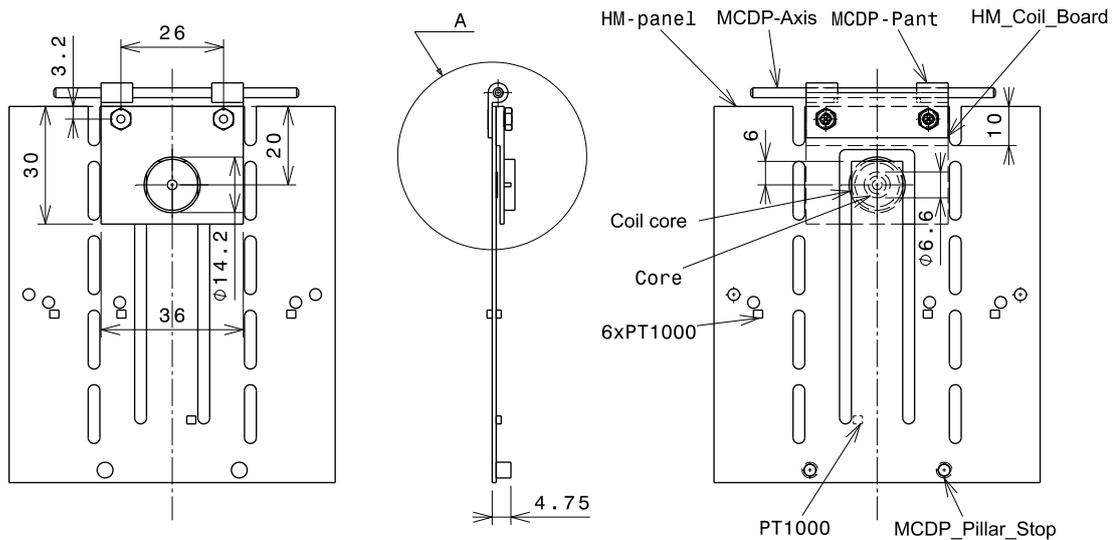


Fig. 4.5: Drawings of HM panel

### ■ 4.8.1 Young's Modulus of Elasticity

Young's modulus is synonym for elastic modulus. It measures stiffness of an elastic material to characterize materials. Modulus is characterized as ratio of stress to strain and used for calculation of natural frequencies of the cantilever [11]. The issue about natural frequencies is described in detail in the thesis of my colleague Martin Urban [1].

### ■ 4.8.2 Attenuation of Signal

Measuring attenuation of the signal is made for verification of elasticity of material. This parameter is only additional to natural frequencies. In the picture Fig. 4.6 is sample of signal which has been measured on the HM panel. It produced damped oscillations with almost exponential envelope.

There are several ways how to get exponential envelope. One is the electrical way that rectifies the signal and filters it with low pass filter. There is one disadvantage though – because of the low amplitude only single diode rectifier can be used. Another option for this purpose is to design a rectifier made of operation amplifiers. This way has been rejected because of higher consumption of energy and it is not necessary to implement it in a physical way.

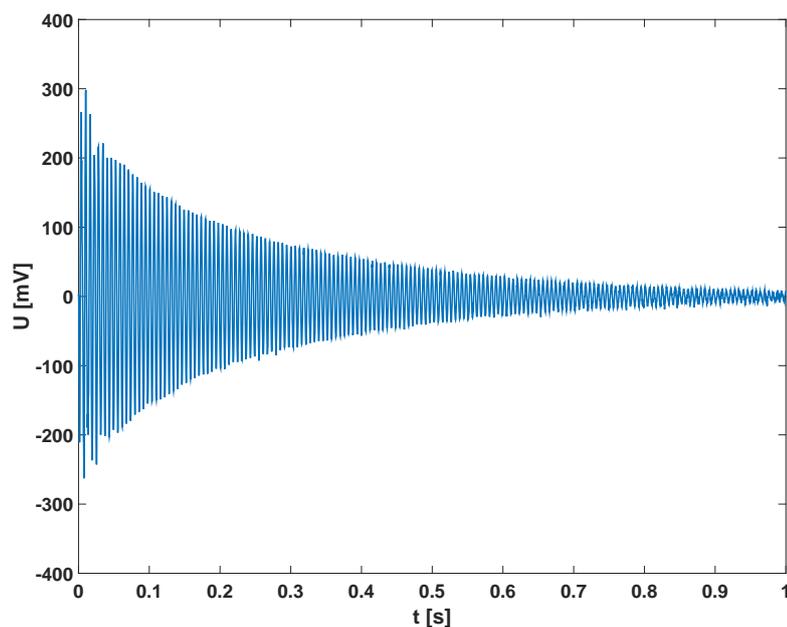


Fig. 4.6: Sample of signal

## 4.9 Computing Process of FFT

Fast Fourier Transform is based on Discrete Fourier Transform (DFT) – equation (4.14), but it is quicker and more suitable for calculation on Personal computer (PC), Microcontroller (MCU), etc. How to get FFT from DFT is more described in the Martin Urban's thesis [1]. Here is only one of the possibilities of implementing it to the Microcontroller.

$$Y_k = \frac{1}{N} \sum_{r=0}^{N-1} y_r e^{-j \frac{2\pi r k}{N}} \quad (4.14)$$

Fast Fourier Transform has two phases, one is bit reversing and second is the main computing process. Bit reversing is shown in the Tab. 4.2 where address of a point is swapped with the other. This operation can be solved in the same memory space as original signal.

Tab. 4.2: Bit reversing

$x_0 \dots 000$	$000 \dots x_0$
$x_1 \dots 001$	$100 \dots x_4$
$x_2 \dots 010$	$010 \dots x_2$
$x_3 \dots 011$	$110 \dots x_6$
$x_4 \dots 100$	$001 \dots x_1$
$x_5 \dots 101$	$101 \dots x_5$
$x_6 \dots 110$	$011 \dots x_3$
$x_7 \dots 111$	$111 \dots x_7$

FFT process is sums of points (x) as show in picture Fig. 4.7 (based on Cooley-Tukey method Radix 2) and detail of one butterfly is in the following picture Fig. 4.8.

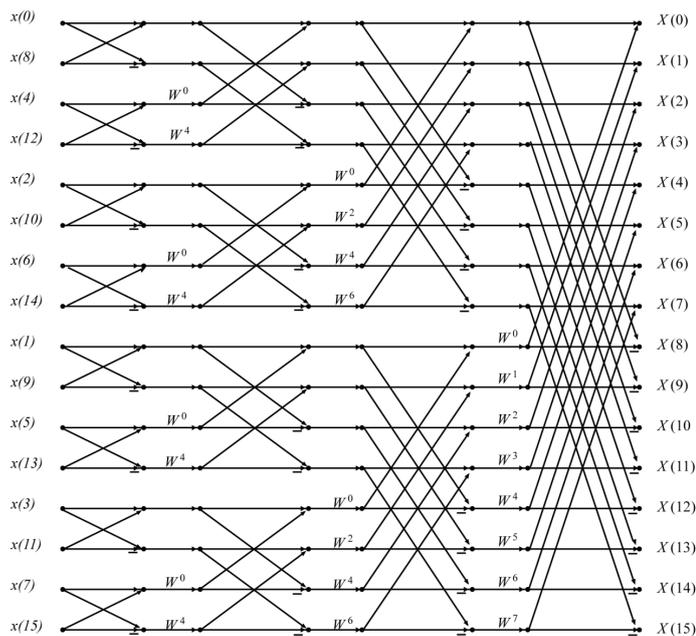


Fig. 4.7: Flowchart of computing FFT with N=16 points

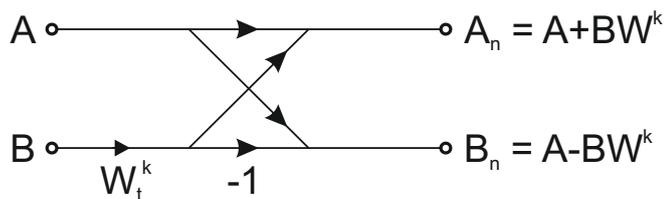


Fig. 4.8: Detail of a butterfly

The FFT process is divided into stages, their number is  $\log N$ . The flowchart Fig. 4.7 has 4 stages of butterflies, where on the left side is the bit reversed input signal and on the right side is the final spectrum. Each butterfly is computed according to Fig. 4.8 using equations (4.15, 4.16). Complex points  $A$  and  $B$  represent each stage of butterflies and  $W^k = e^{-j\frac{2\pi k}{T}}$ .

$$A_n = A + BW^k \quad (4.15)$$

$$B_n = A - BW^k \quad (4.16)$$

These equations could be divided into real and imaginary part of numbers as shown in six following equations (4.18 - 4.23)

$$C = BW^k = [\Re(B) + j\Im(B)] \cdot \left( \cos \frac{2\pi k}{T} - j \sin \frac{2\pi k}{T} \right) \quad (4.17)$$

↓

$$\Re(C) = \Im(B) \sin \left( \frac{2\pi k}{T} \right) + \Re(B) \cos \left( \frac{2\pi k}{T} \right) \quad (4.18)$$

$$\Im(C) = \Im(B) \cos \left( \frac{2\pi k}{T} \right) - \Re(B) \sin \left( \frac{2\pi k}{T} \right) \quad (4.19)$$

$$\Re(A_n) = \Re(A) + \Re(C) \quad (4.20)$$

$$\Im(A_n) = \Im(A) + \Im(C) \quad (4.21)$$

$$\Re(B_n) = \Re(A) - \Re(C) \quad (4.22)$$

$$\Im(B_n) = \Im(A) - \Im(C) \quad (4.23)$$

One butterfly has six additions and four multiplication operations. It is not so hard to calculate on small MCUs in case that values of sine and cosine functions are precalculated. When all butterflies are computed, the last step is to get values of every frequency of the signal. This is performed in absolute value as in the equation (4.24) [12–14].

$$|x| = \sqrt{\Re(x)^2 + \Im(x)^2} \quad (4.24)$$

## 4.10 Computing Process of Attenuation

Envelope of the signal represents attenuation. By using signal processing damping constant, Attenuation of system ( $\delta$ ) is extrapolated.

The process consists of a few steps:

1. Rectify signal
2. Compute moving averages
3. Logarithm signal
4. Compute least square method

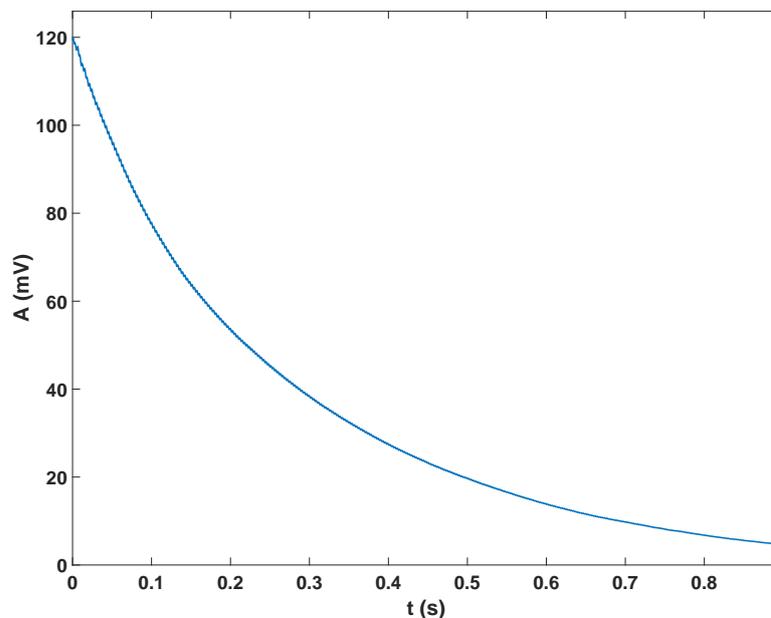
### ■ 4.10.1 Rectify and Moving Averages

Signal rectification is quite simple task. It is only makes an absolute value over the sampled signal. When it is performed, the next step is to compute moving averages, which is only sum of points in time divided by number of point. Expression for moving averages is in equation (4.25).

$$x_i = \frac{1}{k} \sum_{n=i}^{k+i} |x_n| \quad i \in \mathbb{Z}, \quad i \in \langle 0; N - k \rangle \quad (4.25)$$

Where  $x$  is Point of signal,  $N$  is Number points of signal,  $k$  is Number points of moving averages.

The result of this step is in the following chart Fig. 4.9. Signal length is  $N=4096$  points and number of moving averages is  $k = 512$ .



**Fig. 4.9:** Result of moving averages

### ■ 4.10.2 Logarithm Moving Averages

Attenuation of damped oscillation is in ideal state exponential. We will suppose that for real measured signal. Expression of any damped oscillated signal could be this (4.26), with one modulated frequency. Simulated signal by Matlab in Fig. 4.2 has similar waveform to real measured signal Fig. 4.6, but real signal has more than one frequency and this is only parable to this situation.

$$y = A \sin(\omega t) e^{-tb} \quad (4.26)$$

Using moving averages to the simulated damped signal gets something similar to the Fig. 4.9. When natural logarithm is used to the result of moving averages, we should get a line. Red line in the picture Fig. 4.10 represents the result of logarithm and the outcome is what was expected – a line.

