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Modelling the effects of impact shock in a MEMS sensor

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Abstract

MEMS (micro-electromechanical system) sensors are part of our everyday life, they are present in our smartphones, earplugs, smart watches, also being part of the critical systems of our cars. The constant advance of technology makes them smaller and more sensitive. This also results in decreased robustness and resilience against the sudden high forces of an impact. However, impacts may be part of the lifecycle of the sensors, as they might fall off the production line, people drop their phones with them inside, or they can experience a car crash. By correctly modelling the propagation of the impact shock in the sensor package, the evaluation of the impact robustness of the sensor becomes possible in an early phase of the design.

In this study, I examine the case of dropping a simplified MEMS sensor on the floor, investigate the propagation of the impact shock and its effect on the sensor structure. Because of the quick timescale of this process, I simulate it with an explicit finite element software. It is demonstrated that the effect of the impact on the structure depends highly on the angle of the sensor before drop and the material characteristics of the floor. Aiming to create a simple and generally applicable (for many materials and configurations) model, I engage in fitting a transfer function for the shock propagation in the sensor package.

Moreover, I also investigate the possibility of exciting the eigenfrequencies of the micrometer-scale structure with a microsecond-scale impact. That is, whether resonance can cause failure of the structure during or after the impact.

Absztrakt

A MEMS (micro-electromechanical system, mikro-elektromechanikai rendszer) szenzorok mára mindennapjaink részét képezik, ott vannak az okostelefonjainkban, fülhallgatóinkban, okosóráinkban, de az autókunk kritikus rendszereinek is fontos részét képezik. A technológia folyamatos fejlődésével a szenzorstruktúrák egyre kisebbek és érzékenyebbek lesznek, az ütközésekkel, hirtelen behatásokkal szembeni ellenállóságuk csökken. Ütközéseknek pedig számos esetben ki vannak téve a szenzorok, például autóbaleset során, illetve leeshetnek a gyártósorról, vagy leejthetjük őket a mobiltelefonunkkal együtt is. A sokk szenzorházban való terjedésének helyes modellezésével lehetőség nyílik a szenzor ütésállóságának értékelésére és javítására már a tervezés korai szakaszában.

Dolgozatomban egy egyszerűsített MEMS gyorsulásmérő szenzor padlóra történő ejtését vizsgálom, az ütközés okozta sokk terjedését, illetve a szenzorstruktúrára gyakorolt hatást. A folyamatot a gyors dinamikára való tekintettel explicit vége-seleemes szoftverrel szimulálom. A struktúrára gyakorolt hatást erősen befolyásolja a szenzor ejtésének szöge és a padló anyaga. A sokk szenzorházon keresztüli terjedésére transzfer függvényt illesztetek, amelynek a célja a minél általánosabban (különböző anyagokra és konfigurációkra) alkalmazható, egyszerű modell megalkotása.

Ezentúl megvizsgálom azt is, hogy lehetséges-e a mikroszekundumok alatt lejátszódó ütközéssel egy mikrométer skálájú egyszerűsített szenzorstruktúra sajátfrekvenciáit gerjeszteni, azaz rezonancia okozhatja-e a struktúra tönkremenetelét.

1 Overview

1.1 Introduction

MEMS (micro-electromechanical systems) sensors have become part of our everyday life, they are present in our smartphones, smart watches, earphones and other gadgets. MEMS accelerometers and gyroscopes help in our navigation, monitor our fitness activities, and also enhance mobile gaming experience. Even safety features are based on accelerometers, some smart devices can detect a car crash and automatically call for aid [1].

They are also important parts of many systems in our cars, for example monitoring the engine and the power train rotational velocities and vibrations. MEMS accelerometers are also used in automotive safety systems, detecting car collisions, providing the signal, e.g., for the deploying of airbags.

In all of these applications, above all in the critical safety systems, it is absolutely necessary to ensure that the sensor remains operational during the entire lifetime of the system. However, the delicate sensor structures are prone to fracture because of their small size and the brittle silicon material they are made of. This is especially so, as even smaller and more sensitive sensors are demanded by the market.

Regarding MEMS sensors, it is worth noting that Bosch Group and more specifically the specialized company Bosch Sensortec is the market leader of the sector [2] with several generations and many different types of sensors developed and marketed [3]. Simulation, measurement, and characterization tasks are also routinely carried out in Budapest. Since both the author and one of the supervisors are Bosch associates, there is a direct opportunity for the industrial utilization of the research results described in this study.

1.2 About capacitive MEMS accelerometers

MEMS accelerometers are based on a capacitive measurement principle. The sensor structures consist of masses and springs all fabricated from polysilicon, which is a material composed of monosilicon crystal grains of a few micrometers in diameter [3][4]. The masses are arranged asymmetrically, so that acceleration turns into a force on the structure, which through the springs is proportional to the displacement. Utilizing the capacitance change, the displacement and thus the acceleration of the sensor can be measured.

Usually, there are several sensor structures in a single sensor package. At least one is included for the three directions each, with additional ones for different measurement ranges. The typical range is a few g-s to a few tens of g-s.

MEMS sensors are packaged like IC (integrated circuit) components, and are soldered to a PCB (printed circuit board) for use. The type of these packages is mostly LGA (land grid array) in which the pins are located on the underside (called lands). They are soldered to the PCB in a surface-mount fashion. Because of their small size (few millimeters), manual soldering is unlikely.

Within the package, the sensor structures are contained in a silicon die. The whole package consists of an ASIC (application specific integrated circuit), a small PCB wiring, and the silicon die with the structures. The ASIC is responsible for preprocessing the measured signals, and the wiring connects the ASIC to the lands on the bottom of the package. All these components are encapsulated by a thermoplastic polymer “mold”. It is added to the package through injection molding, hence its name.

1.3 Fracture by impact

MEMS sensors have to endure many impacts during their life-cycle. They can be dropped from the product lines during manufacturing, they are dropped within smartphones and other devices. They even experience impact during a car collision. The possible drop event in the course of the manufacturing is especially important, as it might be the largest load the sensor experiences during its lifetime. Even though it has not even been deployed.

The sensor structures are composed of few micrometers wide components made of brittle silicon. Because of this, fracture during impact is a common problem. To create a structure that is able to withstand the effects of impacts, several simulation studies should be conducted throughout the design phases. Because of its importance in industry, the fracture of MEMS sensor structures is an actively researched area, see for example [5] and [6].

The sensors are always encapsulated in the sensor package which has a size on the order of millimeters, whereas the structure is on the order of a few tens of microns. So simulating the package and the structure together on a daily basis is infeasible, yet the effect of the package should be incorporated into the structure simulations. By understanding the propagation of the impact shock through the package and determining what exactly reaches the structure, adequate boundary conditions for the structure simulation can be formulated. That in turn helps making sensor design more robust.

To sum up, the aim of the presented research is to investigate the impact events, study how the shock propagates through the sensor package and find a way of conveniently modeling it. Moreover, it is also demonstrated, that in spite of the short time of an impact, the induced oscillations of the sensor can excite matching resonance frequencies of the structure components.

1.4 Employed methods

An impact is a dynamical problem with a very short timescale (few microseconds). Clearly, the inertial forces involved are also large. Consequently, explicit finite element method is preferred for simulation.

In this study, the explicit finite element software LS-Dyna [7] is applied, which is now part of the Ansys Mechanical software suite. Simulation is carried out through Ansys Workbench and Mechanical, whereas the results are postprocessed with both Mechanical, LS-Prepost and Matlab [8].

Explicit simulation requires no iteration, has no convergence issues. But, to ensure stability and physically correct results, the Courant–Friedrichs–Lewy (CFL) condition should be respected. This states that

$$\Delta t \leq n \frac{L}{c}, \quad (1)$$

where Δt is the time step size, L is the element size, c is the speed of sound, and n is a safety factor. Essentially, a traveling wave in the body should not be able to pass through more than one element during a time step. Consequently, the smallest element determines the time step. That is why a homogeneous mesh size is preferred without serious mesh refinements. Note moreover, that to avoid the need for costly matrix inversion, the mass matrix is always diagonal in LS-Dyna.

During an impact elastic waves will emanate from the area of contact and possibly travel back after being reflected on boundaries. This makes these problems harder to solve both by analytical and numerical methods. To avoid dealing with waves, the typical analytical

treatment of impacts involves modeling the bodies as rigid, connected by nonlinear springs. The nonlinear spring characteristic is then defined based on Hertzian contact theory. However, this assumes that the contact area is small compared to the contacting bodies [9]. This is the case, e.g., for large spheres. For a sensor package, however, this cannot hold. The whole underside of it can be contacting area and that is definitely comparable to the size of the body. Thus, because of the complex physics involved, an analytical solution of this problem is out of scope of this study, if not infeasible.

Regarding this study, it is also worth mentioning, that a measurement-based validation would be more than beneficial. However, it is not straightforward to carry out such a measurement, as the timescale is extremely short (about 5 microseconds). A fast camera recording is out of question for example. A laser-based measurement seems feasible, yet that would also need costly equipment and careful preparation. Many parameters are to be controlled, for example the impact angle and floor material along with the surface roughness. Thus, conducting measurement for validation remains a future opportunity.

2 The MEMS model

2.1 Package model

The investigated simplified package model has the outer dimensions of the commercially available Bosch Sensortec BMA456 accelerometer sensor [10]. It has a $2\text{ mm} \times 2\text{ mm}$ square base and a height of 0.65 mm .

The bottom of the package consists of a small PCB wiring with 5 layers: soldermask, copper wiring, core material, copper wiring, soldermask. These are modeled with 5 homogeneous plates on top of each other, neglecting the insulation between wires, neglecting vias, etc.. As it is clearly visible in Figure 1 (left), above the PCB, the silicon parts are covered by the mold. It provides protection and gives the package its form.

