PROJECT RC ACCELEROMETER

B. Bojkow, T. Djalilov, K. Teymurov, D. Loef, Sz. Letkiewicz, V. Kulić Golja
Group 11

Abstract
This paper focuses on the design process and performance of an accelerometer intended to measure the acceleration during collisions of a remote controlled car.

Introduction

An accelerometer is a device that measures the acceleration of motion, or vibration, of a dynamic structure. Remote controlled cars, often implement an accelerometer to detect impacts and collisions remotely, in case the vehicle would be damaged when beyond the view of the driver. By sensing the amount of dynamic acceleration, the device provides the driver with the necessary information, about the state of his car. For this application, the accelerometer requires some specific characteristics. Firstly, the accelerometer must be mobile and provide a digital output that can be relayed to the driver in real time. Secondly, the driver must know the severity of the collision and with what acceleration his vehicle has collided. Consequently, the accelerometer must be amplitude range of $\pm$ 2g force swings, as the car may experience sudden starts and stops [2]. Lastly, the device must be compact and lightweight so that the performance of the car remains unaffected when attached to the vehicle. To keep the design compact, the accelerometer should not exceed 15x15x15cm and weight more than 600g as, the performance of the RC-car will suffer significantly beyond that point. Table 1 shows the design specifications.

Variable	value	unit
Amplitude range	$\pm$ 19.61	m/s^2
Total mass	600	g
Dimensions	15x15x15	cm
Mass of frame (M)	140	g
Spring constant (K)	1373.2	N/m

Table 1: Design specifications and parameters

Design and analysis

Accelerometer unit

The design of the capacitive accelerometer was inspired by MEMS[1], due to their small form factor and weight. The unit consists of a mass M that experiences a displacement x with respect to the frame inside which it is suspended, when subject to an acceleration a_{frame}. In between the frame and the mass, a differential capacitor is located, to measure the change in capacitance as the mass moves. Instead of using traditional coil springs to mount the mass, four doubly-clamped cantilever beams are used to suspend the mass 1mm above the underside of the frame, to prevent static friction. Cantilever beams were chosen, because their dimensions directly influence their spring constant. Consider Fig 5 as reference. The motion of the system, can be described by the 2nd order differential equation 1, where K is the spring constant, and D is the damping constant.

$$\frac{d^2x}{dt^2} + \frac{D}{M} \cdot \frac{dx}{dt} + \frac{K}{M} \cdot x = -a_{frame} \tag{1}$$

Since the device is designed to measure the acceleration of single, fast occurring collisions, the assumption can be made that the system is not time dependant. Therefore equation 1 reduces to a linear relation between acceleration and displacement shown in equation 2.

$$x = -\frac{M}{K} \cdot a_{frame} \tag{2}$$

To keep to the small form factor, the capacitor plates were limited to 18x18mm aluminium sheets of 1mm thickness. As a result, per the generalized equation of a parallel plate capacitor $C = \epsilon \frac{A}{d}$, the distance d was kept to 2mm, so that the output ranged at a sensible (pF) order of magnitude. This limited the displacement x 2mm. In addition, a dense material was desired for the mass due its high mass and low volume. Copper and brass blocks, as shown in table 2, were considered, whereas a mass of 140g brass was chosen due to availability at the TCO workshop. Using these values and the desired amplitude range, the spring constant was calculated to be 1373.2 (4x343.3) using equation 2. With the design parameters, the damping coefficient D at which critical damping occurs, can be determined using equation 3. The type of damping is not a crucial aspect of the accelerometer, as it aims to measure the acceleration during the impact and the peak amplitude in a step response is not dependent on the damping type. However, a critically or over damped system would be more beneficial, because it would provide addition information accurately.

$$D = 2M\omega_n = 2\sqrt{KM} \tag{3}$$

To achieve critical damping D = 27.3Ns/m, consider Fig 1 showing the system's simulated frequency response and Fig 2 showing the simulated step response.