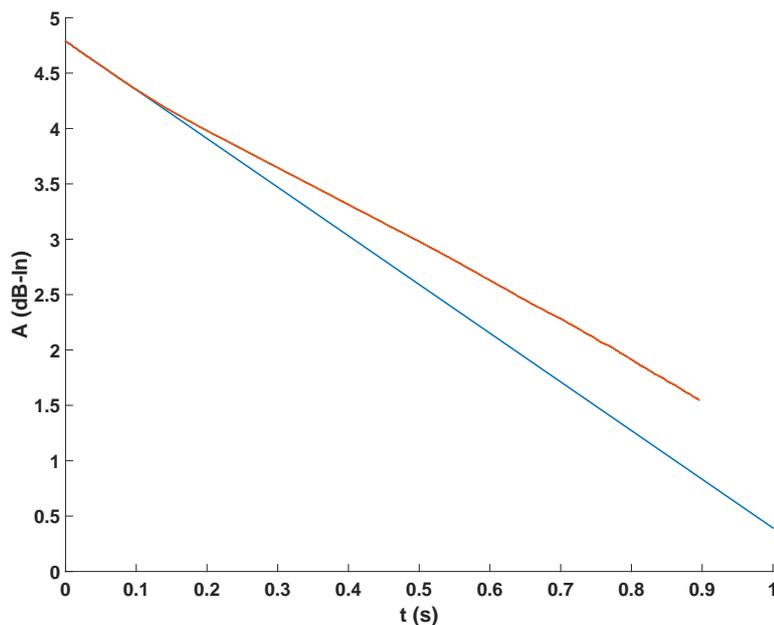


Fig. 4.10: Attenuation with directive

### ■ 4.10.3 Least Square

Last step of evaluation of attenuation is compute directive of line. Here are two possibilities. First is defining two points and calculate directive from them. Second,

more sophisticated and more computing expensive is using an approximation of curve, but more precise than using method of two points.

The most elementary is linear approximation called least square method or linear regression. Also waveform could be better approximated by a higher degree of regression or another type such as exponential or logarithm.

For our purpose linear regression is enough and its representation is equation of line, for example as  $y = kx + q$ , where Offset of line ( $k$ ) is computed by equation (4.27) and Offset of line ( $q$ ) is computed by (4.28).

$$k = \frac{N \sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i}{N \sum_{i=1}^N x_i^2 - \left[ \sum_{i=1}^N x_i \right]^2} \quad (4.27)$$

$$q = \frac{\sum_{i=1}^N x_i^2 \sum_{i=1}^N y_i - \sum_{i=1}^N x_i \sum_{i=1}^N x_i y_i}{N \sum_{i=1}^N x_i^2 - \left[ \sum_{i=1}^N x_i \right]^2} \quad (4.28)$$

where  $N$  is Number of point least square method,  $x_i$  Time point in least square method,  $y_i$  Amplitude point in least square method,  $k$  Directive of line,  $q$  Offset of line,

Linear regression could be used for the whole signal – only in the case that signal is a line in the whole length. Although, this claim is questionable. For safer and more reliable result, in autonomous mode, it is recommended to use small part of the signal. The best part is the beginning. In the picture Fig. 4.10 is a result of least square. The blue line is an outcome directive of linear part of signal. The approximation is used in length approx. 0.2s. Length of least square method is configurable for further improvement of measurement on orbit, in depends on quality of sampled signal.



## 5 Device for Mechanical Changes Measurement

The idea of measuring mechanical changes is to measure resonance frequency of the material and recursively calculate elastic modulus and other properties. So it leads to creation of the measurement system – HM panel and HM board.

### 5.1 HM panel

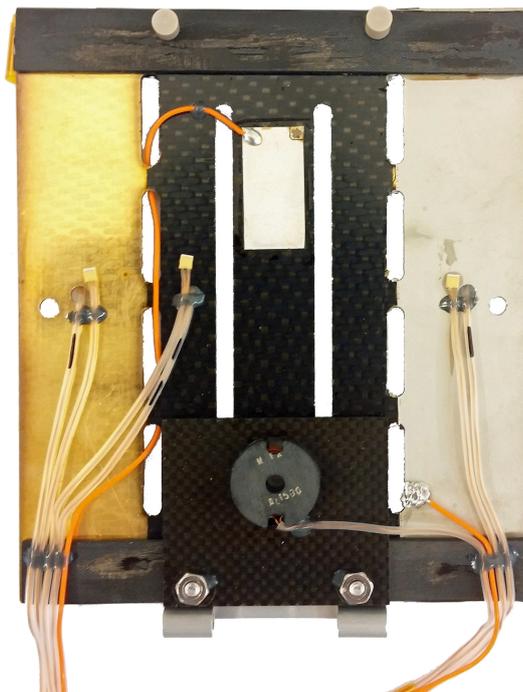


Fig. 5.1: Picture of HM panel

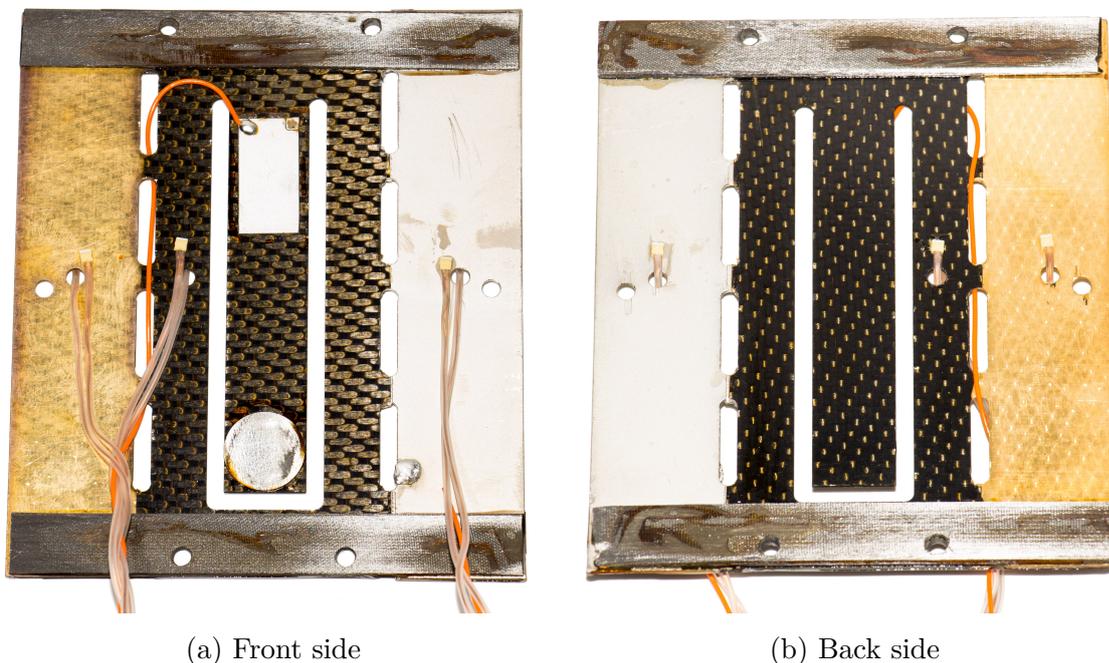
Health Monitoring panel is made from carbon-fibre material and milled cantilever shown on the drawing Fig. 4.5. HM panel is mounted as tilting panel on the top of the satellite, as shown on Fig. 3.1a.

The HM panel consists of some important parts for measuring, like excitation coil which attract permalloy target glued on the cantilever, under the coil. It causes

oscillations which are measured by piezo-electric element glued on the most stressed position at the opposite side of the cantilever. Piezo is situated in place of the highest mechanical changes. Assembled HM panel is in the picture Fig. 5.1.

Surface of the panel is covered by two reflective materials. There is nickel compound on the left side and golden compound on the right side. These materials should reflect thermal radiation for example from the Sun.

Health Monitoring panel has six sensors PT1000 which measure temperature transmission through the panel. Temperature is also important factor for calibration of measurement, because properties of carbon fibre material could change. Final assembling of these sensors are shown in the pictures Fig. 5.2.



**Fig. 5.2:** Detail of HM panel

All temperature sensors are connected to the *measure board* which measure temperature from almost all PT1000. Board could be called by any payload through I<sup>2</sup>C interface via CSP. Wires from coil and piezo are connected to the HM board which processes all measurements of mechanical changes. Piezo is connected to the connector marked as *Piezo* and coil is connected to the connector called *Coil*.

## 5.2 HM board

Health Monitoring board is shown in the picture Fig. 5.3 which consists of parts such as main connector which is not standardized for CubeSat, because of the weight and also board is the last one in row in the probe. So it is not necessary to connect all signals to the board, only power supply and I<sup>2</sup>C interface. Next part is external oscillator connected to the MCU *ATxMega128A4U* from Atmel company. Microcontroller is responsible for signal sampling from piezo and excitation of coil assembled on HM panel.

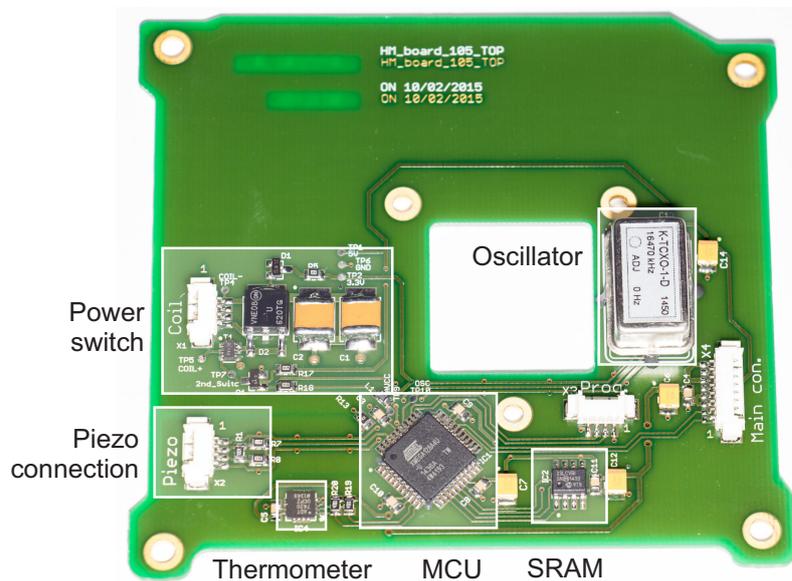


Fig. 5.3: Picture of HM board with highlighted parts

### 5.2.1 Microcontroller for Payloads

Microcontroller *ATxMega128A4U* has been chosen for payloads, which is one of many compatible devices with CSP. It is quite powerful MCU for simple tasks, such as signal sampling, temperature measurement, communication with other boards, etc. Basically it is focused on easy tasks but for measuring mechanical changes it is necessary to get the frequency.

One of the possibilities how to find out the frequencies is to calculate period. Using this method is not too much reliable for more than one frequency contained in sampled signal. So it have to calculate FFT. It is not too much suitable for this

purpose, because of the computing power, but with more time for calculating, it is possible to do it. The best way to process FFT is use a DSP Microcontroller. It will calculate it in shorter time, because it has specialized instructions for it.

The MCU *ATxMega128A4U* is from AVR family of chips and value 128 signifies the size of internal Flash memory, it has 128 kB of it. Some selected parameters of the Microcontroller are in the table Tab. 5.1.

**Tab. 5.1:** Parameters of MCU ATxMega128A4U [15]

Type	Parameters	Description
<i>Flash</i>	128 kB	Size of internal program memory
<i>SRAM</i>	8 kB	Size of internal data memory
<i>EEPROM</i>	2 kB	Size of internal data memory, non-volatile
<i>Speed</i>	up to 32 MHz	Maximal speed of external/internal oscillator, crystal, ...
<i>ADC</i>	up to 12	Number of single ended inputs
<i>ADC</i>	up to 8	Number of differential inputs
<i>ADC</i>	12 bits	Resolution of ADC
<i>Timers/Counters</i>	5	Number of 16-bits Timers/Counters in MCU
<i>Supply</i>	2.7 – 3.6 V	Tolerance of supply voltage in range of frequencies 0 – 32 MHz

## ■ 5.2.2 Oscillator

The source of accurate clocks is necessary for signal sampling. It means finding the best crystal or oscillator for this purpose. Common crystals have low temperature stability, about  $\pm 25$  ppm in  $-30^\circ\text{C}$  to  $+80^\circ\text{C}$  temperature range.

The oscillator *TCX0-1A* is very precise and is tuned to 16.470 MHz. Frequency stability vs. temperature is better than  $\pm 2$  ppm. Oscillator usually comes with an internal capacitive trimmer, but for space mission it would be very unsuitable because it could change frequency during the mission and the results would be invalidated. Evaluation depends mostly on frequency change of cantilever in time. That capacitive trimmer was replaced by solid capacitor with fixed value. This was special requirement for an oscillator [16].

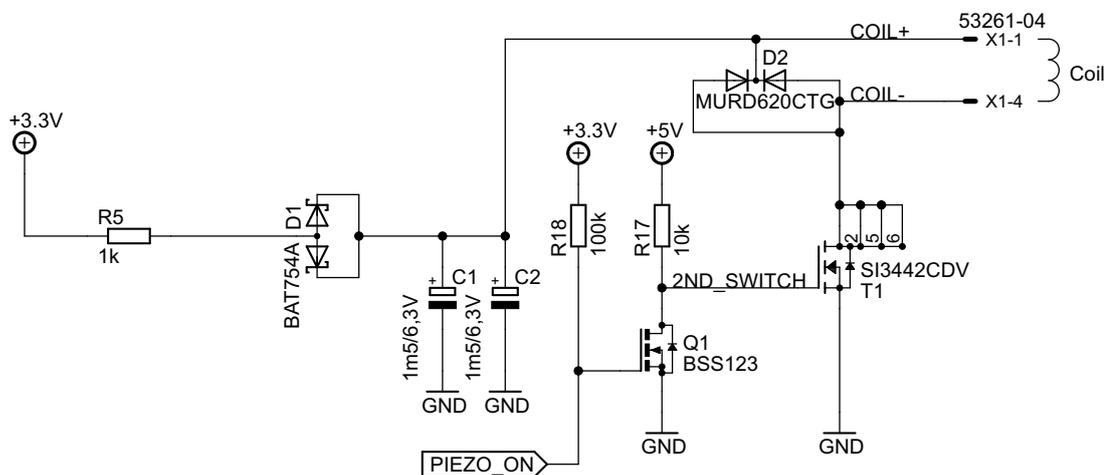
### ■ 5.2.3 External Memory

For high number of points of FFT is necessary to have more memory space. Internal RAM has only 8 kB and almost 3/4 of it is used for variables and FreeRTOS. Because of that external memory connected to the MCU is necessary. FRAM memory is valuable for use in space because it is more reliable than EEPROM and SRAM. But it is quite difficult to find a suitable chip. All commonly have parallel interface, so it is necessary to have many Input/Output (I/O) pins for connection to the memory. EEPROM has one disadvantage and that erase and write cycle takes a lot of time, about 5 ms. So it led to a choice of SRAM memory. It has almost instant write and read cycle but when power supply is disconnected data are lost. For computing FFT data loss does not matter, required results are stored in data-keeper.