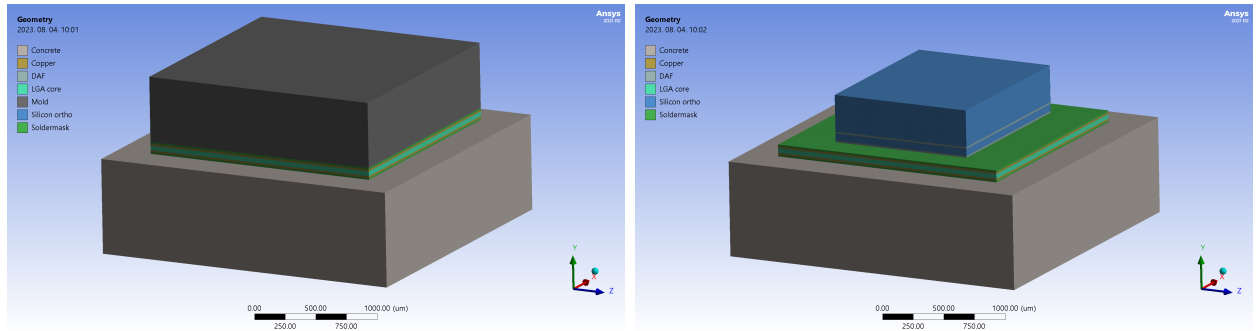


Figure 1: The simplified package model (left) and the same model with the mold hidden, exposing the silicon parts (right). The brown body is the concrete block representing the floor.

The silicon block just atop the PCB is the ASIC, responsible for preprocessing the sensor signals. In this mechanical simulation it is conveniently modeled by a simple block. Note moreover, that it is connected to the PCB by a thin layer of adhesive, commonly called DAF (die-attach film).

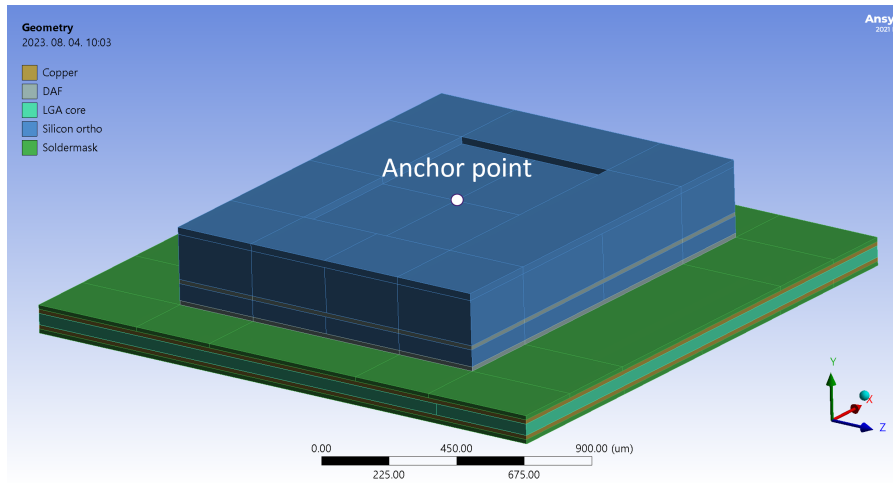


Figure 2: The cavity in the silicon die, that contains the structure (not modeled). During the simulations the behavior of the anchor point (in the middle) is of interest.

On top of the ASIC, again connected by a layer of DAF, is the silicon die containing the structure. Since it would result in a significant reduction in the explicit simulation time step size, the structure is not modeled. However, the cavity in which it would be situated is clearly visible in Figure 2. The structure would be connected to the silicon die through the anchor point, which is situated in the middle of the cavity (in this simplified model). Because of this being the connection point, the primary interest lies in determining the movement of this point.

2.2 Materials

In the model, all materials applied are linear elastic, and the silicon model is orthotropic. For the glues, the mold, and the polymer materials in the PCB a viscoelastic material model may be necessary. This seems especially important in case of the mold, because of its relatively large size and mass. Investigating the effects of viscoelastic models, however, is out of scope for this study.

The materials in the model are listed in Table 1. Note, that the properties of the polymer materials can vary significantly, so for this simulation reasonable values were used after consulting the material database Campus[©] [11].

Materials	Young's modulus	Poisson's ratio	Density
Mold	30 GPa	0.25	2000 kg/m ³
PCB core	20 GPa	0.2	2000 kg/m ³
Soldermask	3.5 GPa	0.3	1500 kg/m ³
Copper	130 GPa	0.35	8960 kg/m ³
DAF	3.5 GPa	0.35	1100 kg/m ³
Concrete	30 GPa	0.18	2300 kg/m ³

Table 1: The materials used in the model.

Silicon, arguably the most important material in the sensor, needs a different treatment. Because of the deposition process, the grains in the polysilicon material are directed approximately the same way, that is, the polysilicon material in the sensor will not be isotropic. Instead an orthotropic material model should be used [12].

An orthotropic material is one which has three orthogonal planes of symmetry. Silicon has three, and can conveniently be described by an orthotropic model. The orthotropic constitutive equation is

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix}. \quad (2)$$

The matrix is invertible and so computing stresses from strains is also possible. However, for the finite element solver, one only needs to input the moduli and the Poisson's ratios, which for the silicon used in MEMS are listed in Table 2.

E_x	E_y	E_z	G_{yz}	G_{zx}	G_{xy}	ν_{yz}	ν_{zx}	ν_{xy}
169	130	169	79.6	50.9	79.6	0.28	0.064	0.28
GPa						-		

Table 2: The orthotropic material properties of silicon used in this study [12]. The y -axis is vertical in the simulation, as it is shown in Figure 2.

2.3 Simulation setup

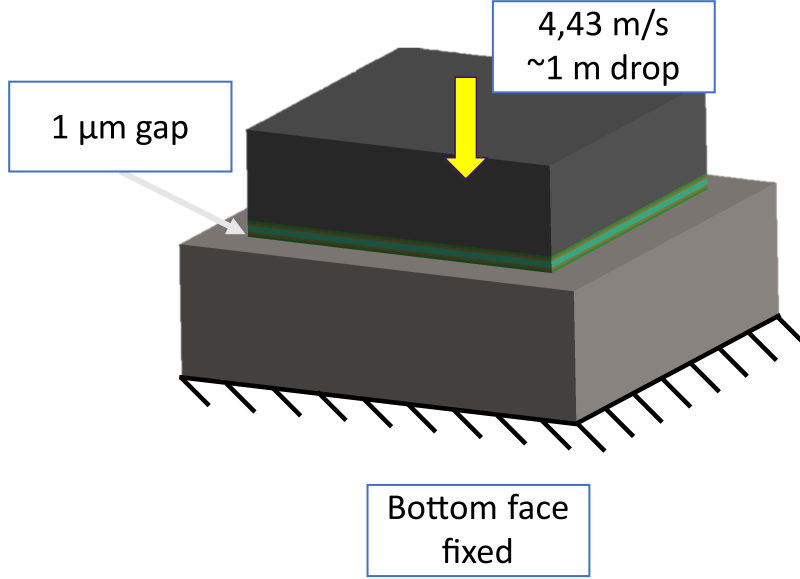


Figure 3: The simulation setup with the initial and boundary conditions.

The simulation is about the impact of the sensor package against the floor, which is represented by a larger block. The setup is depicted in Figure 3. The bottom face of the floor block is fixed. The whole sensor package has an initial velocity of 4.43 m/s corresponding to a drop from 1 m height. The contact between the floor and the sensor package is open at the beginning of the simulation, a gap of 1 micrometer is present between the bodies. This also means, that the impact will begin after

$$t = \frac{s}{v} = \frac{1 \mu\text{m}}{4.43 \text{ m/s}} = 0.226 \mu\text{s}. \quad (3)$$

The increase in speed because of the standard gravitational acceleration during this time would be

$$\Delta v = gt = 2.2 \mu\text{m/s}, \quad (4)$$

which is negligible. The two bodies are in contact for about a microsecond, then the sensor package starts to fly away upward.

Also, recall from Section 1.4, that the time step size is changed adaptively based on the CFL condition (1) and that the mass matrix is diagonal.

2.4 Mesh dependency

In case of explicit simulation a hexahedral mesh is preferred. One of the reasons behind this is that a hexahedral mesh needs less elements than a tetrahedral for the same body. This in turn means larger elements and thus larger time step size. Moreover, the element size applied to the floor body was significantly larger, because the primary interest lies in the sensor. So to say, the floor body is only there to affect the package.

The simplified sensor package model used in this study consists of rectangular bodies, so a hexahedral mesh is feasible, albeit needs some cut up of the parts. The main problem of meshing is the several connected bodies in the model. To achieve a conformal mesh for all the bodies in the sensor package, the mold body had to be cut up into 9 smaller rectangular parts. When the optimal cutup has been found however, the meshing became robust and predictable. Although, a rule of meshing inner bodies first had to be respected.

So hexahedral meshes were created with four different element sizes, as listed in Table 3. The coarsest mesh has a worse quality, as there are some skewed elements, but there are only a few of them present, so it is still an acceptable mesh. The other three meshes are excellent based on the Jacobian ratio measures. Note also, that the finest mesh has two elements for resolving the thickness of all thin plates (soldermask, copper, DAF layers).

Element size [μm]	Floor element size [μm]	Minimum Jacobian ratio	Number of elements	Simulation runtime
30	200	0.28217	152,280	37 s
20	75	0.96541	422,731	1 m 50 s
15	50	0.99854	883,866	7 m 14 s
10	30	0.99853	3,169,021	13 m 56 s

Table 3: Parameters and quality of the meshes.

The simulation results inspected for convergence are the following:

- Contact force between the floor and the package
- Anchor nodal velocity

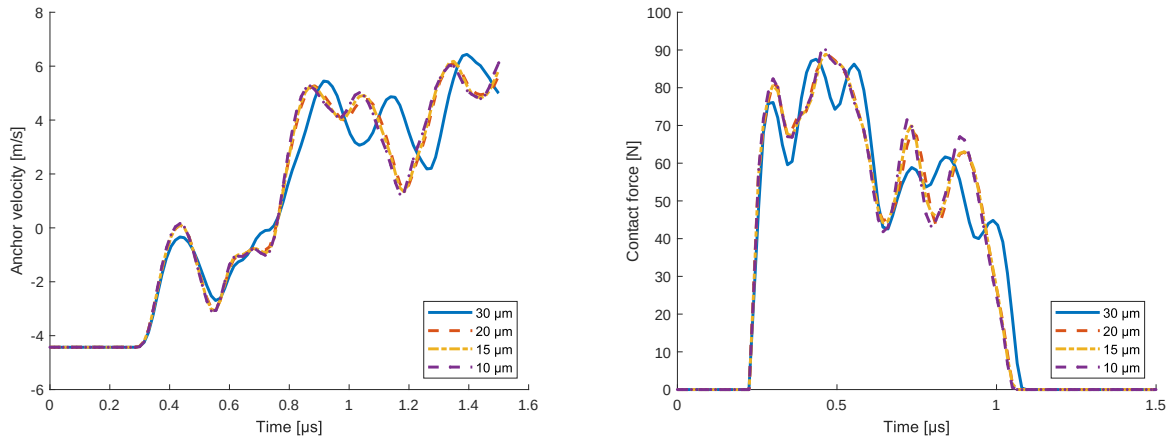


Figure 4: The velocity of the anchor and the contact force for 4 different meshes.