[1] Microelectromechanical systems

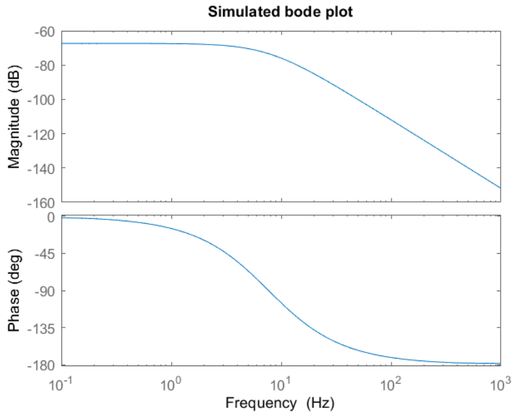

Figure 1: Simulated bode plot for the mass-spring model at critical damping

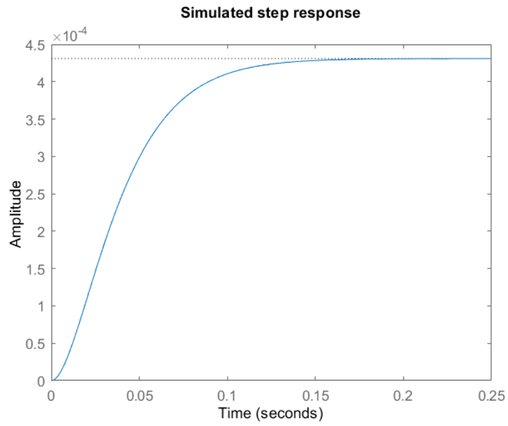

Figure 2: Simulated step response for the mass-spring model at critical damping

To create springs with the desired spring constant, the material and dimensions of the beams need to be considered. Table 2 shows the evaluated materials. All three considered materials are filaments for a 3D printer, as the springs require precise dimensions. Ultimately, Thermoplastic Polyurethanes (TPU) 65D, was chosen as it is the most flexible of the three options. Consider Fig. 3 illustrating the behaviour of the beams.

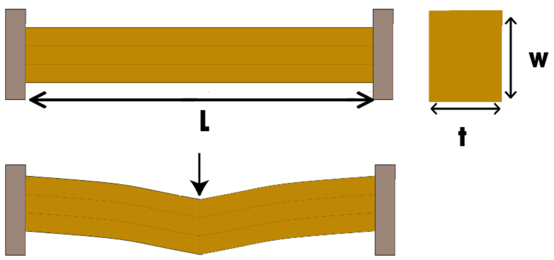

Figure 3: Schematic of a doubly clamped cantilever beam, in stationary state and under pressure with labelled parameters

The beams can be described using equations 4 and 5, where E is the material's Young's E-modulus, L is the length of the beam, w is its height and t the thickness.

$$K = 4 \cdot \frac{3EI}{L^3} \tag{4}$$

$$I = \frac{1}{12} \cdot w \cdot t^3 \tag{5}$$

From the design of the differential capacitor, the length of the beam is set to 24mm and the height is 18mm. However, determining the E-modulus is more complex, as the material's hardness is provided by the manufacturer in the sheer scale. The conversion between the two values is described in [4] and has an error margin of 25%. This error has a significant impact on the system's damping, however as mentioned above, the damping is not of significant importance of the application. For that reason, a was omitted from the design. Using the conversation, the E module is found to be 6.99 MPa, and thickness is calculated to have a value of 10mm.