As external memory has been chosen 1 Mb of SRAM Serial Peripheral Interface (SPI) memory *23LCV1024* [17].

### ■ 5.2.4 Power Switch

Power switch on the board serves for excitation of coil, which attracts permalloy on the cantilever. Detailed schematic is in the following picture Fig. 5.4.



**Fig. 5.4:** Schematic of power switch

Power switch consists of parts such as power MOSFET connected as switch. There is a reversed polarized diode between drain of the transistor and power source

for catching peaks of voltage from the coil. If the diode would be omitted it could cause damage the transistor in the best case. In the worst case, it could destroy whole satellite. So it is necessary. The second switch is used for separation of 5 V and 3.3 V power supply. 5 V to the gate of transistor is more suitable for high current through power transistor T1.

Energy for high power peak is stored in two tantalum capacitors with total capacitance of approx. 3 mF. It is enough for excitation of the coil with high amplitude on the piezo. Amount of energy can be controlled by width of pulse to the *Piezo\_on*.

### ■ 5.2.5 Piezo Connection

Piezo element is connected to the MCU's ADC through resistor divider. Schematic of input measurement is in the picture Fig. 5.5.

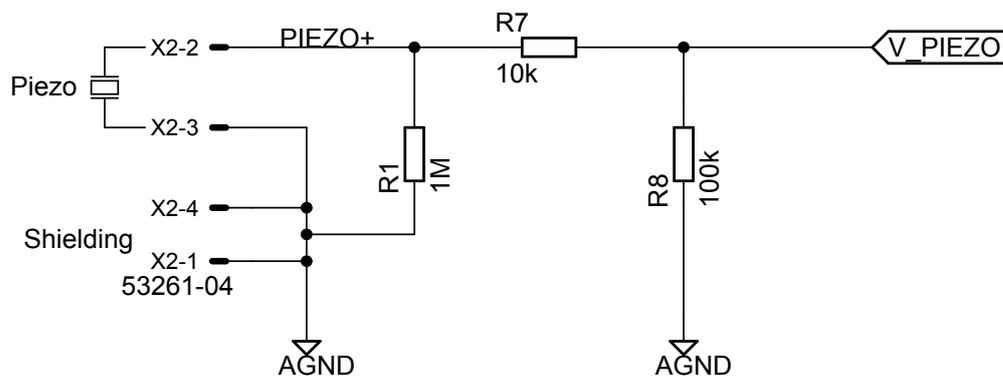


Fig. 5.5: Schematic of piezo connection

Divider reduces amplitude of the input signal. Signal is alternating around zero voltage and minimum amplitude of input voltage must be greater than  $-0.4\text{ V}$ , otherwise signal is clipped by internal diode. Unfortunately this problem was discovered in time when board was already created and assembled, and there was not enough time to change it. In the end it was not a problem, measured signal could be trimmed slightly by width of pulse to the coil and then the amplitude is reduced to the appropriate value.

For further using of differential input of ADC is better to shift up virtual zero (negative input) to the half of reference voltage, to approx. 1 V.

## ■ 5.2.6 Thermometer

Health Monitoring board is equipped with one thermometer *ADT7420* communicating through I<sup>2</sup>C interface. Its resolution is 16 bits with sign. In the following table Tab. 5.2 are shown other basic features.

Maximum allowed number of these devices is four, because this chip provides four different addresses. Address can be changed by two pins *A0*, *A1* on the package. Rest is set by the manufacturer and the address range (in hexadecimal format) is from **0x48** to **0x4B**. Pins *A0*, *A1* on HM board are connected to the ground – logical zero, thermometer ADT7420 has address **0x48**.

**Tab. 5.2:** Parameters of thermometer ADT7420 [18]

Parameter	Value	Description
<i>Resolution</i>	up to 16 bits	Maximal resolution of thermometer
<i>Temperature range</i>	−20 to +105 °C	Temperature range of thermometer
<i>Precision</i>	±0.25 °C	Accuracy of thermometer in temperature range from −20 to +105 °C
<i>Supply</i>	2.7 to 5.5 V	Power supply voltage range

Thermometer is connected through I<sup>2</sup>C interface and the bus required external pull-up resistors with resistance about 4.7 kΩ.

Value from the thermometer can be get by one CSP packet if any board needs to know it. Parameters of the communication are specified in chapter 6.4.4. Delay between command and return value is approx. 250 ms. This time is derived from the length of conversion which is about 240 ms. All parameters are from datasheet [18].



## 6 Communication with Other Boards

Communication is one of the most important things. Without it, data cannot be transmitted and boards do not know what to do. In this case, board communicates with the rest of the probe (connected to the same bus) via I<sup>2</sup>C interface. All boards have specific communication protocol called CubeSat Space Protocol. It is an universal protocol specially for CubeSats.

### 6.1 I<sup>2</sup>C Interface

Generally I<sup>2</sup>C interface is connected via two wires SDA and SCL with common ground. The bus required two pull-up resistors, usually in range of 470–10 k $\Omega$ . It depends on specification from the manufacturer. With more devices on the bus, it is recommended to reduce the resistance. When bus is idle, positive voltages are on SDA and SCL wires. Visualization of the connection is on the follow figure Fig. 6.1. Resistors  $R_{PU}$  are not necessary at every device, one on each wire is enough.

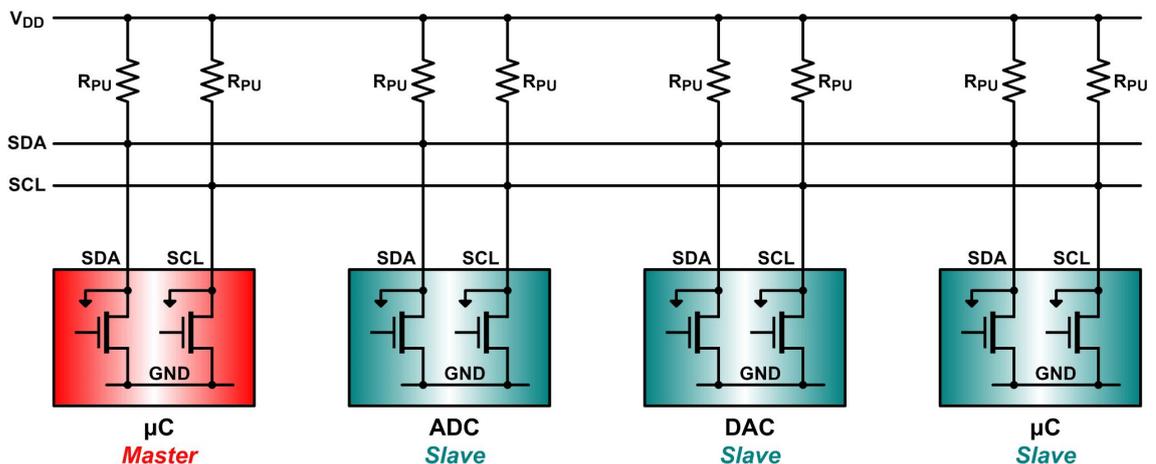


Fig. 6.1: Schematic of connection I<sup>2</sup>C devices [19]

Communication protocol between master and slave unit is shown on the next figure Fig. 6.2. Communications starts with start condition – SDA falling edge prevents SCL falling edge. Then follows 7-bits address and last bit is read (high)



After header follows data. Maximum size of data is not generally set, but it is not recommended to transfer huge amount of data, because transfer could overload bus and other boards have to wait until bus is free. It has been established that optimal size of data is up to 64 Bytes per packet. Disadvantage of sending huge amount of data is memory demands on both sides of communication and busy line of one transfer.

Whole CSP is suited for running on FreeRTOS [21].

## 6.3 FreeRTOS

FreeRTOS is shortcut for Free Real Time Operating System. This system is multi-platform and it can run on 32-bit platform as well as on 8-bit. It is primarily suited for embedded systems based on ARM cores but it is possible to use on small devices such as ATxMega.

Only requirement of FreeRTOS is one dedicated system timer. Timer is used for switching (multitasking) of each used task which are declared in the beginning of the code. Recommended time for switching tasks is 1 ms. When shorter time is used, it has been observed that MCU has been halted by switching between tasks.

### 6.3.1 Creating Tasks

Every task has some necessities when it is created – task name and function, place where it is created, memory allocation size, task priority, ...

Command which creates a task is called *xTaskCreate* and it has six parameters:

```
xTaskCreate(pvTaskCode, pcName, usStackDepth, pvParameters,
            uxPriority, pxCreatedTask)
```

Each parameter is shortly described in the table Tab. 6.1 . All created tasks are started by scheduler's start command – `vTaskStartScheduler()`. With this command all tasks start doing their functions. All running tasks has their own part of RAM memory space, which in sum must be lower then dedicated size of memory for FreeRTOS. This prevents any dangerous state or data loss.

**Tab. 6.1:** xTaskCreate Command Parameters [22]

Parameter	Description
<i>pvTaskCode</i>	Function pointer
<i>pcName</i>	Task name
<i>usStackDepth</i>	Stack size
<i>pvParameters</i>	Parameters of the task
<i>uxPriority</i>	Task priority
<i>pxCreatedTask</i>	Used for backward handle

Every task usually works in infinite loop similar to *main* function. The next Code 6.1 represents example of a task without any function – only body [22].

**Code 6.1:** Main loop of any task

```
int task_name(void * pvParameters){
    // initialization here
    while(1){
        // do something here
    }
    return 0;
}
```

## 6.4 Communication with HM Board

I would like to express big thanks to my colleague *ing. Tomáš Báča* for help with the basics of implementing FreeRTOS and CSP to the HM board.

As is written previously, all boards communicate via CSP and the HM board has several commands coupled with ports and its address is 6. Between basics functions of all board are ping that board is still alive and House keeping (HK) data – it returns information about board. Between user defined commands are for example return data, signal, etc. All functions are in the table below Tab. 6.2.

Tab. 6.2: Communication ports of HM board

Port number	Description
18	Measure starts
19	Returns signal to DK
20	Returns results of measurement
21	Returns temperature of HM board

Meaning of commands from table Tab. 6.2 are as follows:

#### ■ 6.4.1 Measure Starts

Measuring starts only when HM board gets packet to the port number 18. Packet could be empty or contain anything, but it does not matter to the program what came. Response to the originator is simple – *ackMes* as text. When signal is sampled, all that is calculated returns results to the DK.

#### ■ 6.4.2 Returns Signal to DK

When this command is called, MCU returns signal of previously sampled to the DK divided into many chunks, each with predefined size – 32 Bytes. When signal is transmitted to the ground, there it will be reconstructed.

#### ■ 6.4.3 Returns Results of Measurement

This command returns only results that have been calculated previously. It means the same thing as at the end of command *Measure starts*. This command is redundant, but it serves as a backup when something goes wrong during performing command *Measure starts*.

#### ■ 6.4.4 Returns Temperature of HM Board

In case any board needs to know the temperature from HM board, it can send a packet to this port. It is sufficient to send any packet to the port 21 and HM board responds by defined message Code 6.2:

Code 6.2: Respond to Get Temperature Command

```
typedef struct __attribute__((packed)){  
    uint16_t temperature;    // temperature from ADT7420  
}hm_temperature_t;
```

## 6.5 Data Keeper

Data Keeper (DK) is used for storing data such as results of measurements, log files, etc. Data are saved on Secure digital (SD) card, which is formatted by UFFS file system suitable especially for embedded systems – NAND flash memories [23].

Every result is stored into DK and each board has a few containers for storing data. Containers are separated files sorted by CSP address of board and a variable – storage number. All data must be divided into chunks, each with unique identification number.

Each storage, when it is created, has fixed data space for configuration data – chunk number zero. When chunk zero is used for configuration data, it must to be created before the first use a storage.

## 7 Measurement Process in HM board

Before the measurement starts, it is necessary to send activation sequence to the board. It is provided by OBC through CSP command. Header of CSP contains destination port which correspond to specific command. Port chosen for the main measurement is 18 as written in the Tab. 6.2.

*Process of the main measurement is divided into several steps:*

1. Read parameters of measurement from DK
2. Get temperatures from all sensors – from Measure Board
3. Get orientation of the probe
4. Get actual board time
5. Excitation of coil for a defined time (loaded from DK)
6. Sampling of signal
7. Signal processing – FFT
8. Signal processing – attenuation
9. Store data to the DK

### 7.1 Read Parameters of Measurement

Parameters of measurement are stored in DK, storage number 1. Configuration contains mainly parameters around computing Young's Modulus of Elasticity, such as range of frequencies where natural frequency is looked for, decimation frequency, pulse length to the coil and number of points of least square method from the beginning of signal. Whole structure of configuration is in listing Code 7.1.

Code 7.1: Parameters of Measurement

```

typedef struct __attribute__((packed)){
// 3x tolerance range of frequencies
  uint16_t f1_min;
  uint16_t f1_max;
  uint16_t f2_min;
  uint16_t f2_max;
  uint16_t f3_min;
  uint16_t f3_max;
// how long is power switch on - current to the coil
  uint8_t   time_power_switch_on;
// to which frequency is decimated to
  uint16_t decimation_factor;
// length of least squares
  uint16_t length_of_ls;
}hm_config_t;

```

Accuracy of frequency (first six variables) is in Hertz and minimum (`fx_min`) have to be less than maximal value (`fx_max`). In the case this condition is false, minimum and maximum value will be swapped. In case frequency exceeds limits of half decimation frequency, maximum value is set this value. Maximal frequency which can be set is 65 kHz – enough for this application.

Time for power switch on (`time_power_switch_on`) is in 1/10 of ms – number 15 corresponds to 1.5 ms. The maximum time is 25.5 ms (255).

Decimation factor (`decimation_factor`) is a value for calculation of spectrum from sampled signal. This value is division factor for decimation of sampled signal, to reduce spectrum of signal.

The directive of exponential envelope is calculated by the least square method.

`length_of_ls` is constant which specifies computing range of this method. Value represents number of calculation points of linear regression.