The anchor velocity is a better measure than the displacement, as the former has more features, and is also better than the acceleration, which contains a large amount of noise that would need filtering. Beside comparing these curves, a visual inspection of the deformation fringe plots was also carried out.

As it is visible on the plots of Figure 4, the performance of the 30 μm coarse mesh is poor, all the finer meshes show similar behavior. Although the finest mesh has somewhat more pronounced peaks in the contact force curve, it also takes a longer amount of time to simulate. The 20 and 15 μm meshes show a similar performance. The 20 μm mesh has been chosen, as it provides good results with significantly shorter simulation times.

2.5 Dependence on floor body

The aim of these simulations are to study the impact of the sensor package on the floor. In real life the floor is orders of magnitude larger than the sensor, it could reasonably be seen as infinite. However for the simulation, a small finite block should be used, so as to save memory and bandwidth during the simulation.

A finite block could be seen as equivalent to an infinite region if the strain waves emanating from the impact site and then turning backward on the boundary cannot reach back before the impact is over. That way, the boundaries have zero effect on the process of the impact, the finite block affects the impacting body the same way as an infinite region would.

For a concrete block of Young's modulus $E = 30 \text{ GPa}$ and density of $\rho = 2300 \text{ kg/m}^3$ the speed of sound is

$$c = \sqrt{\frac{E}{\rho}} = 3611 \text{ m/s.} \quad (5)$$

As it was already shown, the impact is over within $t_i = 0.8 \mu\text{s}$, that means the waves created at the beginning of the impact can travel a distance of

$$s = ct_i \approx 3 \text{ mm.} \quad (6)$$

Waves should travel both to the boundary and back, so between the edge of the sensor and the floor boundary there should be at least $s/2 = 1.5 \text{ mm}$. Knowing the sensor package width to be 2 mm, the floor block should be at least 5 mm wide and 1.5 mm high.

This analytical assessment being only a rough estimation, a small parameter study was carried out to find a suitable block size. First, the necessary width was determined, then the required height. The simulation parameters are listed in Table 4 and a picture for each of the concrete block versions is shown in Figure 5.

Case name	Block	
	width [mm]	height [mm]
Narrow	2.6	0.8
Wide	6.6	1.8
Wider	12.6	1.8
Wide & tall	6.6	2.5
Wide & taller	6.6	2.8

Table 4: Parameters of the four blocks used in the floor dependency study.

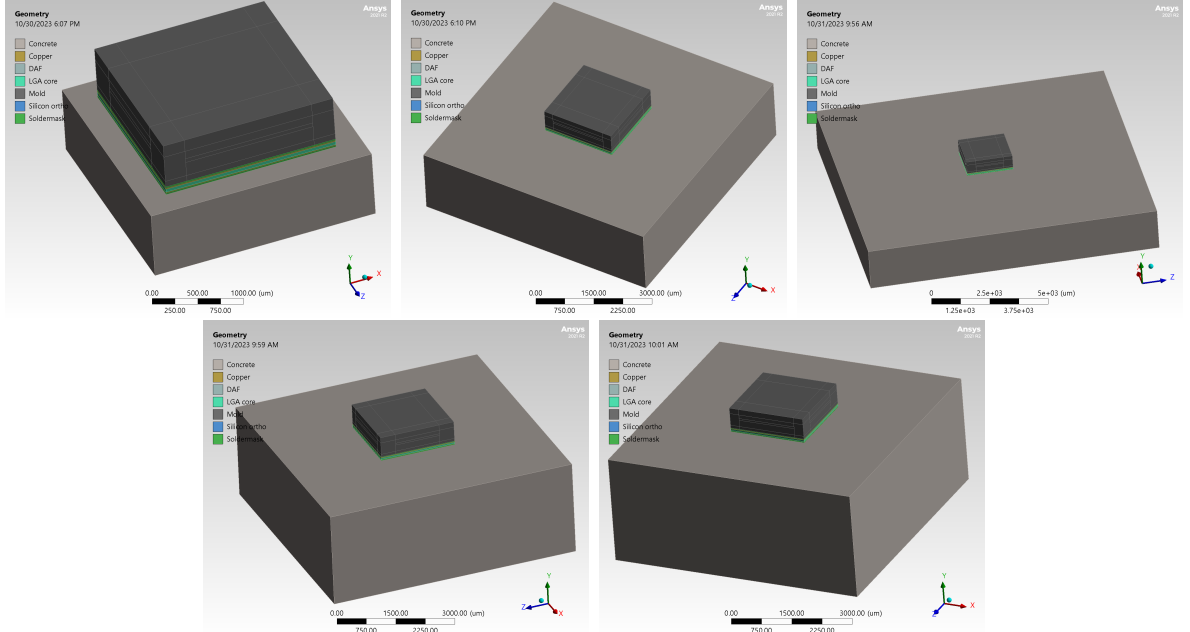


Figure 5: The floor block variants from left to right: *narrow*, *wide*, *wider* (top) and *wide & tall*, *wide & taller* (bottom).

In Figure 6 the time evolution of the nodal average velocity and the contact force is shown. The nodal average velocity is calculated by summing up the nodal velocities and dividing by the number of nodes. The main advantage of using the nodal average velocity is that it can easily be obtained from the simulation. Also, because of the homogeneous mesh size and the small strains involved, it is approximately equal to the volume-averaged velocity.

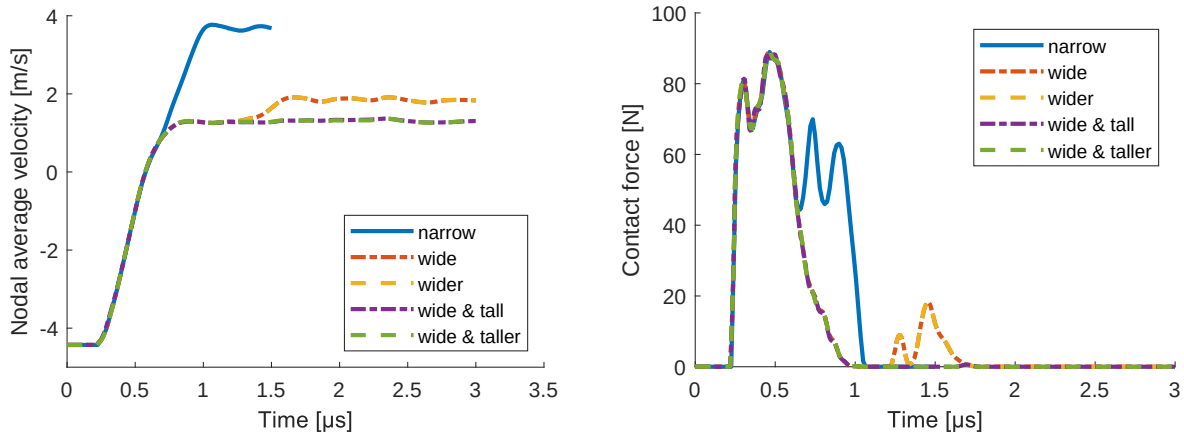


Figure 6: The nodal average velocity of the package and the contact force for different floor body sizes. Note how the *wide & tall* ones converge to a simple sigmoid-like function.

So, as it can be seen on the plots of Figure 6, the *narrow* version differs significantly from the others. The small concrete block takes away a smaller amount of the initial kinetic energy of the sensor package, so its nodal average velocity will be higher after the impact. By making the block wider, larger amount of energy is transferred into the block, resulting in lower average

velocity. There is also a jump in the *wide* and *wider* versions, which can be understood by taking a look on the contact force curves. Namely, after the main contact the block touches the package again, even though the sensor is already flying away upward. This phenomenon is caused by the waves created during the impact returning and inducing such a large deformation on the top middle of the concrete block, that it can actually reach the flying package. Nevertheless, by making the block taller, this after-bounce can be reduced and eliminated.

The *wide & tall* (6.6×2.5) version is used throughout the following chapters, as the larger blocks do not improve the results significantly.

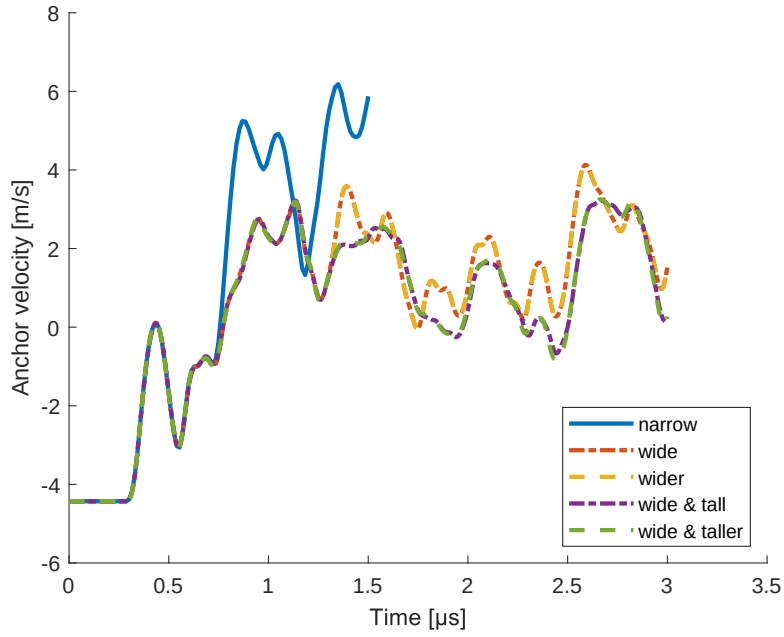


Figure 7: The velocity of the anchor for different floor body sizes.