Component	Considered material
Mass	Brass
	Copper
Spring system	TPU 65D
	TPU 80A
	PETG

Table 2: Considered materials for certain components

Electronics

The electronics section of the accelerometer focus on measuring the capacitance, converting it to acceleration and transmitting it to a computer. To measure the capacitance, three positively charged plates are spanned over the mass, with two small plates on both sides and at either ends of the plates. This creates a differential capacitor consisting of 12 individual capacitors. Each capacitor on one side of the three plates is wired in the C_1 series, whereas the the remaining plates form the C_2 series. As the mass moves, causing an increase in capacitance on one of the series, the other decreases respectively. The two analogue inputs are recorded by the Arduino Uno, where the highest capacitance is used as the measurements. With this interface, the direct proportionality between the output voltage and the displacement a_{frame} is evidence [1], which can be used to get equation 6.

$$a_{frame} = -\frac{K}{M}x = -\frac{K(C_1 \cdot C_2)}{M(C_1 + C_2)} \tag{6}$$

With the use of equation 6, the Arduino Uno was programmed using Arduino Web IDE to convert capacitance reading to acceleration, and offset it to 0 acceleration at standstill [3]. This reading is sent to a ESP8266 WIFI Board Module, that uses a 18650 battery 3.7V 6800mAh as a power source. The battery also has a holder, a charging module and a two pin On/OFF switch to control the device. The WIFI module, is used to transmit the data from the Arduino, through *Blynk* services, directly to a phone. Once again, to retain the small form factor, all the electronic components are attached to a two 5x7cm copper Perfboards and mounted below the accelerometer unit. Fig 4 illustrates a rendered model.

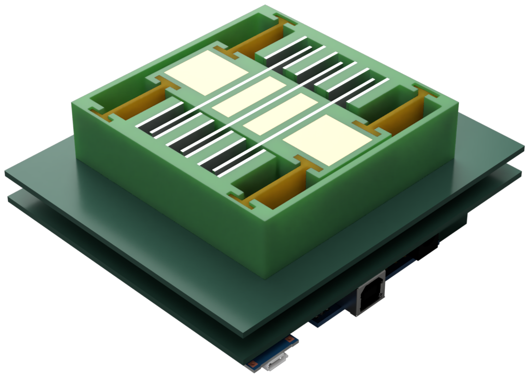

Figure 4: Render of accelerometer unit, and electronics without outer casing

To house the design, an outer casing consisting of PLA with acrylic panels on the top and button is used to house and protect the accelerometer. This housing is 13.0x10.7x7.0cm.

Realization

Table 3 displays component list and budget.

Component	Total	Price
Arduino Uno	1	22.35
18650 Battery 3.7V 6800mAh	1	3.31
18650 Battery holder	1	0.50
18650 Battery charger module	1	1.04
ESP8266 WIFI Board module	1	3.13
Brass	120g	0.74
Aluminium sheet (10x10cm)	2	1.45
PLA filament	300g	10.00
TPU 65D filament	50g	3.00
2 pin ON/OFF switch	1	0.25
Jumper cables	20	2.27
Copper Perfboard (5x7cm)	2	0.98
Connector pins	20	0.48
M3 screws	4	0.12
CA glue	1	0.78
Total		50.40€

Table 3: List of components

Due to the complexity of precise dimensions of the design, a flexible method of manufacturing was chosen, 3D printing. The schematic shown in Fig 5 was modelled in Fusion 360 where the frame, mass holder and outer casing were printed using polylactic acid (PLA). PLA was chosen because it is a sturdy yet lightweight material. The building technique for the metal components, was cutting them to size using the machinery available at TCO. Furthermore, the electronics were soldered to the perfboards and wired using connector pins and jumper cables. Lastly, CA glue was used to mount the capacitor plates and acrylic in place, four screws were used to close the casing as well. Sourcing the components and assembling the accelerometer is feasible as the components are widely available. The difficulty is accessing the equipment required to manufacture the unit, the capacitor plates and the mass. Specifically, the 3D printer and metal cutting machinery.

Characterization and discussion

To test the performance of the accelerometer, a static and dynamic characterization were conducted. To measure static behaviour, the device was mounted in a horizontal beam. Then a protractor ($\pm$5%) was used to measure the rotation of the beam, causing the accelerometer to tilt. Fig. 6 shows the change in acceleration with tilt angle.