## 7.2 Get Temperature, Orientation and Time

Health Monitoring panel has six PT1000 thermometers in total which measure thermal transfer through material and/or surface of it. Temperatures are available on Measure board and they can be obtained by CSP command. The board return temperatures and MCU on HM board store them to the memory for further transfer into DK. Orientation and board time is available on OBC. Process of reading is same as temperature but with other board.

## 7.3 Excite of Coil and Sampling of Signal

When all parameters are loaded and other variables are read from the boards, measurement process can start. Microcontroller has one dedicated timer for timing of excitation coil which stops excitation.

Also one timer is dedicated for sampling of signal with higher priority of interrupt – for precision timing. All points are sampled and averaged four times and then stored into SRAM to the space dedicated for sampled signal. Number of points is 4096 at  $f_s = 4\text{ kHz}$ . It covers a little bit more than 1 s of signal. From this determination of Sampling frequency is possible to have spectrum up to 2 kHz.

## 7.4 Signal Processing – FFT

The most important part of signal processing (for our purpose) is computing FFT to find out resonant frequencies of sampled signal. More detailed description about meaning of looking for frequencies is in chapter 4.8.1. Introduction to the FFT process is in Martin Urban's thesis [1] and in chapter 4.9 with all equations for calculations.

Here I will only simply describe how to calculate it in 8-bits MCU and the implementation into the Microcontroller. The whole FFT computing process has two parts – address bit reversing and the actual FFT process.

### 7.4.1 Decimation and Address Bit Reversing

Decimation is used for reducing the spectrum of signal, but Shannon-Niquist theorem of  $f_s \geq 2f_{\max}$  for searching frequency must be followed, in this case  $f_{\max}$ . With the same length of window for computing FFT, resulting spectrum has better resolution in frequency. Sampled signal has default  $f_s = 4\text{ kHz}$  and decimation factor is 4. It is according to new sampling frequency 1 kHz. Decimation factor could be changed by the setting stored in DK – decimation factor. But if the factor is one, decimation will not be used.

Bit reversing is one of the requirements for computing FFT when is used Decimation in time (DiT) or Decimation in frequency (DiF) method. Main difference between DiF and DiT is in order of performing bit reversing and FFT process. Decimation in time consists of this: bit reversing and then FFT process and Decimation

in frequency has reversed order.

Process of bit reversing is simple. Take one point of signal with known address, swap all address bits and store the point into this changed address. In the table Tab. 4.2 is visualised this claim, addresses for example are in binary form in length of 3 bits.

From this point of view it is recommended to use DiT method and combine advantageous decimation with bit reversing. Every point is loaded and stored one time from/into the memory. For simplification of reversing, all bit reversed addresses are stored in array in Flash memory of MCU. In the following code listing Code 7.2 is implementation of decimation and bit reversing.

**Code 7.2:** Decimation and bit reversing

```
void decimate_and_store(void){
// here is variables and verification
// of decimation frequency in configuration

// storing and bitreversing raw signal into spi memory
for (u_int16 i=0; i<NO_POINTS; ++i) {
    position = pgm_read_dword_far(&bitrev[i]);
    decimation_position = (long) position * DECIMATION_FACTOR;
    if (decimation_position<MEM_SIGNAL_POINTS) {
        read_data = spi_mem_read_word(decimation_position*2 +
            MEM_SIGNAL_BEGIN) - signal_offset;
        point.real = read_data;
    }
    else
        point.real = 0;

    // store into SPI memory
    spi_mem_write_complex((long) MEM_FFT_BEGIN + i*8, point);
}
}
```

Where DECIMATION\_FACTOR is ratio of  $f_s$  and  $f_{dec}$ , MEM\_SIGNAL\_BEGIN, MEM\_FFT\_BEGIN are positions of beginning address of SPI memory, NO\_POINTS is number of points of sampled signal, bitrev is an array of bit reversed addresses and signal\_offset is value for elimination of DC part of signal [12].

## 7.4.2 FFT Process

FFT process is based on Cooley-Tukey method of computing according to equations (4.18 - 4.23). Functions sine and cosine are precalculated in a table instead of computing it in MCU to save time. Final spectrum is represented as an absolute value of complex point (4.24). For our purpose it is necessary to know only the maximum peak and from this point of view is square root omitted to save time of calculations. The code used for computing the FFT is in following listing Code 7.3 [13].

Code 7.3: Calculation of FFT

```
n=1; // actual state
angf=NO_POINTS/2; // twiddle factor
while(n<NO_POINTS){ // number of iterations log2(NO_POINTS)
    pointer_A = MEM_FFT_BEGIN; // address of beginnig memory space for FFT
    pointer_B = pointer_A + n*8;
    Fnk = 0;
    for(k=0;k<n;k++){ // distance between butterflies
        dsin = read_sincos(Fnk++); // read sin and cos from table
        dcos = read_sincos(Fnk++);
        for(s=0;s<angf;s++){ // butterflies
            A = spi_mem_read_complex(pointer_A);
            B = spi_mem_read_complex(pointer_B);
            C.real=(B.real*dcos - B.imag*dsin);
            C.imag=(B.real*dsin + B.imag*dcos);
            B.real=A.real - C.real;
            B.imag=A.imag - C.imag;
            A.real=A.real + C.real;
            A.imag=A.imag + C.imag;
            spi_mem_write_complex(pointer_A,A);
            spi_mem_write_complex(pointer_B,B);
            pointer_A += n*16; // nextpoint in memory 2x 2x4B
            pointer_B += n*16;
        }
        pointer_A-= (NO_POINTS-1)*8;
        pointer_B-= (NO_POINTS-1)*8;
        Fnk+=(angf-1)*2;
    }
    n<<=1;
    angf>>=1; // twiddle factor /2
}
```

## 7.5 Signal Processing – Attenuation

After computing FFT, the next step is to calculate attenuation of signal, which is expected to have exponential envelope. By using equation (4.27) the directive is computed – attenuation of signal, from linearised signal. There is a dedicated memory space for the whole computing process of directive and has same size as sampled signal. Sample of code is in the listing Code 7.4 where is only the main part of calculation.

Code 7.4: Calculation of attenuation

```
copy_signal_attenuation(); // copy and decimate signal
average_signal();       // rectify, average and logarithm the signal

for (i=OFFSET_AVERAGING_POINTS; i<((int)OFFSET_AVERAGING_POINTS + n);
    i++){
    loaded_value = spi_mem_read_word(i*2 + MEM_ATTENUATION_BEGIN);
    point = (float) loaded_value;
    sum_x_i_y_i *= point;
    sum_x_i += i;
    sum_y_i += loaded_value;
    sum_x_i_squared += i * i;
}
// recalculation from samples to the time
sum_x_i_y_i /= fs;
sum_x_i /= fs;
sum_x_i_squared /= (fs * fs);

reg_k = (n*sum_x_i_y_i - sum_x_i*sum_y_i) / (n*sum_x_i_squared -
    sum_x_i*sum_x_i)*100;
reg_q = (sum_x_i_squared*sum_y_i - sum_x_i*sum_x_i_y_i) /
    (n*sum_x_i_squared - sum_x_i*sum_x_i);
```

where `OFFSET_AVERAGING_POINTS` is constant offset in time (samples) since least square is computed, `MEM_ATTENUATION_BEGIN` is offset in memory where stored signal for computing attenuation begins, `n` is number of averaged points.

The function `copy_signal_attenuation()` is only copying signal from one part of external memory to the other and decimate the signal according to `DECIMATION_FACTOR`.

The function `average_signal()` consists of the following processes, rectifying of signal using `abs` function (make absolute value), moving average for curve smoothing and logarithm them for linearisation of signal according to chapter 4.10.1 and 4.10.2.

Code has one main `for` cycle where all sums in this loop according to equation (4.27). The `for` cycle does not calculate with time, because it would mean additional time for calculation. Recalculation to the time is performed after the `for` loop using reciprocal value of  $f_s$ .

Final results of least square method are in `reg_k` which is a directive of line – our attenuation and in `reg_q` is an offset of line. Only directive is stored, offset is not stored because it does not corresponds to the maximal value of original signal and also it is not necessary for further evaluation.

## 7.6 Store Results

All measured and received data will be saved to the DK with the following structure Code 7.5 and than transmitted to the earth for next process.

## 7.7 Conclusion

The small MCU *ATxMEGA128A4U* is able to compute FFT with 8192 points, but it takes a lot of time, approx. 15s because the code is not very optimized for speed. On orbit there will be a lot of time for this task – it is established that the shortest delay between measurements will be at least 5 min. So 15s is enough with a huge reserve – it is not calculated with other delays from getting the temperature, time from OBC and orientation of the probe. Totally, it is estimated on around 20-30s from start command to saving the results. When is required also raw signal, to this time is added approx. next 15s to store the data.

Code 7.5: Output structure

```

typedef struct __attribute__((packed)){
// status of HM board and HM panel - 0 = OK, 1 = problem
uint8_t xtal          : 1; // xtal works
uint8_t sram          : 1; // sram OK
uint8_t loaded_MB     : 1; // loaded temperatures from Measure Board
uint8_t loaded_OBC_time : 1; // loaded time from OBC
uint8_t config_out_dec : 1; // configuration is invalid,
// decimation = 0 or > 4000 Hz - applicated 1000 Hz
uint8_t config_out_freq : 1; // configuration is invalid, any of the
// frequencies is out of range greater then decimate_to_f Hz/2 -
// applicated decimate_to_f/2 Hz
uint8_t config_out_ls  : 1; // configuration is invalid, least
// square averaging is out of range 200 - 1000 points -
// applicated 200 Hz
uint8_t config_out_power : 1; // time of power switch is zero,
// default value is 10

uint32_t OBCTime;          // time of measurement
int16_t f1;                // 3x frequencies
int16_t f2;
int16_t f3;
int16_t attenuation_directive; // (k) directive of attenuation -
// from equation  $y = kx + q$ 
int16_t tempADT;          // temperature from ADT thermometer
int16_t temp1;           // 6x temperature from HM panel
int16_t temp2;
int16_t temp3;
int16_t temp4;
int16_t temp5;
int16_t temp6;
int16_t orientation1;     // 5x orientation of probe
int16_t orientation2;
int16_t orientation3;
int16_t orientation4;
int16_t orientation5;
} hm_output_data_t;

```

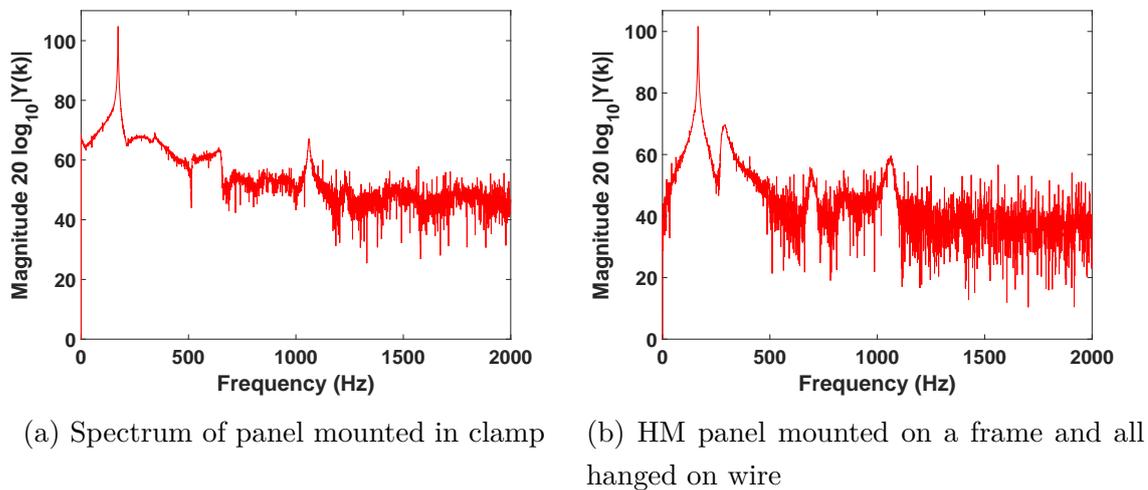
## 8 Measurements, Testing and Results

It is necessary to verify the final device in many climate conditions such as temperature changes, pressure, etc. same as reproducibility of measurement in the same conditions. All measurements precede theoretical calculations and simulations of gained signal, natural frequencies of cantilever, etc. and then we compare real data to theoretical results.

At first it is good to know natural frequencies of oscillated cantilever. From equation (4.11) natural frequencies are gained. For HM panel with these parameters:

- cantilever dimensions  $13.2 \times 67.4 \times 1.2$  mm
- elastic modulus is  $E = 3.8 \cdot 10^{10}$  Pa
- material density is  $\rho = 2300 \text{ kg} \cdot \text{m}^{-3}$

the first three natural frequencies are 171.6 Hz, 1075 Hz, 3011 Hz. The first two frequencies satisfy Shanon-Niquist theorem that says the sampling frequency ( $f_s = 4$  kHz) must be at least two times higher then maximum sensed frequency. Third and next cannot be directly measured.

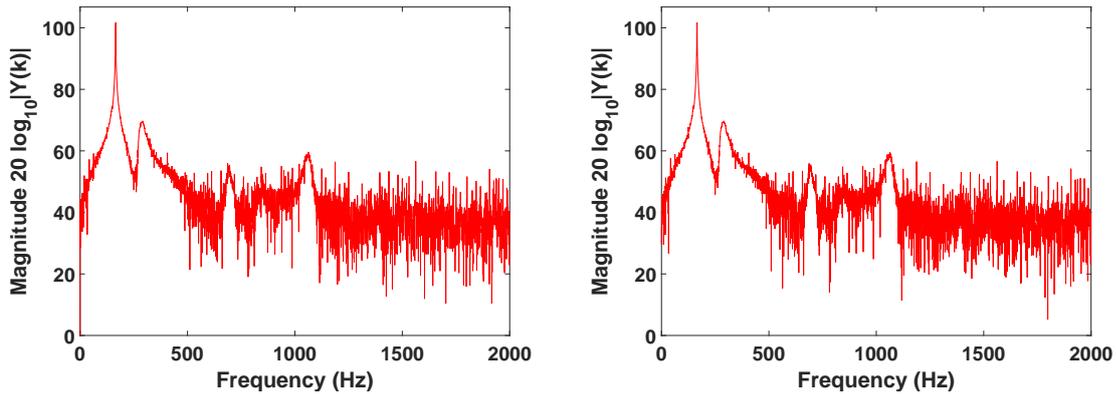


**Fig. 8.1:** Difference in spectra with different placement

Pictures of real measured signal in Fig. 8.1 are comparing the difference of spectrum in dependence on placement of HM panel. Both charts contain first two natural frequencies, but the second one Fig. 8.1b has extra peaks on frequencies around 300 Hz and 750 Hz. Peaks are probably caused by other resonances of a metal frame,

because the left chart does not have them. Health Monitoring panel mounted in jaws at the fixed side of cantilever and it may be considered a reference sample for further evaluation.