3 Simulations

Several simulations were carried out to understand the behavior of the sensor package during and after the impact. Generally, the package falls until it reaches the block, they are in contact for $0.5...0.8 \mu\text{s}$, then the sensor flies away upward, while oscillating with a frequency of its own. In case of the floor, waves start out from the impact site, travel to the boundary then back. Because of the size of the block, they can no longer travel back in time to affect the sensor but they still participate in the oscillations of the floor block.

In this chapter, several parameters of the simulation will be changed to see their effect, including drop height, contact friction, impact angle and the material of the floor.

3.1 Drop height

The easiest parameter to change is the drop height, which is represented by the initial velocity of the sensor package. To see the effect of the drop height, three different cases were investigated. These are listed in Table 5 with the drop height, the corresponding initial velocity and the time required for the package to travel $1 \mu\text{m}$ distance. That is, to reach the floor at the beginning of the simulation.

Drop height	Initial velocity	$1 \mu\text{m}$ travel time
30 cm	2.4257 m/s	$0.4122 \mu\text{s}$
1 m	4.4287 m/s	$0.2257 \mu\text{s}$
3 m	7.6707 m/s	$0.1304 \mu\text{s}$

Table 5: Drop heights and corresponding initial velocities.

The anchor velocities in case of the three simulations are plotted in Figure 8 (left). They all look similar. Scaling by the corresponding final nodal average velocity and shifting by the time required for traveling $1 \mu\text{m}$ in each case results in the matching curves of Figure 8 (right). So, despite the nonlinearity introduced by the contact, the system exhibits linear behavior towards the initial velocity and thus the drop height. This indicates that a linear transfer function can indeed be a good model for the shock propagation in the sensor package.

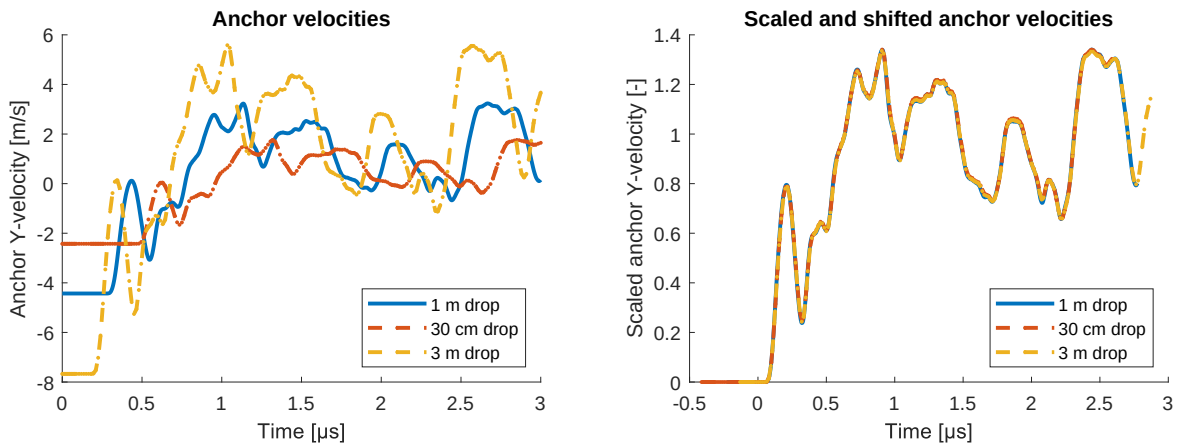


Figure 8: The velocity of the anchor for different drop heights. They all look similar to each other. A scaling and shift reveals how much they match.

3.2 Friction coefficient of the contact

Defining the contact between the sensor package and the floor is somewhat arbitrary, since no information regarding the friction properties of such contact was available from measurements. The obvious solution is to apply a frictionless contact. This has been done for all the simulations presented in other sections.

However, it is not easy to intuitively see just how much effect introducing contact friction would have on the simulation results. On the one hand, during the short time of impact, the contact surfaces can only slide a small amount, so the friction is small. On the other hand, the sensor package itself is small, so the dissipated energy might be quite significant. In general, friction is of prime importance in micromechanics and MEMS design, that is why the effect of the friction coefficient has been addressed.

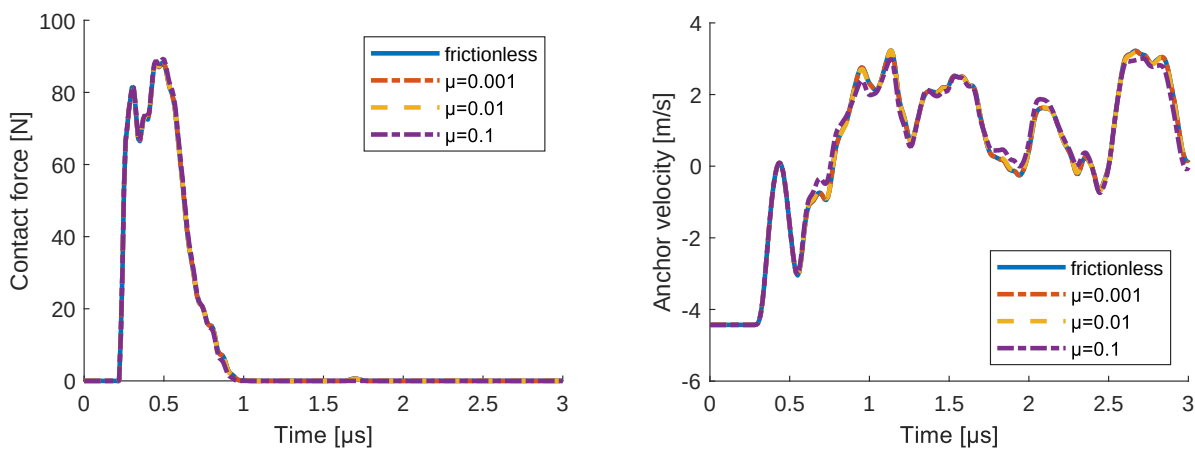


Figure 9: Time evolution of the contact force (left) and the anchor velocity (right) for contacts with different friction coefficients (μ). All four curves match closely.

Three different friction coefficients were evaluated along with the frictionless variant. Comparing the curves of Figure 9 one can conclude, that the friction coefficient has no great influence on the overall behavior of the package. However in a fringe plot of, e.g., the y-velocity, differences can be found. It is thus likely, that the friction coefficient would influence the anchor velocity more significantly, if the anchor was located closer to the sides. That is the case in most commercial sensors, that have several sensor structures for the three directions and for different measurement ranges. Nevertheless, in this simplified model, contact friction plays no important role.

3.3 Impact angles

In a real drop scenario, the sensor package would be somewhat tilted, its bottom face not parallel with the floor. It may even fall on another side or on one of its edges or vertices.

In Figure 10 the model configurations of three simulations are depicted. One is the standard version, the other has a 90° rotated package that contacts with one of its side faces, and the third is a 45° tilted variant experiencing edge contact. The corresponding contact force curves are plotted in Figure 11. The maximum of the contact force decreases with decreasing area, and the time of the contact is extended. Consequently, the most dangerous load to the sensor structure, which is located deep within the package, is clearly the standard configuration with

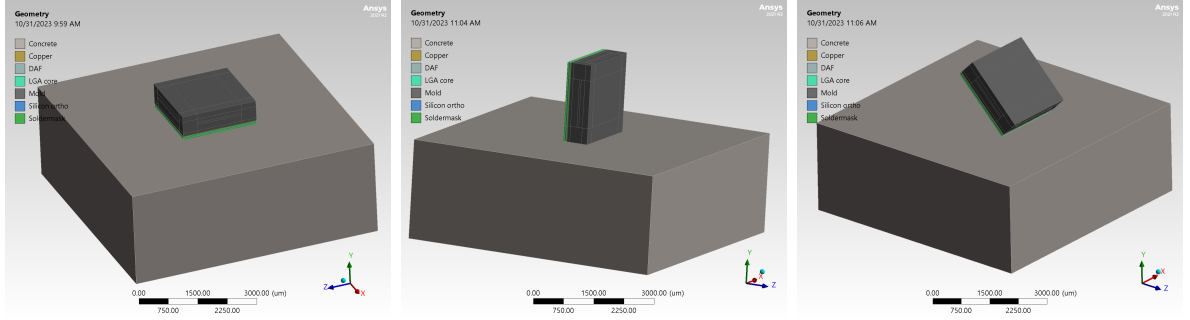


Figure 10: Models with tilted sensor package, contacting on bottom, side face and edge.

the largest force peak. So by having assumed bottom face contact throughout this study, the worst case was considered, at least from the perspective of the structure.

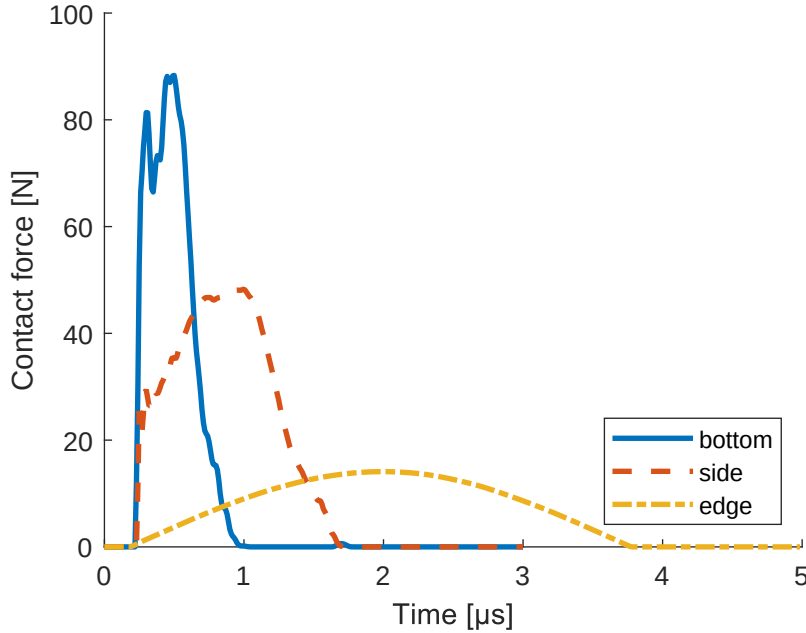


Figure 11: Time evolution of the contact force for three different configurations. The bottom face contact is the most critical, as it results in the highest peak contact force.