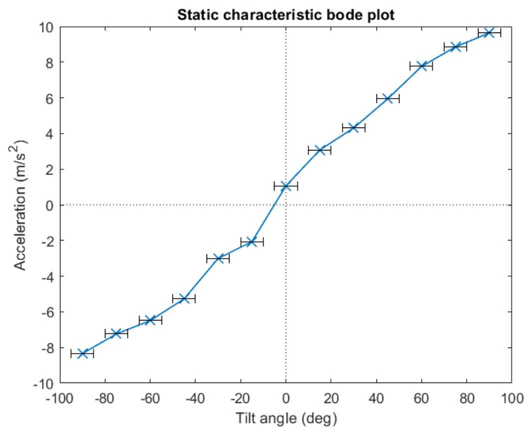

Figure 6: Static behaviour measurements of accelerometer tested on 05/07/2022

Since the accelerometer is not moving the and the force of gravity is the only acceleration acting on the mass. As a result, a linear trend from -9.81 to 9.81 m/s^2 passing through (0,0) is expected. A linear trend can be seen from Fig 6, however the acceleration reads approximately 1 m/s^2 when there is no tilt present. From maximum tilts, it also looks like the acceleration is offset by 0.80 m/s^2. A reason for this result could be an error in the assembly, or an incorrect offset value in the programming. For the dynamic behaviour measurements, a bipolar operational power supply/amplifier (KEPCO) set to 100mV output and arbitrary waveform generator (Agilent 33220A) with varying frequency, were used to power an electro-dynamic vibration exciter (MB electronics PM-50), to which the accelerometer was horizontally mounted. A frequency response was then created by plotting the amplitude against frequency, shown in Fig 7.