Spectrum above Sampling frequency ( $f_s$ )/2 does not affect main part of it, only smooths it a little. This statement is based on using Finite impulse response (FIR) filter on sampled signal, where differences in spectrum with and without using FIR filter are minimal. Comparison of them is in the pictures Fig. 8.2.



(a) Spectrum of signal without using FIR (b) Spectrum of signal with using FIR filter

Fig. 8.2: Differences in spectra without and with using FIR filter

## 8.1 Beginning of Research

The main part of research has began in the spring of 2014 when the highest possible resolution in frequency was expected around 0.1 Hz. At the beginning of research we took only the part to 250 Hz, where the main peak, the first natural frequency of the cantilever is located. All these claims are based on similar spectrum to reference Fig. 8.1a which was sensed by oscilloscope for the first time.

At first it was required to learn about the used Microcontroller *ATmega128A4u*, so we got development kits with this MCU. Picture of it is in the photo Fig. 8.3.

The kit consists of main MCU with three user buttons, alphanumeric Liquid crystal display (LCD), two LEDs and Universal synchronous and asynchronous serial receiver and transmitter (USART) which could be used for bootloader for downloading a new version of FW into the chip.

The kit has the advantage during debugging in that display could serve feedback what is happening in the MCU. USART can be advantageously used for downloading measured data or uploading commands for affecting processes in the chip.

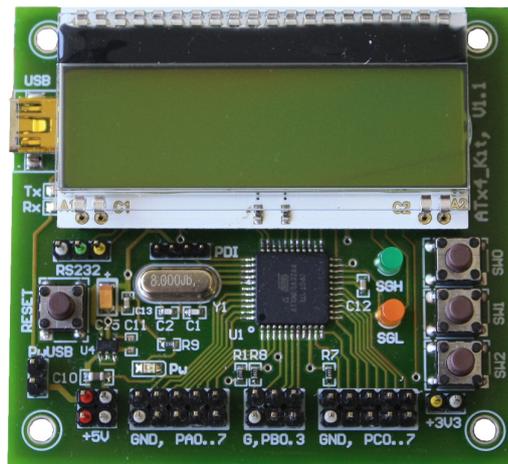


Fig. 8.3: Photo of development kit [24]

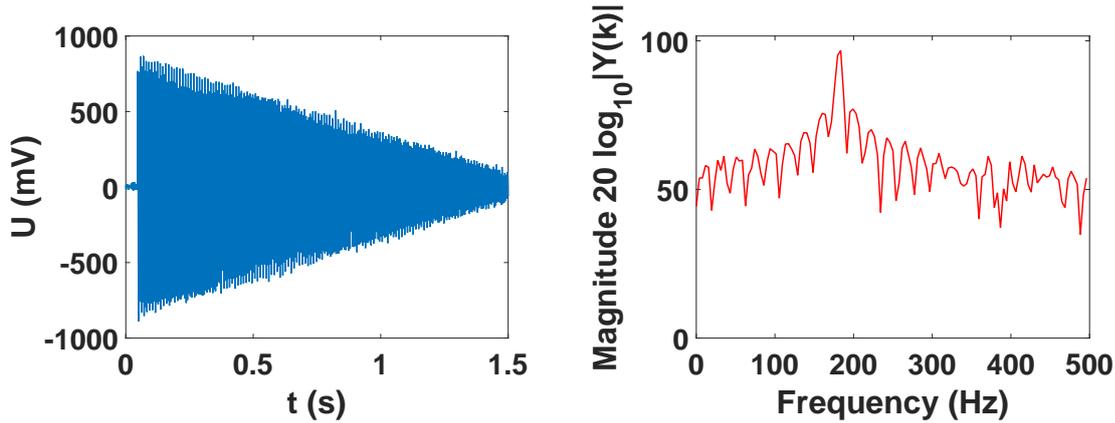
One of the first things what were needed to do was commissioning ADC and downloading signal via USART. ADC was set-up as single ended input on first analog input of MCU with a result saving into internal SRAM. Amount of samples, which could be saved, is estimated at 2500 points in 12 bits resolution (16 bits variables). These points are downloaded into PC and then evaluated. For evaluation of signal in the computer, environment Matlab was used. Next step was implementing the FFT, based on sampled and evaluated signal.

## 8.2 Research During Internship in Japan

Part of the research I and my colleagues Martin Urban and Veronika Stehlíková did, was done during summer internship in 2014 at Hosei University in Tokyo, Japan. There has been done implementing of FFT into chip together with storing data to the external SPI memory. Knowledge about signal processing was provided by professor Kazuo Yana, Ph.D., to whom I would like to express huge thanks [25], as well to other staff of the University for providing laboratories and equipment for testing and verifying progress of implementing functions into the MCU.

First step of verification was done on sinusoidal signal with triangular envelope, as shown in the Fig. 8.4. The implemented FFT was calculated with 256 points only (time saving), for verifying that the algorithm works with external memory. Results were what had been expected. More points of FFT calculation were added later, to one of the last versions of Firmware (FW) or for the calibration measurement.

Second step was verification of signal attenuation. Basics could be performed on triangular envelope, but to get closer to real situation, it is better to measure



(a) Sine signal with triangular envelope (b) Spectrum of signal with using FIR filter

**Fig. 8.4:** Signal with triangular envelope

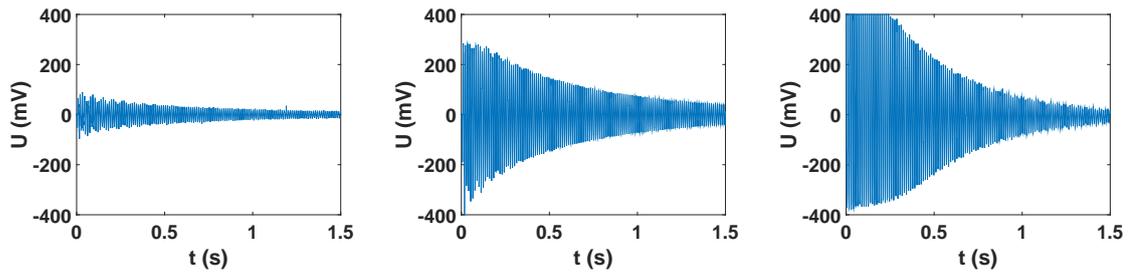
a signal with exponential envelope. For testing purposes a generator was made at Hosei University which produced the required waveform. The generator needs only a power supply and an external oscillator with requested frequency of the signal with defined output amplitude [26]. Computing process of attenuation is in the chapter 4.10.

Resulting attenuation was sent to the computer and then saved into a file. After that evaluated and compared with theoretical value. The difference between the value computed by MCU and Matlab was minimal - better than 0.5% (compared with single and double precision of calculations). For example Matlab computed attenuation as  $-4.08$  vs. MCU as  $-4.07$ .

### 8.3 Testing of Pulse Width

Examination of right pulse width is necessary to determine a proper waveform which is not clipped and must have maximal amplitude of  $\pm 400$  mV as mentioned before in chapter 5.2.5. Waveforms in Fig. 8.5 shows the comparison of differences of signal in dependence on pulse width. The Fig. 8.5a was sensed with 0.5 ms pulse width, Fig. 8.5b with 1 ms and Fig. 8.5c with 2 ms. From this point of view it is best to excite the coil by 1 ms pulse width.

In the last picture is shown how an internal diode of MCU clipped the sampled signal in negative values. Positives values has normal amplitude. This disadvantage could be solved with additional voltage reference at half of ADC range, in our case the reference should be  $(3.3/1.6)/2 = 1.03$  V. Supply voltage is 3.3 V and the division factor 1.6 is chosen as an internal reference of ADC [15].



(a) Sampled signal with too short pulse width (b) Sampled signal with ideal pulse width (c) Sampled signal with too long pulse width

Fig. 8.5: Differences between pulse widths

## 8.4 Different Climate Conditions

The creation of a reference for further processing is necessary to measure all boards and parts of the experiment in different climate conditions. The HM board and panel were tested only in temperature oven, not in the vacuum, because the chamber is not big enough for HM panel with frame hanged on a wire.

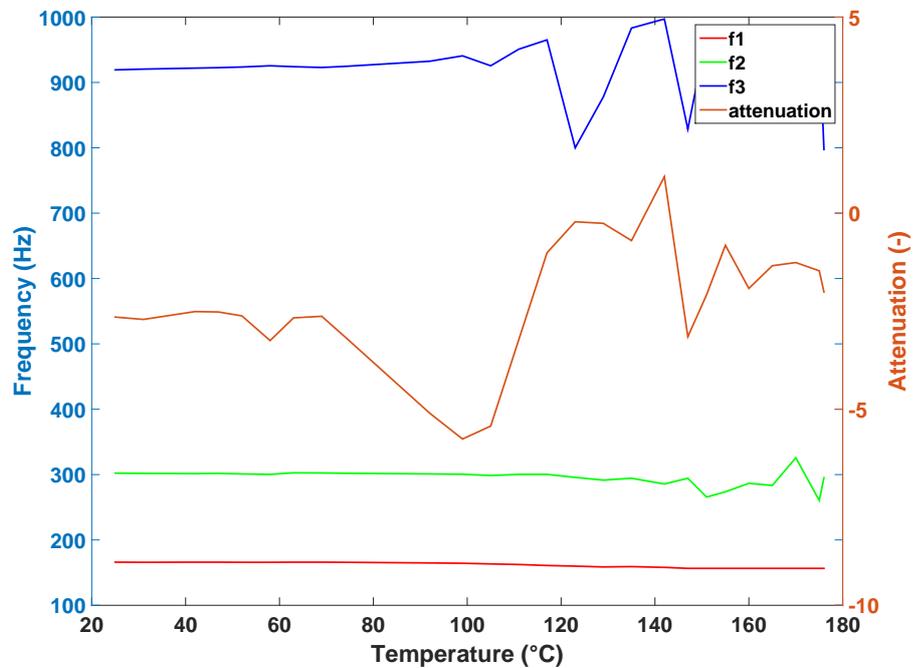
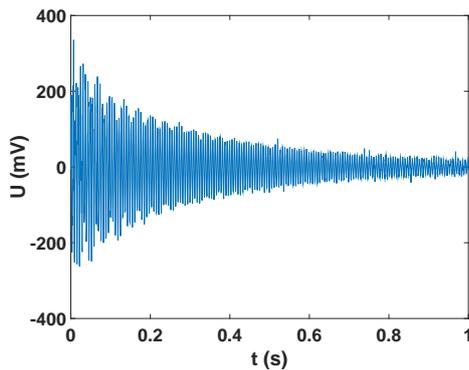


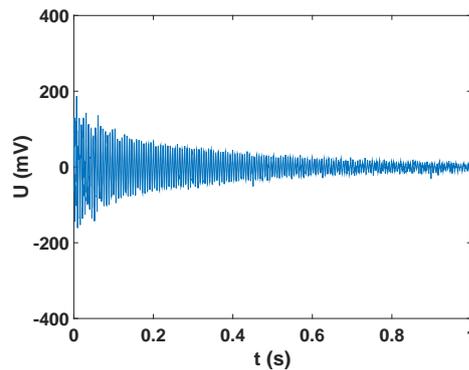
Fig. 8.6: Chart of different climate conditions

We made climate testing only in heated oven. This test was performed in temperature range from 25°C to 176°C as shown in the chart Fig. 8.6, where frequency of first natural frequency ( $f_1$  line) is almost unchanged in the whole range of measurement conditions. Second line ( $f_2$ ) is an now unspecified frequency peak at 300 Hz, probably is natural frequency of the frame. Its changes began at temperature around 140°C. Third frequency ( $f_3$ ) should not be here, it is mirrored from 1050 Hz. This fact is caused by undersampled signal, only 2 kHz sample rate, on testing equipment. This test was performed at time, when we were determining sampling frequency and method, how to get the most precise frequency (0.1 Hz resolution) of the first natural frequency.

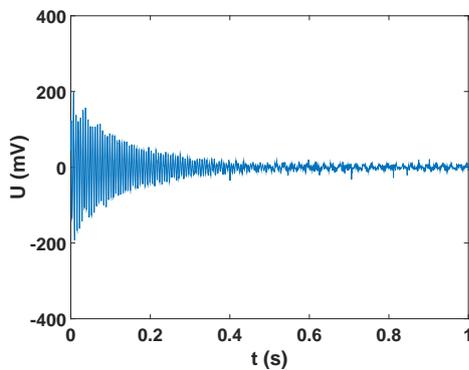
The frequency line  $f_3$  has began to change significantly at 100°C. This could be affected by the quality of glue hardening, at this temperature glass transition temperature of glue has been reached. The attenuation has been affected already at lower temperature of 75°C, then the attenuation is changed. Also signal level at temperatures over 100°C was quite low, so it affected frequencies as well as the attenuation.