It is to be noted, that the edge and point contacts can and are known to damage the package. Small pieces can easily break off from the affected regions. Yet, the energy needed for that would be lost and thus wouldn't affect the structure. This further supports the theory that a large contact area is needed for sufficient effect.

3.4 Floor material

The impact greatly depends on the material of the floor. To build an intuition of this dependency, simulations with three different linear elastic materials were carried out. The applied materials and their parameters are listed in Table 6.

The nodal average velocity and anchor velocity curves from the simulations are plotted in Figure 12. It is clearly visible that the higher Young's modulus results in larger average

Materials	Young's modulus	Poisson's ratio	Density
Concrete	30 GPa	0.18	2300 kg/m ³
Steel	200 GPa	0.3	2300 kg/m ³
Glass	50 GPa	0.22	2500 kg/m ³

Table 6: The floor materials used in the study.

velocity after the impact, and also introduces some oscillations. The average velocities are approximately the same with a scaling, however, the anchor velocity curves are not scaled variants of each other. It seems reasonable to assume, that the difference in the floor material introduces a nonlinearity into the system.

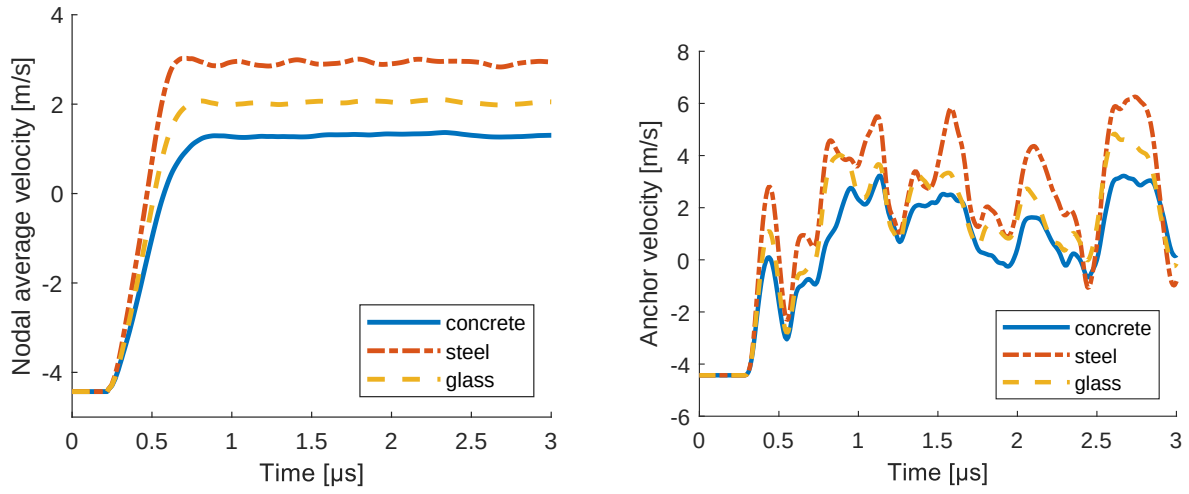


Figure 12: The average velocity of the sensor package (left) and the velocity of the anchor (right) for different floor materials. Nonlinear behavior is clearly seen on the anchor velocity curves.

4 Transfer function fitting

Since the sensor structure is much smaller than the package, explicit simulation of both needs an unnecessarily long time. However, to check the impact resistance of structure designs, the effect of the package should also be incorporated, as it is demonstrated in Section 5. Because of the small size of the structure, its effect on the package can be neglected. So one may simulate the package impact separately and export a characteristic quantity, which can be used as an excitation in the structure simulation. Moreover, to eliminate the need for the package simulation and thus make the design checks considerably faster, a relatively simple model of the effect of the package was developed.

4.1 Theory

To create a relatively simple and computationally fast model of the impact shock transfer in the package, suitable inputs and outputs need to be found.

The output was chosen to be the y -directional velocity of the anchor point (v_a). The acceleration and position curve was also considered, but the former was found to be too noisy, whereas the latter has few features and is dominated by the rigid body motion.

For the input, three quantities were taken into consideration: the average nodal velocity of the package $\bar{v}$, the contact force F_c and the average velocity of the bottom face $\bar{v}_b$. Each has its own advantages. Owing to its simple nature, the average velocity can easily be constructed intuitively knowing a Newtonian coefficient of restitution. Moreover, it could also be determined by a laser-based measurement. The contact force, however, is somewhat hard to measure, but could still more easily be modeled than the average velocity of the bottom face.

Knowing that the employed material models are linear, and having witnessed a linear behavior in the drop height dependency (see Section 3.1), a linear transfer function model seems to be a good approximation for the propagation through the sensor package. Denoting the transfer function in Laplace domain by $G(s)$, it is assumed that

$$V_a(s) = G(s)X(s), \quad (7)$$

where $V_a = \mathcal{L}\{v_a(t)\}$ is the Laplace transformed anchor velocity and $X(s)$ is one of the possible inputs in the Laplace domain. The transfer function is written as a polynomial fraction:

$$G(s) = \frac{\sum_{j=0}^k b_j s^j}{\sum_{i=0}^n a_i s^i}. \quad (8)$$

The number of poles (n) and zeros (k) are to be given, then the coefficients (a_i, b_j) can be determined by the fitting process explained in the next section.

4.2 Fitting process

The data used for the fitting comes from a simulation with adaptive time steps, so the input and output time series were interpolated linearly to an equidistant grid $\Delta t = 0.01 \mu s$. The inter-sample behavior for the inputs was set to first order hold (linear interpolation), since a continuous time transfer function fit was needed and no analog-to-digital conversion requiring a zero order hold is involved.

In addition, the velocity curves were shifted with the initial velocity:

$$v_{\text{shift}}(t) = v(t) - v(0), \quad (9)$$

so that the zero point denotes the case when every points of the package move together. This also means, that our reference system is falling with the initial velocity, so at the beginning of the simulation the package is at rest. Moreover, in this reference, the floor is going upwards with the initial velocity and it impacts the sensor at rest, leaving it flying away. This way, differing initial velocities can be treated easily by the shift of the velocity curve.

The fitting is carried out with the in-built Matlab function `tfest` [13]. The number of poles (n) and zeros (k) are to be input, with $k \leq n$. The process then starts with initializing the coefficients of the transfer function using the Simplified Refined Instrument Variable Method [14].

The initialized parameters are then iterated with a non-linear least squares search method. Several line-search algorithms are applied to get direction proposals and the first one leading to error reduction is utilized. The first two algorithms applied are Subspace Gauss–Newton and Levenberg–Marquardt [15]. A method from the other family of nonlinear search algorithms, the trust region type `lsqnonlin` was also checked, but was found to cause no significant difference in the fit results.

The initial conditions corresponding to the measured output can also be estimated or given. All were set to zero, since at the beginning of the simulation every point of the package moves with the same velocity. That is, the material points are at rest compared to each other and no prestress effects are incorporated. Setting the initial conditions, or estimating them made no large difference in the fit quality.

Quality of the fit is defined by the so-called *FitPercent* measure [13]:

$$FP = \left(1 - \sqrt{\frac{\sum_{j=1}^n (y_{p,j} - y_j)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}} \right) \times 100\%, \quad (10)$$

where y_i is the i -th real output value, $y_{p,i}$ is the i -th predicted value and $\bar{y}$ is the mean of the output. The maximal value, 100% indicates perfect fit, whereas under 0% the fit is worse than a constant line of the mean ($\bar{y}$) would be. In this regard, it is similar to another common measure, often used in regression analysis:

$$R^2 = 1 - \frac{\sum_{j=1}^n (y_{p,j} - y_j)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}. \quad (11)$$

However, the square root function inserted in *FitPercent* leads to a better differentiation among the good fits. This comes from the fact, that for good approximation the fraction would be small ($\ll 1$). The square root of a small number is a larger one, thus the smaller difference is magnified. So the *FitPercent* value is a good indication of the model quality, but a visual inspection is always needed to correctly evaluate performance.

4.3 Inputs and fitted models

First, a model fit was sought with the simplest input, the nodal average velocity of the package. A parameter sweep for the number of poles and zeros was carried out, resulting in the diagram

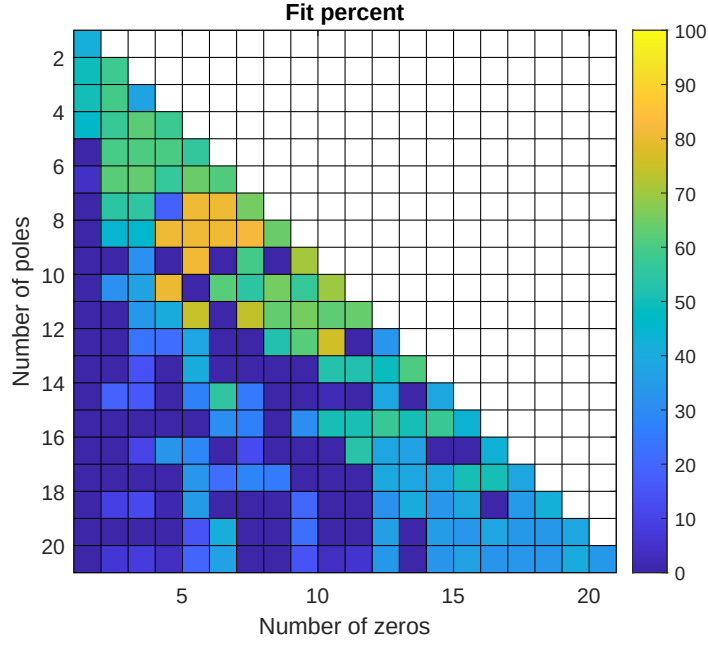


Figure 13: FitPercent of the fitted models for different number of poles and zeros. The model input is the nodal average velocity of the package. Note, that smaller than zero values of any magnitude are all indicated with dark blue.

of Figure 13. The fits are generally quite low quality with lower order models being mostly better. There is a peak with $FP \approx 80\%$ at around $n = 8$ poles, $k = 6 \dots 7$ zeros.