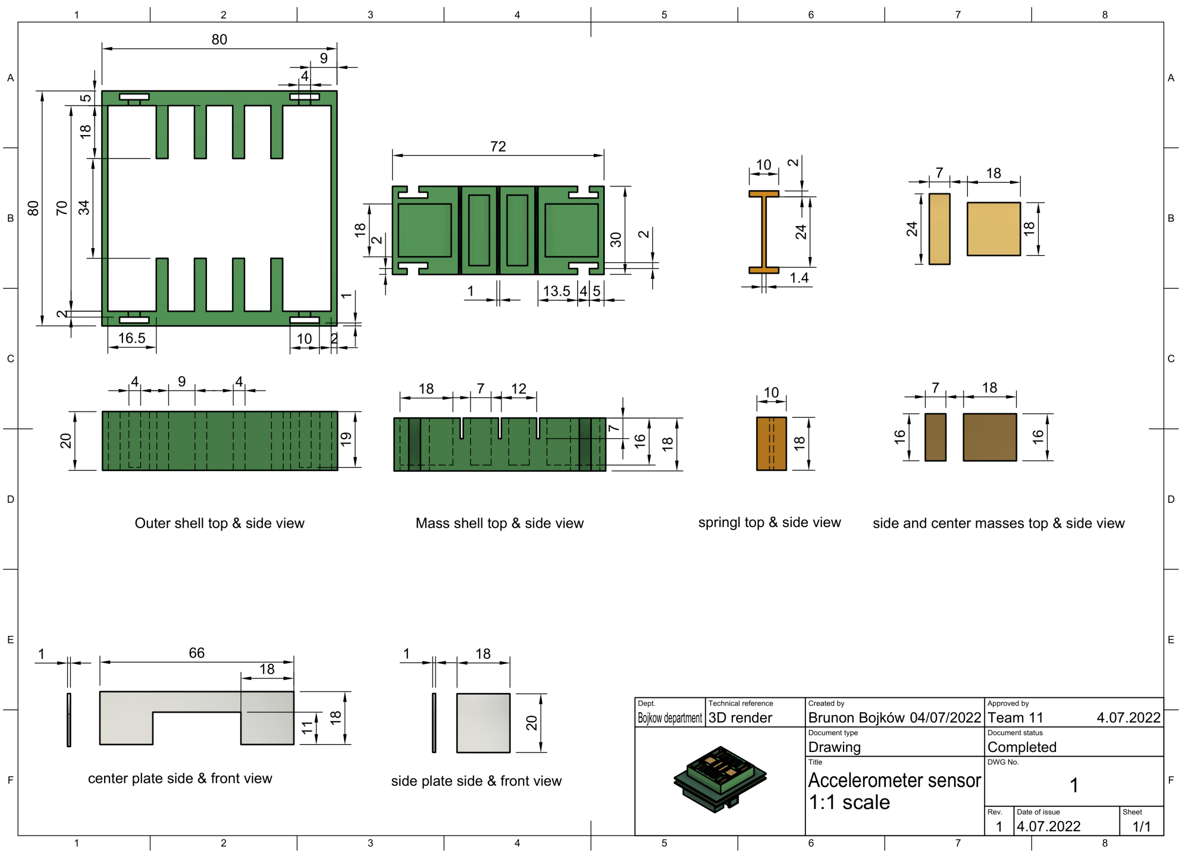

Figure 5: Schematic of accelerometer unit design with dimensions

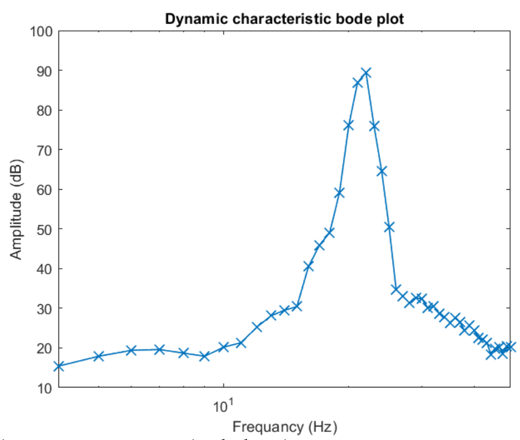

Figure 7: Dynamic behaviour measurements of accelerometer tested on 05/07/2022

At first glance, it can be seen that the system does not behave as expected. The system is clearly heavily under damped, at a damping factor of ζ 0.012. According to the conversion from sheer hardness to Young's E-modulus, can have a 25% error, it is not the reason for error. In addition, Fig 7, suggests that a bandwidth of 1 - 50 Hz is present. In comparison to 1, it can also be seen that the frequency ω_n is at 22Hz instead of 10Hz. Lastly, the observation can be made that the sensitivity of the system is 200mV/g. Nonetheless this observation is not very accurate, as the system experiences an unexpected change in acceleration when in proximity to a conducting material. This is due to the jumper wires creating an electric field that impacts the capacitance reading. To avoid this issue, zero resistance wires should have been used.

Conclusion

The does accelerometer meet the physical build specifications such as dimensions, mass, wireless and amplitude range. In addition, it measures the acceleration to a $\pm$ 0.80 m/s^2 accuracy. Despite that, the system is more under damped than foreseen. In the future, the accelerometer could be improved by revising the damping of the system. Another beneficial improvement would be using zero-resistance cables instead of jumper wires. Lastly, the offset used in the programming could be revised to improve the static readings.

References

[1] Giuseppe Ferri, Francesca Romana Parente, and Vincenzo Stornelli. Current conveyor-based differential capacitance...sensing application. *AEU - International Journal of Electronics and Communications*, 81:83–91, 2017.

[2] Freescale Halbleiter Deutschland GmbH. Accelerometer Terminology Guide, May 2007.

[3] jon. PIC Tutorials - Capacitance Meter Mk II, January 2014.

[4] Kent Larson. Can you estimate modulus from durometer hardness for silicones? 09 2017.