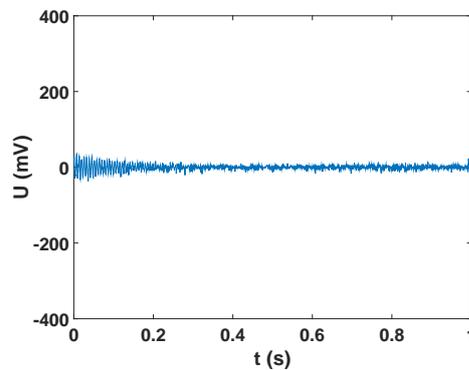
(a) Signal level at 25°C



(b) Signal level at 52°C



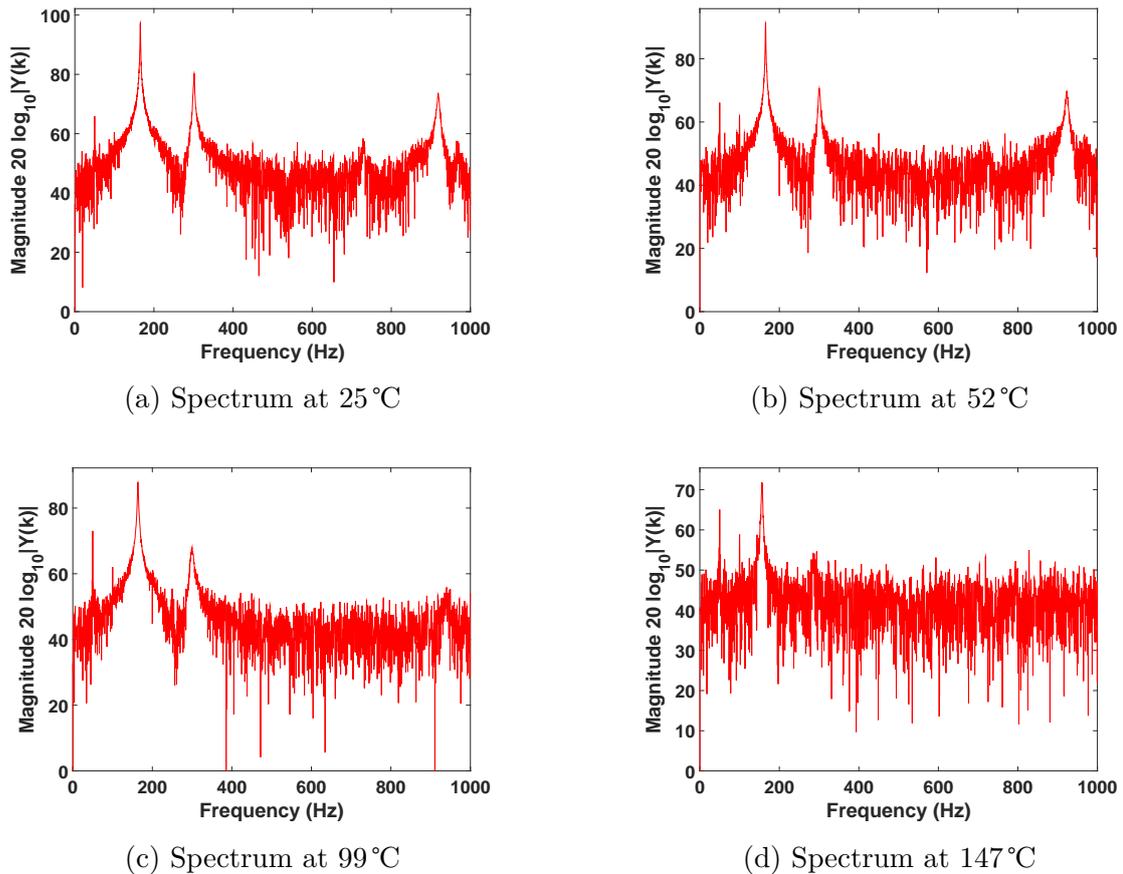
(c) Signal level at 99°C



(d) Signal level at 147°C

**Fig. 8.7:** Signal level comparison at different temperatures

In Fig. 8.7 are shown charts with different temperatures. It is quite certain, that at higher temperatures the signal is weak. The nanosatellite should operate probably up to 80°C, where signal is strong enough. Results over 90°C are useless, because of signal level. One of the possible solutions how to increase an amplitude is to prolong the pulse to the coil. In the Fig. 8.8 are shown spectra of signals mentioned above. At temperature 99°C and above the spectral peak at 970 Hz is suppressed and at 147°C the spectral peak at 300 Hz is suppressed as well.



**Fig. 8.8:** Spectrum comparison at different temperatures

Frequency peaks were searched in narrow band of spectrum, so the results in Fig. 8.6 at higher temperatures are random. Search ranges were basically established according to Tab. 8.1.

**Tab. 8.1:** Searching ranges of peaks in the spectrum

Line	Range
f1	120 Hz to 200 Hz
f2	260 Hz to 330 Hz
f3	700 Hz to 1000 Hz

## 8.5 Final Implementation

Final step of implementation was adding the operation system FreeRTOS together with CSP for further communication with OBC. All previous progress of implementation was divided into several functions depending on called function – computing attenuation, FFT, etc.

Further testing was performed on OBC emulator, which runs under Linux and communicates via serial port through development kit, where the data were translated into CSP packet and sent via I<sup>2</sup>C bus to the device, in this case HM board. This solution has the advantage that it is not necessary to have flight board of OBC for testing. There are some disadvantages as well, such as testing on real HW or communication with other boards such as measure board.

The implementation of functions to the chip of HM board was made according to the chapter 6.4, where tasks in dependence on communications ports are simply specified. Also, it was necessary to write code into OBC for communication with HM board. The code contains only start commands of specified actions, such as start measure process, get raw signal and etc. Data which can be saved are send directly from the board to the datakeeper and stored. Some measurements were performed and worked fine, for example sampling signal, receive data, temperature or final results.

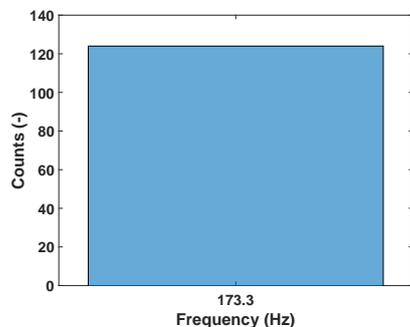
When the program is written, it is recommended to transfer data in network format – big or little endian to avoid a conflict with format. Then when data should be used, they must be decoded from network into board format. This could be a source of errors when the data are decoded.

## 8.6 Final Measurements Before Flight

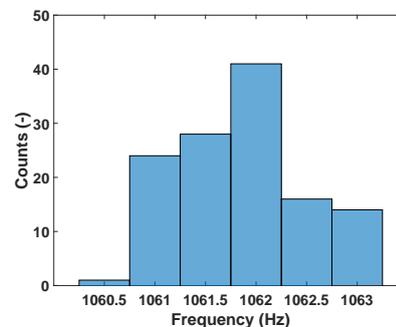
Before the final assembly of any board it is required to verify functions of the each measurement system. Verification of HM board and panel was performed in stable environmental conditions in VZLÚ in room with stable temperature, around 23.5°C and about 80% of relative humidity, with small oscillations of these values.

Many measurements in a row were performed in these conditions. Resulting spectra were similar to Fig. 8.1a and results of first natural frequencies were the same 173.3 Hz in all cases. The second natural frequency oscillates between 1 060.5 Hz and 1 063 Hz. Median of the frequency range is at 1 062 Hz.

Oscillations around this value are probably caused by the quality of the signal or noise in the spectrum which can be seen in the Fig. 8.1a. Histograms of these natural frequencies are in pictures in Fig. 8.9.



(a) Histogram around 173 Hz

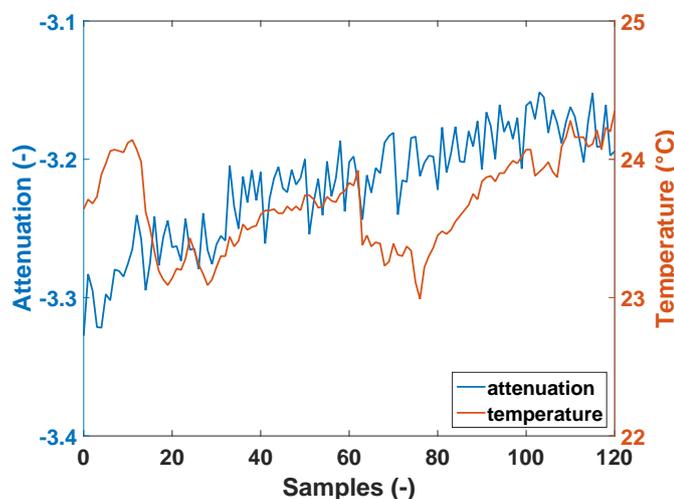


(b) Histogram around 1062 Hz

**Fig. 8.9:** Histograms of natural frequencies

Second examined parameter is the attenuation of signal. Their results were quite unexpected during a measurement in the same conditions. The attenuation is decreasing in absolute value according to Fig. 8.10 and it does not depend on the temperature. At the beginning of measurement, the temperature goes down and then up, but attenuation still goes down in its absolute value.

Maybe in case of more than 120 measurements, results could be same. Amplitude of signal at beginning and at the end of measurement is the same. This could be caused probably by changes of material after fabrication. This claim was not possible to verify during the finishing of this thesis, because another measurements have to be performed.

**Fig. 8.10:** Chart of temperature and attenuation in time

## 8.7 Conclusion

Many measurements were made. For example the tests in the oven included frequency and attenuation change depending on the temperature. Results of them were surprising. The value of natural frequencies do not change in dependence on the temperature. Value of attenuation, in this case, has changed at temperatures above 80°C (according to Fig. 8.6). For trustworthy results more measurements at one stable temperature should have been made than one as seen in the Fig. 8.10.

These measurements are very time demanding at least waiting to the right temperature, another problem is computing time of signal processing in the chip and also the download of signal of each measurement. This time was estimated to 27s per one measurement (estimation is based on previous measurements of 120 samples).

Also it would be good to know the characteristics of the whole satellite and how to affect the resulting spectrum of sensed signal. If the construction of the probe produces another natural frequencies, the piezo should show it in the case of strong signal. The MCU must be prepared for each situation to solve it by setting parameters of measurement. These tests will be performed in September 2015, unfortunately after finishing this thesis. Also the probe will be tested in the whole range of operation temperatures and climate conditions.

## 9 Conclusion

The small satellites from CubeSat family are useful for University teams to build them for their "low" price. Probes have a quite great portfolio of basic products such as OBC, power systems, solar panels, chassis, etc. Teams can use these products or develop their own, but must observe some specification like dimensions, weight, etc. From this point of view a new technology for further missions can be developed.

During this mission sensors, materials and devices will be tested in space conditions. For example testing carbon-fibre material for radiation shielding, mechanical quality and evaporation from the material. Another example is verifying the Lobster Eye optics together with Medipix/Timepix detector, which detects X-ray radiation from the stars, but mainly from the Sun.

This master's thesis *Measurement of changing mechanical properties of carbon composite on nanosatellite miniCube mission QB50* describes one of the many ways, how to measure Young's modulus of elasticity for verification of quality of any material. In this case natural frequencies were gained using FFT and from them modulus of elasticity was retroactively calculated.

Additional parameter is a damping factor (attenuation). It serves to better specify a model of HM panel using FEM and for computing of all parameters retroactively and with a greater accuracy.

The whole measurement process in HM board is controlled by the main Microcontroller which has to communicate with other boards, mainly with OBC. This connection must be perfect and reliable, because when it fails, the measurement cannot be started anymore. Same requirements apply for assembled parts on the boards. They also must be robust enough to resist radiation from space and in some cases low or high temperatures. For mission on low orbit these conditions are not so strict, but they should be observed for further missions, where worse conditions then on low orbit may occur.

Tests of reliability of communication with OBC were performed on many commands which were sent to the MCU on the HM board. Responses were positive almost every time, but once had happened that HM board stopped to communicate and had to be rebooted. This was performed by switching power supply off and then on again. After this step the MCU communicated normally.

This could happen during an unexpected situation on the bus by coincidence,



which could cause the error. From this point of view it is required to implement detection to prevent this state, use Watchdog or another way to ensure the stability of operation. For a space mission it is necessary to implement any system to prevent every hazardous state. When any system is not programmed and if board will not respond, it will be disconnected from power source and then connected again. After that, board should work normally. Some of the reasons why board could not work properly include a damaged chip, memory, losing connection with OBC, unplugged piezo or coil and also damaged wires.

When this state happen, it is recommended to change plans of reservation time and power for the experiment to zero. This could save a little power for running experiments or for what else is needed. During this state it is possible to test the communication from time to time and to determine if the results are correct. If this is true, the plans can change and again include the board which previously did not respond properly.