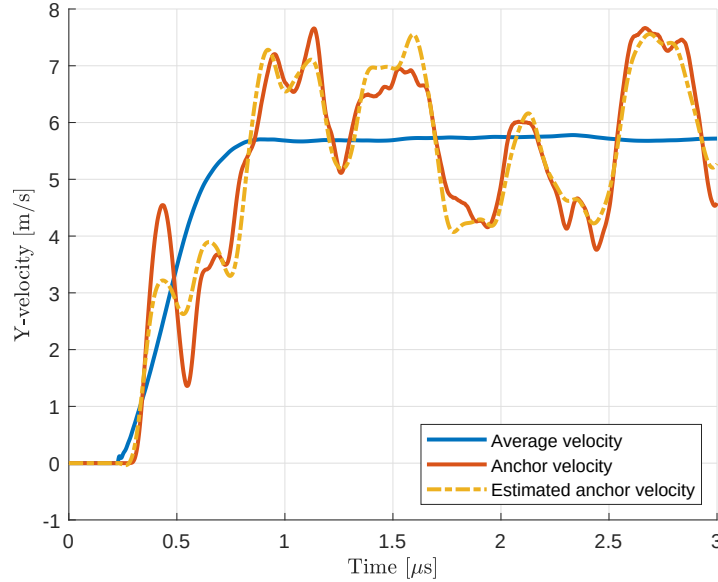


Figure 14: Performance of a fitted model with 8 poles, 6 zeros, and average velocity input. The overall temporal behavior looks nice, but the peak values have differing magnitudes.

One of the better fits with $k = 6$ and $n = 8$ is depicted in Figure 14. The main problem of

the fit lies in the magnitude of the peaks. Especially the first peak, clearly resulting from the impact, is hard to be modeled, as from the average velocity input the direct impact effects are filtered out. It is generally true, that the input has too few features compared to the output, so the low fitting performance seems understandable.

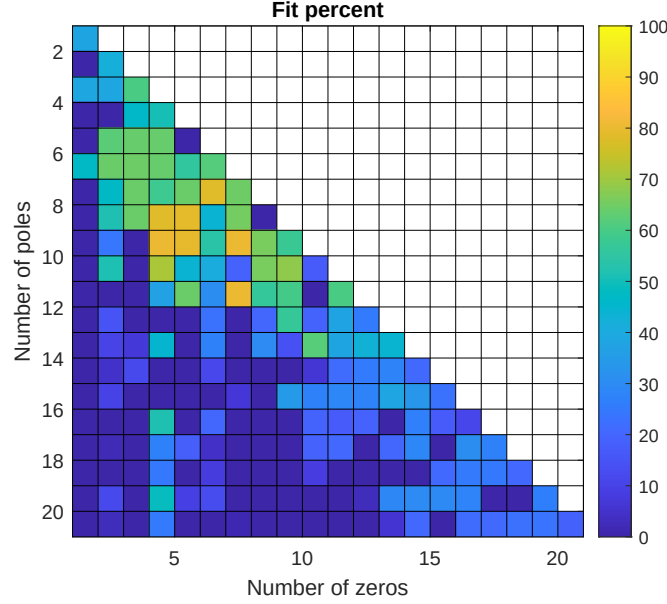


Figure 15: FitPercent of the fitted models for different number of poles and zeros. The model input is the contact force. Note, that values smaller than zero are indicated with dark blue.

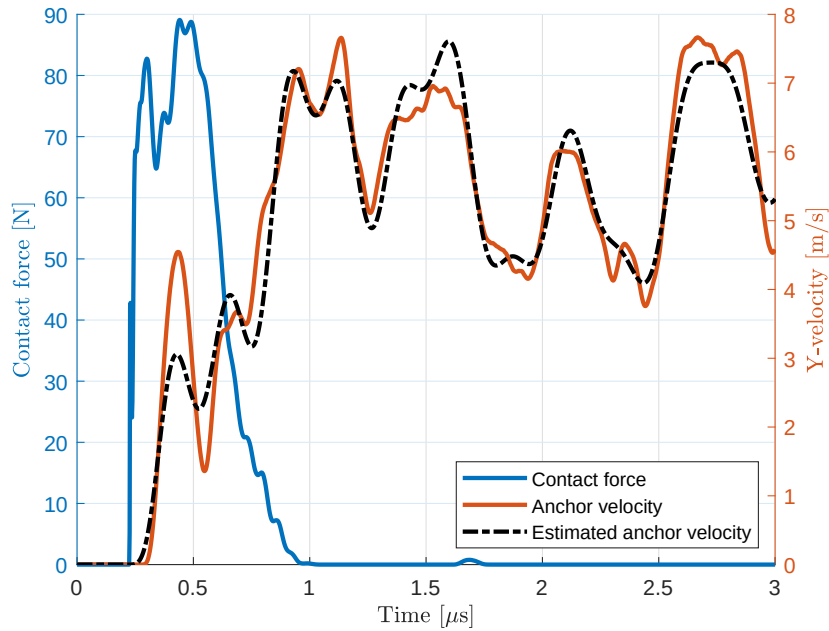


Figure 16: Performance of a fitted model with 8 poles, 5 zeros, and contact force input. The overall temporal behavior looks nice, but again the first peak is modeled poorly.

The next input used for modeling is the contact force, which being an impulse-type function, is supposed to hold information about the impact and the first peak in the anchor velocity. The parameter sweep for the appropriate number of poles and zeros provided similar results to that obtained in the case of the average velocity. As can be seen in Figure 15, the fits are again generally low quality and the better fits are located approximately at the same number of poles and zeros.

The performance of one of the best fits ($n = 8, k = 5$) is visualized in Figure 16. The first peak is still represented poorly in the estimated output. Although it is possible to find a fit that models the first peak right, such a model is unfortunately not able to keep the high mean value of the anchor velocity, it slides slowly back to zero. Thus, contact force was found to be an inadequate input.

The third input option discussed in this study is the average velocity of the bottom face ($\bar{v}_b$). The parameter study for the good fits results in the diagram of Figure 17, showing quite a few good fits with even $FP \approx 90\%$ quality.

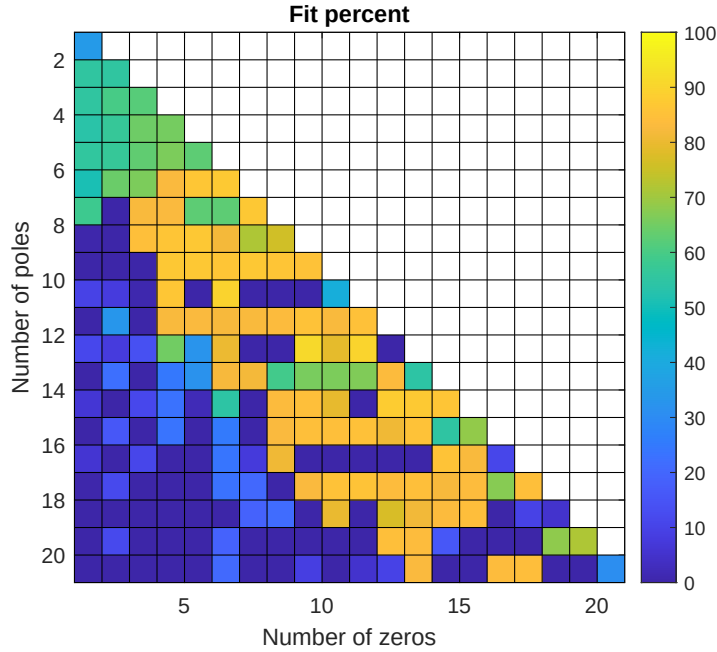


Figure 17: FitPercent of the fitted models for different number of poles and zeros. The model input is the average velocity of the bottom face. Note, that negative values are indicated with dark blue.

A good fit of poles $n = 12$, zeros $k = 9$ along with the average bottom face velocity input can be inspected in Figure 18. The fit has not only a good FitPercent value of $FP = 91\%$ but it is also visually correct. The first peak modeled adequately, since a much steeper peak is already present in the input, during the transfer it only gets a bit smoothed. One may also reasonably think, that the good fit is a consequence of a real physical connection between the bottom face velocity and the anchor velocity, however no proof for this is provided.

Nevertheless, the average bottom face velocity is found to be an adequate input. It also has the advantage, that it can easily be obtained from the simulation of a larger device (e.g. smartphone, watch), even when the sensor package is not modeled in it, only its place is present. This would not be possible for contact force for example.

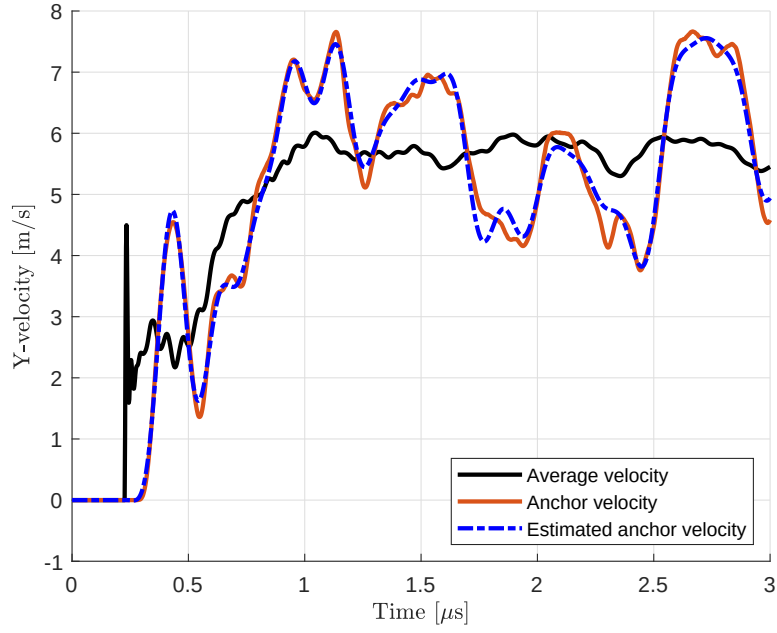


Figure 18: Performance of a fitted model with 12 poles, 9 zeros, and average bottom face velocity as input. The fit is visually correct, even modeling the first peak correctly.