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# A Schematic of the board

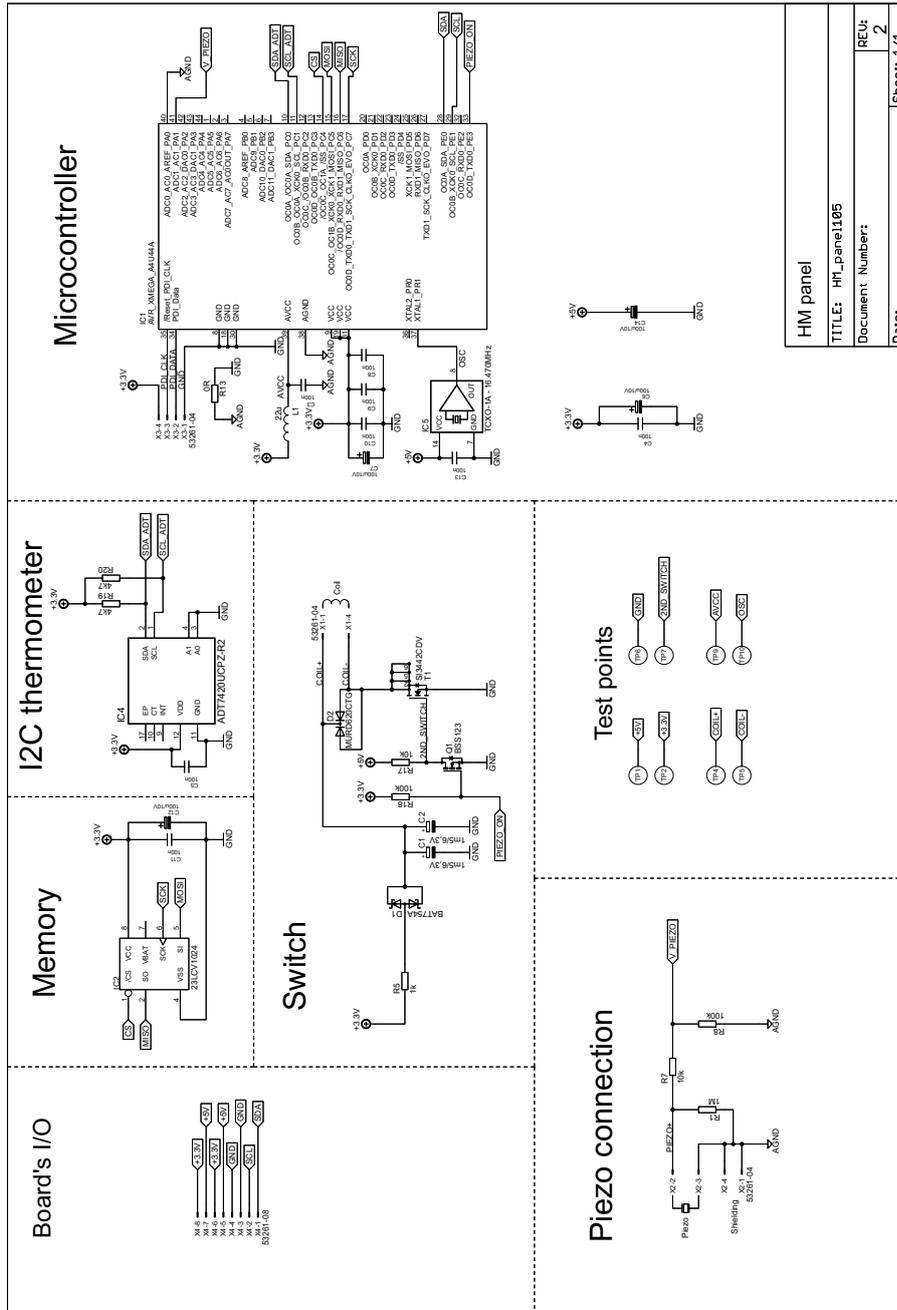


Fig. A.1: Schematic of power switch



## B HM board

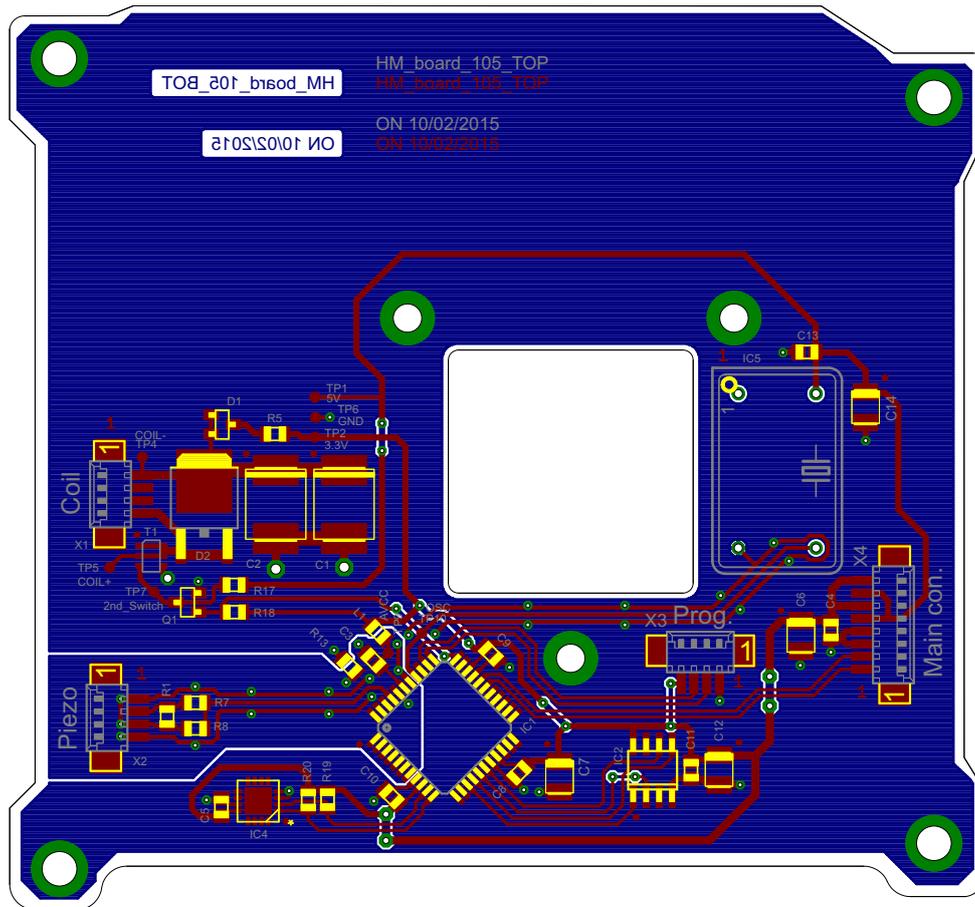


Fig. B.1: HM board

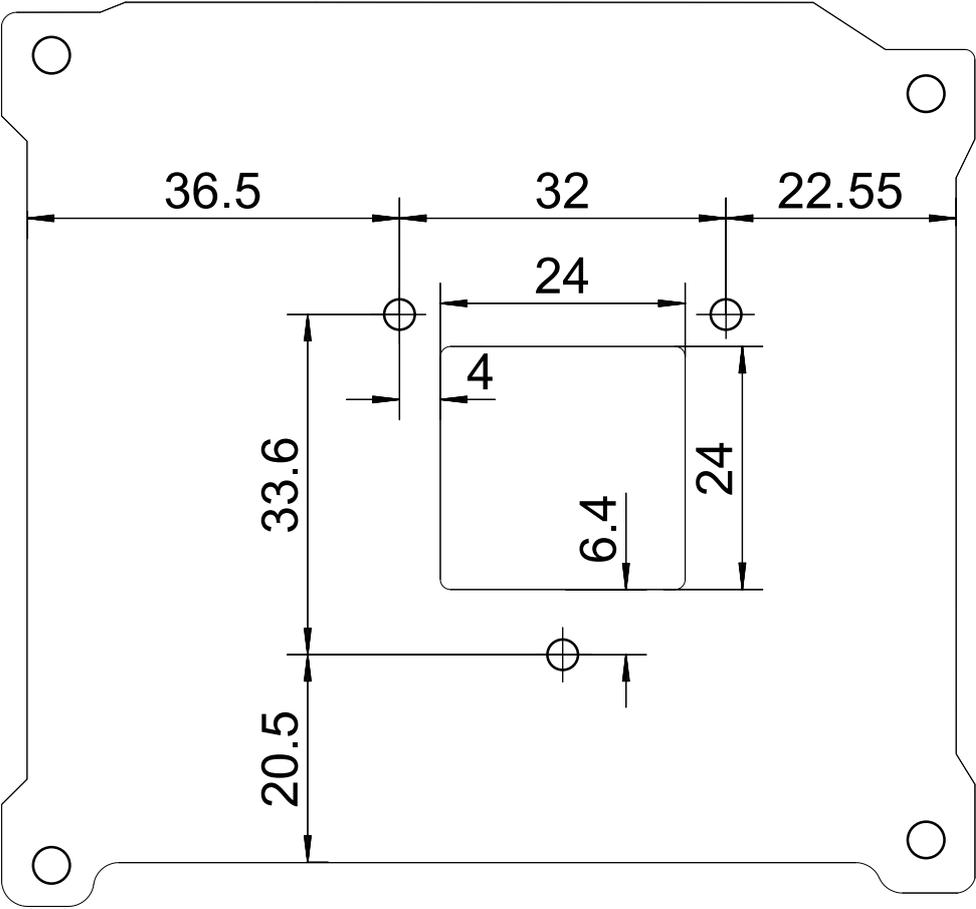


Fig. B.2: Dimensions of HM board

## C Article from Japan

# Measuring carbon fiber aging on orbit

*Bc. Martin Urban<sup>1</sup>, Bc. Veronika Stehlikova<sup>1</sup>, Bc. Ondrej Nentvich<sup>1</sup>,  
Ing. Ladislav Sieger, CSc.<sup>1</sup> and Kazuo Yana, Ph.D.<sup>2</sup>*

<sup>1</sup> Czech Technical University in Prague, Prague, Czech Republic

<sup>2</sup> Hosei University, Koganei City, Tokyo, Japan

**- Abstract -** This paper describes the outcome of internship at the faculty of science and engineering, Hosei University in summer 2014. The goal of the project is to design a measuring system of aging properties of a carbon fiber reinforced composite in space. The project is a part of the nano-satellite project at Czech Technical University in Prague, scheduled to be launched in 2016. The measurement environment in space is different from the standard measurements performed on the ground in laboratory. The system design specification has a large constraint in size, weight and power consumption by the limit of space probes. To meet these requirements, the basic measuring system of the mechanical damping characteristics of the carbon fiber composite is designed in this internship project. A damping oscillator to simulate the response of the target material has been assembled and measuring parameters are optimized. The optimized algorithm has been implemented in the chip to be launched on the space orbit.

### I. PROJECT QB50 AND PROBE VZLUSAT1

During our internship at Hosei University we were working on CubeSat project QB50 concretely on the probe VZLUSAT1. This project runs under the auspices of Czech Aerospace Research and Test Establishment (VZLU) and Czech Technical University in Prague (CTU). In this project also cooperates many other companies, for example, Rigaku Innovative Technologies Europe, s.r.o., 5M s.r.o., TTS s.r.o., Innovative Sensor Technology s.r.o., DENTEC and with many other individuals and specialists.

The goal of it is to carry on the orbit a nanosatellite, which will perform diverse experiments. The QB50 project relies on building satellites of defined measures, based on cubes 10x10x10 cm, which can be combined up to three cubes in a row for one probe this time. In the future should be constructed bigger satellites up to 2x2x3 units. Their conformity allows to carry a large number of different probes to the orbit together. The reason of the project's name is, that there will be space for 50 units of two cubes (2U) standardized units aboard. One of each 2U have to had maximum power supply up to 2 Watts and up to 2 kg.

The philosophy of this project is, to make a path for cheaper and easier manufacturing of satellites in the future. To build and carry a satellite to the orbit is not a cheap thing, so it is the reason why even on high-end projects are still used old verified materials and technologies. They simply are proved by time and the project sponsors

do not want to risk using any new and untested parts, due to which the whole project could crash.

Compared to these large, separate projects, the SpaceCube program offers an opportunity for lots of scientist, who need to test something new on the orbit without risking lots of funds. These small satellites are carried on next to a main standard satellite, a little bit like a stowaway, which is the carrier primary used for. So these nanosatellites like SpaceCube are depending on projects of standard space research, without the possibility of an independent start. As a small satellite, it does not have own active power also.

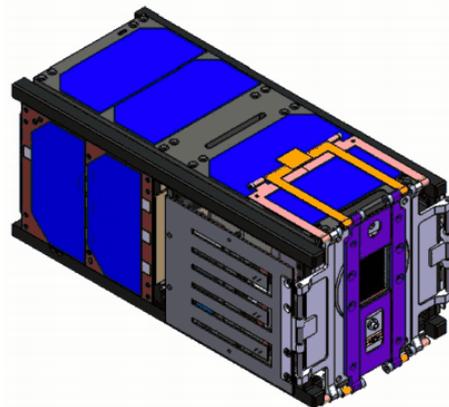


Fig. 1: Appearance of the cube sat VZLUSAT1

In general, the main part of people working on SpaceCubes recruits among the college students and their mentors. It is a chance to work on an interesting project with a possibility of future extension. It is our case too. After the launch, we will cooperate with University of west Bohemia, in Pilsen, where will be the headquarters for communication with orbit. We will get the raw measured data from them that we will process into final results.

## II. VZLUSAT1 IN GENERAL

Project VZLUSAT1 carries ten experiments in total. These experiments have various aims. There are two main tasks on the satellite. One tests a new carbon fiber reinforced composite panel with metallic coating made by 5M and TTS companies for utilization on space probes from the perspective of strength, weight, radiation shielding, durability and evaporation, the second one is Wide-angle X-ray imaging system.

Examining of this composite panel could lead to verification of suitability for this kind of material, which, if it pass, could be used as shielding material for standard satellites e.g. GPS and communication satellites, etc. in the future. Naturally, due to the rising popularity of this cheap nanosatellites like type QB50, this proved material could be used for producing standardized parts of skeleton and shielding for them too. It means an advantage for future experimentators, who will be able to fully concentrate to their research itself, without solving questions of construction and shielding.

Wide-angle X-ray imaging system with Timepix detector is a special type of lens, which works with reflexivity instead of refractivity.

Because the probe doesn't have active engine, there are at least coils for all three dimensions, which will slightly orient the probe in dependence on Earth's magnetic field.

One of next parts of measuring is measuring of humidity. There will be several sensors in the probe, which are connected with the main computer through I<sup>2</sup>C. The computer has to be programmed to switch between desired sensors and get measured values.

Last but not least of our tasks is measuring of space radiation and shielding capabilities of composite panel. The probe will have three measuring diodes aboard and they will be shielded by none, one and two layers of composite. This task

is complicated due to low sensitivity of diodes in case of high temperatures, and cooling in free space is hard to solve. There also is a problem with additional radiation from inside, from irradiated construction of probe; there will be not only measured signal from space, but this unwanted radiation too. It is necessary to try to separate both environments or subtract it for relevant results.

Space cube carries also many other tasks. For example, there will be sensors for measuring temperature in different parts of probe, or humidity sensors (made by Innovative Sensor Technology s.r.o.), which will measure vaporization rate of tested composite during transition from atmosphere to vacuum. These tasks don't have so high importance and due to the power limitation of whole device they run only when main tasks are switched off, like in case of Timepix doesn't look into the Sun. That means, all tasks are sharing processor time as in time multiplex and have solar and backup battery power together.