4.4 Model validation

Having acquired a working transfer function model for the sensor package in an impact scenario, the next step is to test it, while varying some parameters of the simulation.

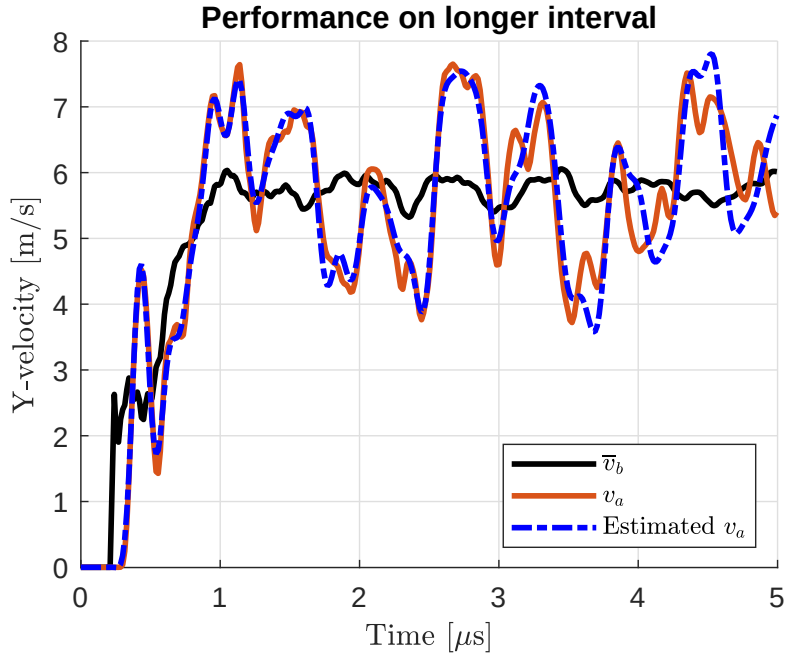


Figure 19: Input, simulated curve and model predictions on the interval $[0; 5] \mu s$. The model was fitted on the interval $[0; 3] \mu s$. The prediction accuracy significantly decreases outside the fit interval.

First, the transfer function is tested on a longer interval. Fitting was carried out on data from the range $t = 0 \dots 3 \mu\text{s}$, whereas in Figure 19 the simulated values and the model predictions up to $5 \mu\text{s}$ can be seen. After $3 \mu\text{s}$ the prediction commits larger errors, even visually the overall behavior seems significantly worse. It can be concluded, that fitting on a longer interval would be needed for a transfer function that models the long-time oscillations accurately. However, the highest forces and accelerations are present in the first few microseconds, and since we are primarily interested in these, the already fitted model is acceptable.

Drop height, that is related to the initial velocity may also be varied. Although it has already been determined in Section 3.1, that the velocity curves corresponding to the different initial velocities are scaled and shifted versions of each other, it still worth a confirmation, whether the transfer function model performs well in this case. Accordingly, in Figure 20 the model predictions are compared with the simulation results. For both of the 30 cm and 3 m drop cases the predictions are fine with FitPercent values of 90% and 87% respectively. The fitted transfer function can be used for a large range of initial velocities.

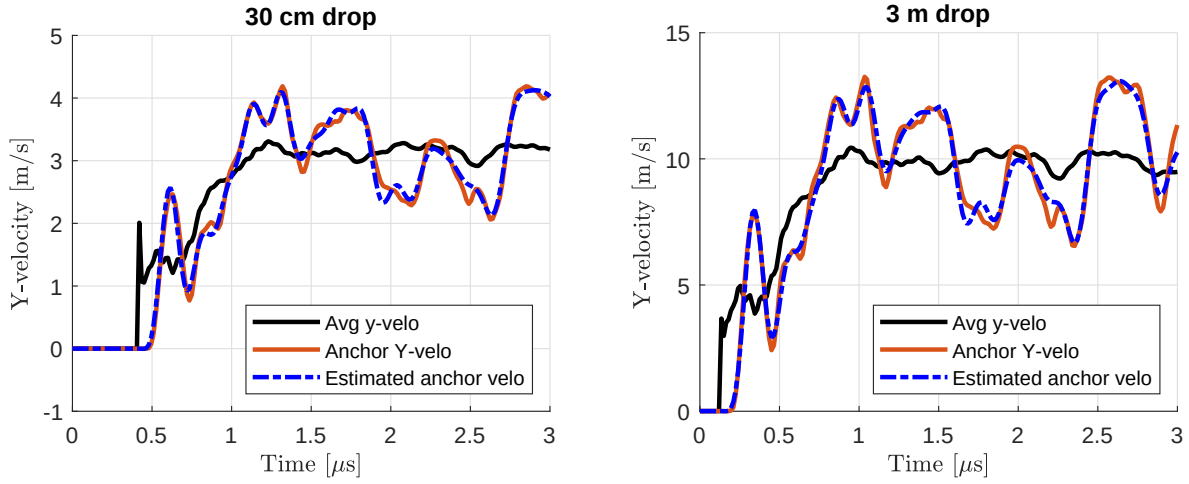


Figure 20: Validation for drop heights of 30 cm (left) and 3 m (right). In both cases the model provides good prediction.

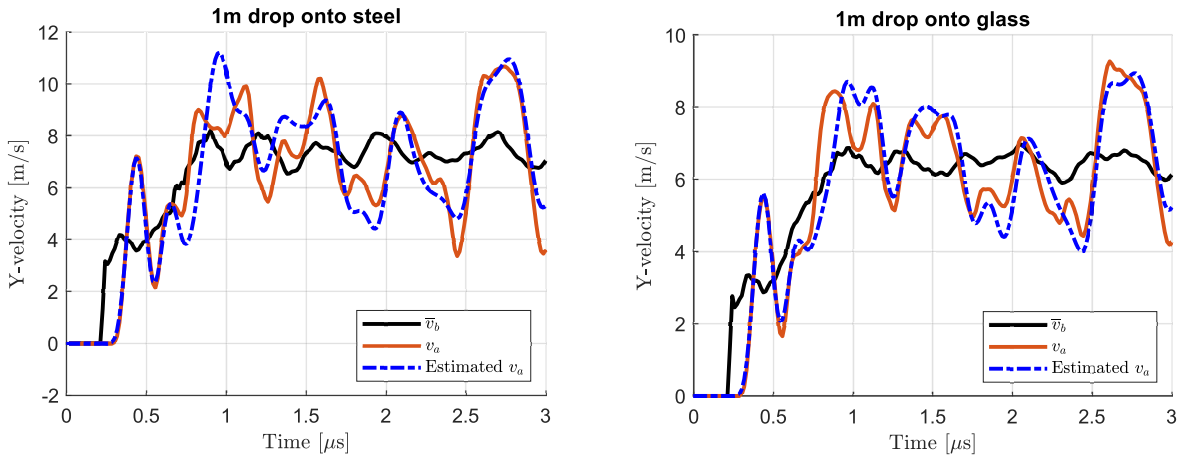


Figure 21: Validation for steel (left) and glass (right) floor material. In both cases the predictions are of a lower quality. Visually, the output in the glass case seems to be more accurate.

The last aspect addressed is the effect of the floor materials. The simulated and model predicted curves for the steel and glass materials introduced in Section 3.4 are shown in Figure 21. For both the steel and glass material the predictions are low quality with $FP = 67\%$ and 73% , respectively. It is to be noted however, that visually the outputs in case of the glass seem more appropriate, regardless of the mere 6% difference in the quality metric. Nevertheless, to create a transfer function model useful even in case of different floor materials, other fitting methods should be tried out.

4.5 Fit for three material models

The validation with different floor material models resulted in suboptimal results. It is reasonable to assume that fitting a transfer function to all three cases simultaneously would improve overall performance.

As in the previous cases, a parameter study was made to find good fits. The resulting diagram is shown in Figure 22. The quality measure of the fit is simply the mean of the three FitPercent values corresponding to the three different cases. The best fits are characterized by an MFP (Mean FitPercent) of around 70...75%, which indicates only a slight improvement compared to the performance of the model fitted on the concrete-floor case and used on the glass and steel cases. However, there are many similar fits, indicating good generalization and robustness.

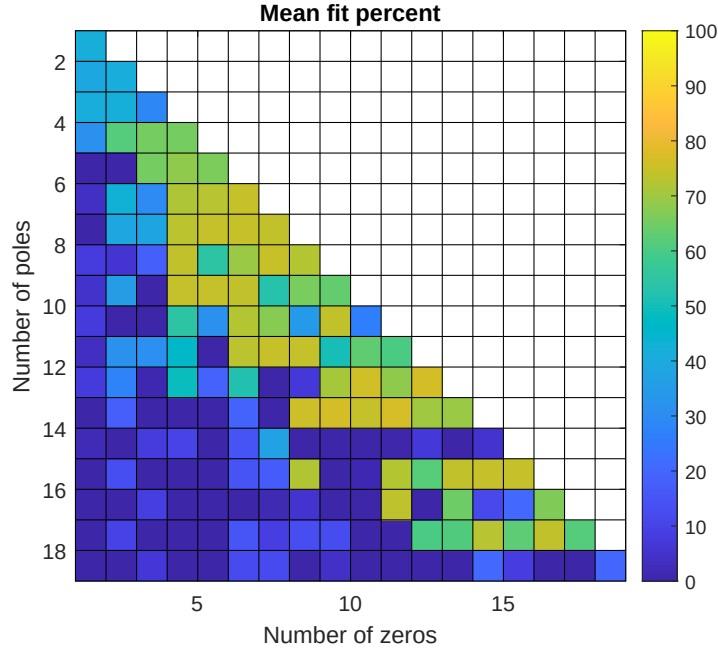


Figure 22: Mean FitPercent of the fitted models for different number of poles and zeros. The model input is the average velocity of the bottom face. Note, that negative values are indicated with dark blue.