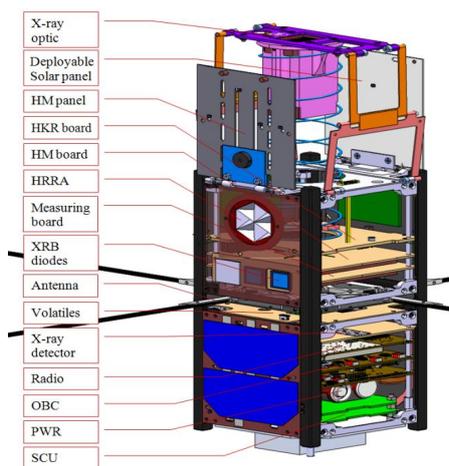


Fig. 2: Measuring boards and inner arrangement

Measured data will be sent to the headquarters in Pilsen when the probe will pass over Czech Republic. It will be approximately twice to day. The speed of data transmission will be changing as well as the time go. Data amount depends on where the probe will be and how long can communicate according to height of orbit where the probe will be. The height of the orbit will reduce over time and data speed will be slower. Due to limited volume of data which is possible to send, is necessary to process raw data on orbit and let to the Earth arrive only results.

Carrier with our VZLUSAT1 will start January 2016 from Brazil, with an Ukraine rocket. It will be brought to low orbit, 350 km high. Then it will collect data at least two month. It depends on how lucky will the probes be during the launch, in case of a great starting angle, it could work half year too. Of course, there are many other possibilities, which can involve lifetime of satellite. It is not sure how well will it deal with temperature changes on orbit, with radiation exposure and other unexpected conditions. Whole time it will send data to the Earth and in the end, space probe will burn in atmosphere.

#### INTERNSHIP AT HOSEI

##### I. SUMMARY

Our work comprises technical solution of measuring aging of carbon fiber reinforced composite, and as an usual projects at CTU, it is quite complex. It begins from theory, mathematical and physics modeling and working out the tasks in simulation programs. Then there is a part of trying to apply proposed resolutions on testing facilities, only to check the possibility in real situation. Simulations, include these with high sophisticated software, still cannot cover the entire range of possibilities that may affect the device as a whole. If the device on a breadboard or testing board works, a printed circuit board proposal follows. Last task is to assemble the final version, last testing and then the device can come to mass production or to science use, as in case of our probe.

##### II. MAIN GOALS OF OUR EXPERIMENT

Whole our work was divided into several parts following one after another. First we had to design printed circuit board for main measuring. This is first step because one testing board must be produced and proved in many tests before the launch. At the moment when design was completed we can start design and write a program for measuring changes in the resonant frequency (due to composite aging).

The main goal is to create and write a program for microcontroller which will measure signal with unknown frequency in range 100-200 Hz (composite material's resonance frequency) by Fast Fourier Transform with the highest possible accuracy in frequency and resolution approximately 0.1 Hz. Another purpose is

calculating exponential envelope damping factor. Microcontroller should be able to communicate with on board computer (OBC) via I<sup>2</sup>C interface. Next goal is measuring temperature by I<sup>2</sup>C thermometer, radiation and evaporation.

Measuring evaporation other gas from the material will ensure by five humidity sensors. These sensors are not only sensitive to humidity but also on some other gases which may be released from the material. To check the will be placed several different types of sensors in the probe. For these sensors was necessary to design the PCB (Printed-Circuit-Board) too.

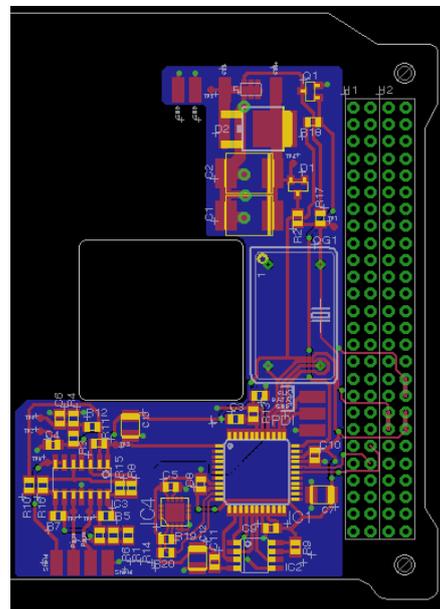


Fig. 3: Printed circuit board for the measurement

##### III. INPUT SIGNAL

Input signal is measured by piezoelectric element glued on composite plate and has approximately exponential envelope modulated by material resonance frequency. Exponential envelope is caused by attenuation in the material. Useful signal length depends on attenuation, which is caused by physical dimensions and material properties in the material and amount of energy excited by coil. In the picture fig. 4 is shown one example of input signal. Measured real signal has total length 0.9 s.

Input signal is sampled by 8 kHz. In case of computing attenuation (envelope) is used all signal for the better resolution in time. This signal is averaged by moving averages. Smoothed result is logarithmed and attenuation is directive of the course.

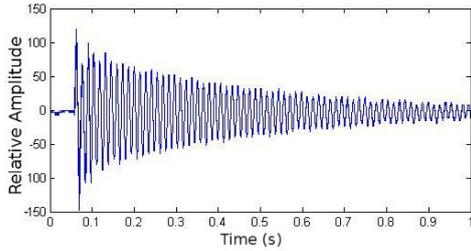


Fig. 4: Measured real damped signal

Resonance frequency is computed from decimated original signal using Fast Fourier Transform. If we use only FFT on the original signal we can calculate only with 1024 points (length of window) because we are limited by memory size installed in the probe. Computing by this process has final resolution more than several Hertz. What is a reason why we used decimation from 8 kHz to 500 Hz? The result of resolution is sufficient for us up to 200 Hz and sample frequency 500 Hz passed Shannon-Nyquist sample theorem with enough reserve.

This theorem says minimal sampling frequency must be two times higher than maximal measured sampled frequency.

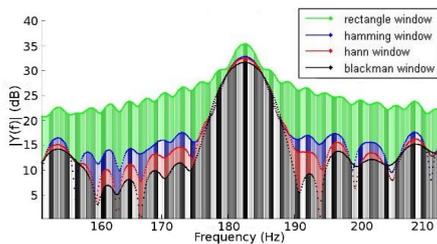


Fig. 5: FFT results with window length 4096 samples and different types of windows

Results for FFT with signal sampling 500 Hz and window length 1024 are better than previous one, resolution is 0.5 Hz, but it is still not enough. (Required is approx. 0.1 Hz.) This limit of

calculation allowed us to save memory and to use larger window. We made interpolation with help of adding zeros behind the signal into expanded window with window length 4096 points. Resolution of the decimated signal to 500 Hz with these calculation parameters is approx. 0.12 Hz according to formula (1). Implemented measurement in the program aboard the probe, must sample signal just only once, so it leads to choose higher sampling rate and then apply decimation on signal to requested sampling rate. All these computations were simulated in MATLAB.

$$\Delta f = \frac{f_s}{n} \quad (1)$$

#### IV. CALCULATION PROCESS

Main process consists of several functions. Here is a brief list:

##### Sampling and storing data

The analog to digital converter included in microcontroller could sample signal up to two million samples per second. So it leads to averaging four-points groups to eliminate glitches. All data are stored into SPI SRAM memory from which are further loaded.

##### Computing damping envelope

First what is needed to do is to perform mathematically absolute value to get one sided envelope. Next step is logarithming signal because it is needed to get attenuation, which represents  $b$  in exponential expression as shown in formula (2). Then is applied moving averages to smooth signal and computing directive using least squares method.

$$f = A \cdot e^{-bt} \quad (2)$$

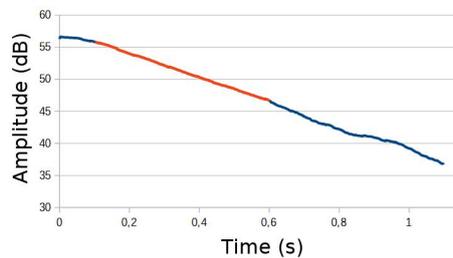


Fig. 6: Attenuation computed by least squares

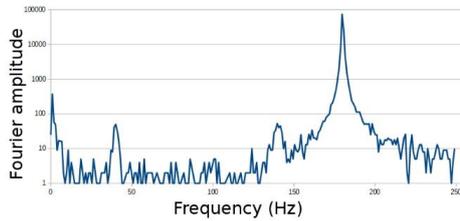


Fig. 7: FFT result by development kit

**Computing Fast Fourier Transform**

It is known, that resonance frequency of new material is in range 100-200 Hz so the signal sampled by 8 kHz must be decimated to 500 Hz to observe condition of the highest accuracy in frequency. FFT algorithm decimation in time is calculated in two steps. First step is to swap sampled points according to address which is bit reversed and next step is calculating Fast Fourier Transform. Program performs decimation and bit-reversing simultaneously. Program chooses one point and stores it to the bit-reversed address into SPI memory. Right address positions are stored in the table. Computation process picks up two points from memory, performs FFT algorithm and stores new points on the original positions. After that program finds the highest peak which corresponds with resonant frequency.

**Store results into memory for further dispatch to the Earth**

Results of attenuation and resonance frequency are stored into internal EEPROM memory of microcontroller for further dispatch to the Earth. Memory can include data amount which corresponds 40 hours of recording and hold data also after power loss.

**V. FUNCTIONALITY VERIFICATION**

During writing a program for development kit was necessary to check all functions. It leads to create device which one generates approximately the same signal as it gets from oscillations on the probe. With this idea came professor Yana who provided us draft of schematic, which is redrawn by Eagle software illustrated in the picture fig. 8.

The circuit produces oscillations with exponential envelope. To the circuit must be connected external oscillator as input of the board.

The board consists of some parts as monostable gate, output is connected to analog multiplier through capacitor which produces exponential envelope. To the multiplier is also brought external oscillator. Both inputs are multiplied in integrated circuit AD633. Output is connected to adder with another input from potentiometer which provide DC offset. Output of the board should be DC shifted in range +/- 15V. The board has power supply +5V and converted to +/-15V through DC/DC converter. Output voltage damped oscillations depends on voltage of oscillator and envelope.

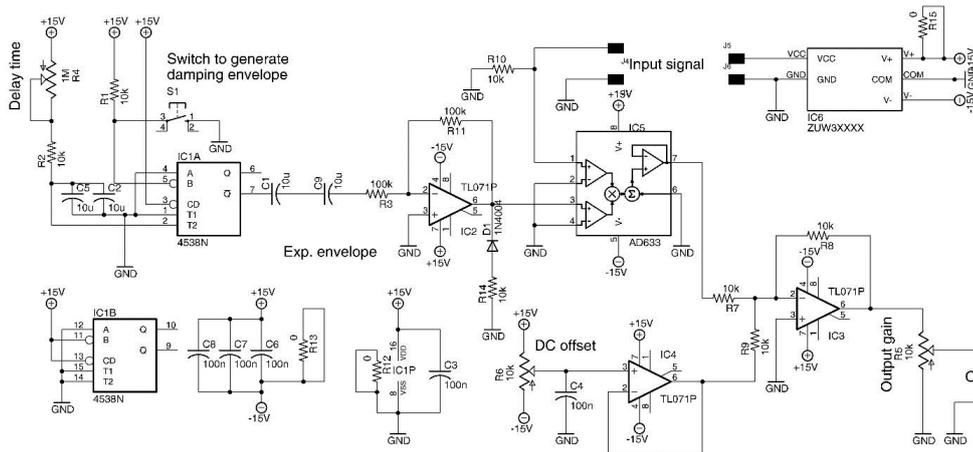


Fig. 8: Damping exponential envelope generator - schematic

Final board is in the picture fig. 9. Professor Yana was benevolent and arranged produce at manufacturer who create some pieces of boards which we assembled from parts who gave us. We are very pleased to create and then testing on it damping oscillations measured by development kit.

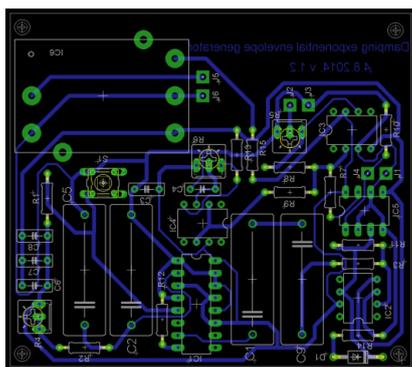


Fig. 9: Damping exponential envelope generator – Printed circuit board

The whole board was assembled and tested under supervision and technical assistance of Mr. Saitoh and Mr. Iki. They kindly provided us their laboratory with all necessary equipment like oscilloscope, signal generator or soldering station. Final assembled board is in the picture fig. 10.



Fig. 10: Assembled damping oscillator

## VI. CONCLUSION

During our internship we collaborated mainly with professors Kazuo Yana, Gaku Minorikawa and Akira Yasuda. These professors helped us to realize internship and during the whole summer helped us not only with the project but with staying in Japan too. Thanks to them we have progressed with our project and got great experience of Japan too.

Project VZLUSAT1 with cooperation VZLU consists of many measurements. One is measuring of material aging in the space. Measurement consists of exciting carbon fiber reinforced composite material by coil and measuring

vibration by piezoelectric element. Damped signal with exponential envelope is sampled by microcontroller and then are calculated resonance frequency and damping factor. Using mentioned process is possibly to get final frequency resolution approx. 0.12 Hz. Every results as resonance frequency and damping factor as humidity and radiation are stored into memory and then are dispatch to the Earth during contact twice per a day.

Space probe CubeSat with name VZLUSAT1 will be launched in January 2016 and is funded by grants Technology Agency of the Czech Republic TA04011295 and TA03011329.

## ACKNOWLEDGEMENT

Authors wish to thank Professors Minorikawa, Ohsawa with the department of Mechanical Engineering and Professor Yasuda with the department of Electrical and Electronic Engineering, Hosei University for their encouragement. Authors also wish to thank Mr. Saitoh and Iki with the department of applied informatics, Hosei University for their technical support.

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## CONTACTS

M. Urban, [urbanm24@fel.cvut.cz](mailto:urbanm24@fel.cvut.cz)  
 V. Stehlikova, [stehlver@fel.cvut.cz](mailto:stehlver@fel.cvut.cz)  
 O. Nentvich, [nentvond@fel.cvut.cz](mailto:nentvond@fel.cvut.cz)

## D Content of DVD

Folder structure of attached DVD:

```
Root/  
├─ Datasheets/  
├─ PCB/  
├─ Samples of signal/  
├─ Matlab files/  
└─ Nentvich_Ondrej_Diploma_Thesis.pdf
```