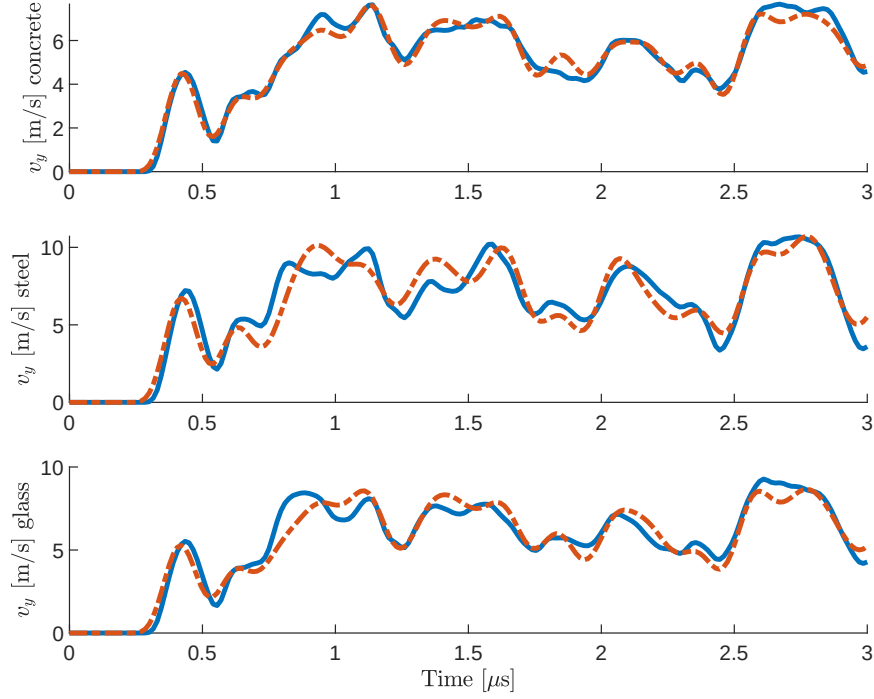


Figure 23: Performance of a fitted model with 13 poles, 9 zeros, and average bottom face velocity as input. The predictions are significantly better for concrete and glass than for steel.

A good fit of 13 poles and 9 zeros is visualized in Figure 23. The fit is best for the concrete case and visually acceptable for the other materials. Previously, in Section 3.4 it was determined that a nonlinearity is present in the simulation caused by the different materials probably through the contact formulation. The result of this fitting seems to provide an evidence, too.

Fitting on simulation data from different cases with distinct floor materials offered no clear advantage over fitting for a given material. The different materials introduce a nonlinear behavior that cannot be managed by a transfer function model.

There is definitely an opportunity for further research here. One of the options is employing nonlinear input-output models. Alternatively, a so to say “hypermodel” could be trained, that would accept the parameters of the floor material and output the correct transfer function parameters to use. It would also be worth investigating, whether the contact force, the package average velocity, or some other quantity contains information about the floor material, and thus a linear, but multi-input transfer function could be used.

5 Exciting resonance in the sensor structure

A typical MEMS accelerometer sensor structure consists of springs and masses, see Figure 24 for an example. The springs are essentially long parallel beams made of polysilicon, which are connected at the ends. The impact-induced fracture of such a structure might have several causes. First, the stresses during the impact might be that large that fracture would occur even under quasi static conditions. Second option is that the oscillation caused by the impact drives the structure into resonance, resulting in breakdown. Thirdly, because of the oscillations, even a fatigue effect could be present.

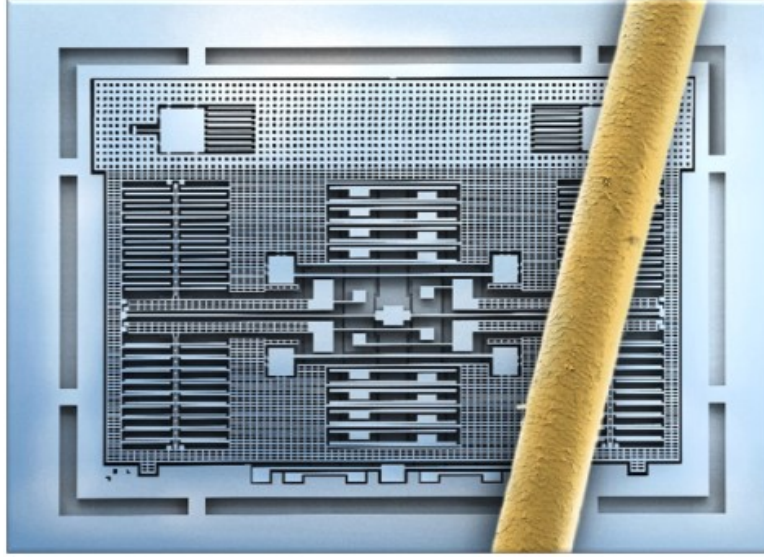


Figure 24: The acceleration sensor structure of Bosch Sensortec BMI160 [16]. A strand of hair is also depicted for comparison.

The first case could be simulated by applying the anchor velocity approximation provided by the fitted transfer function. The first 1-2 microseconds should be enough, as the largest accelerations occur exactly at that interval.

The case of resonance is a somewhat open question. Since the impact is over within a few microseconds, one might argue that it is impossible to achieve so large amplitudes that can cause failure. On the other hand, the sensor structure is quite small, on the order of 10...100 microns, so the relevant eigenfrequencies of individual beams can fall into the MHz range. In this section, simulations about such beams will be presented, that have eigenfrequencies closely matching the dominant frequencies of the excitation, the anchor velocity.

Last, the fatigue of polysilicon springs is an observed and important phenomenon especially in the case of MEMS gyroscopes, see for example [4]. Yet, a polysilicon structure needs far more cycles until failure, than what is available during and after an impact. This is especially so, since the oscillations are expected to be dissipated in reality by a viscoelastic mold. So, for a fatigue failure a large number of impacts would be necessary, which is unlikely under typical manufacturing and operating conditions.

5.1 Frequencies of the anchor velocity

One of the most important components of MEMS acceleration sensor structures are springs, which are essentially comprised of beams. The core idea is, that such a beam can have an eigenfrequency that resonates with the after-impact sensor oscillations.

In order to prove this, the peak frequencies of the anchor velocity are first needed. To determine the smaller frequencies accurately, a simulation for $t = 20 \mu\text{s}$ was carried out. Note that in this section a less tall concrete block is used corresponding to the “*wide*” version from Section 2.5.

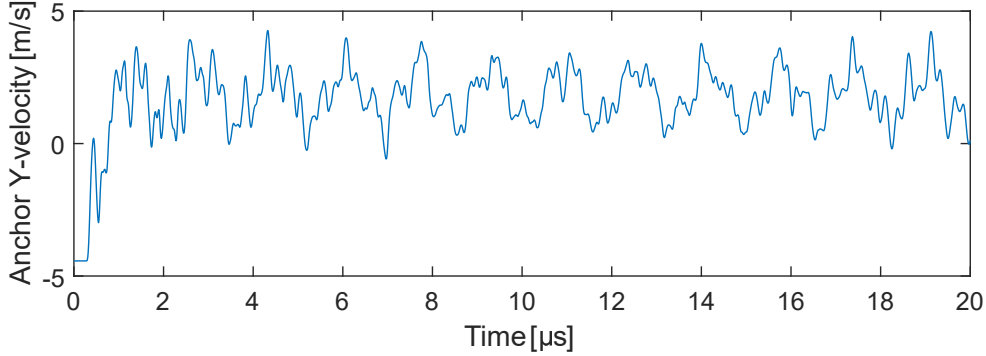


Figure 25: Anchor velocity simulated for $20 \mu\text{s}$.

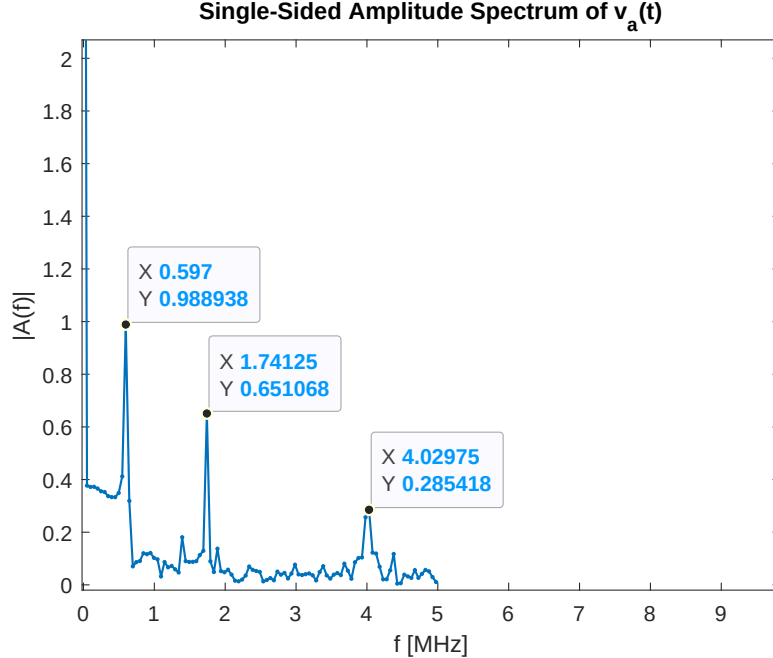


Figure 26: FFT spectrum of the anchor velocity.

The anchor velocity curve from the simulation is shown in Figure 25. Some sinusoidal components can almost be seen in this plot. There is for example a component with a wavelength of about $\lambda = 2 \mu\text{s}$, that is about 0.5 MHz frequency. The fast Fourier transform (FFT) of the signal was made, the corresponding spectrum is shown in Figure 26. A 0.6 MHz component

can be identified in the spectrum, not far from the previous estimate. There is also a peak around zero frequency, that corresponds to the large change in the average velocity caused by the impact.

Knowing the important frequency components of the anchor velocity, a matching beam can be designed and added to the sensor package simulation.

5.2 Modeling part of the structure

The hypothetical small part of the structure prone to resonance is depicted in Figure 27. The sizes of this cantilever beam are to be determined in a way, that its eigenfrequencies match that of the anchor velocity peak frequencies.

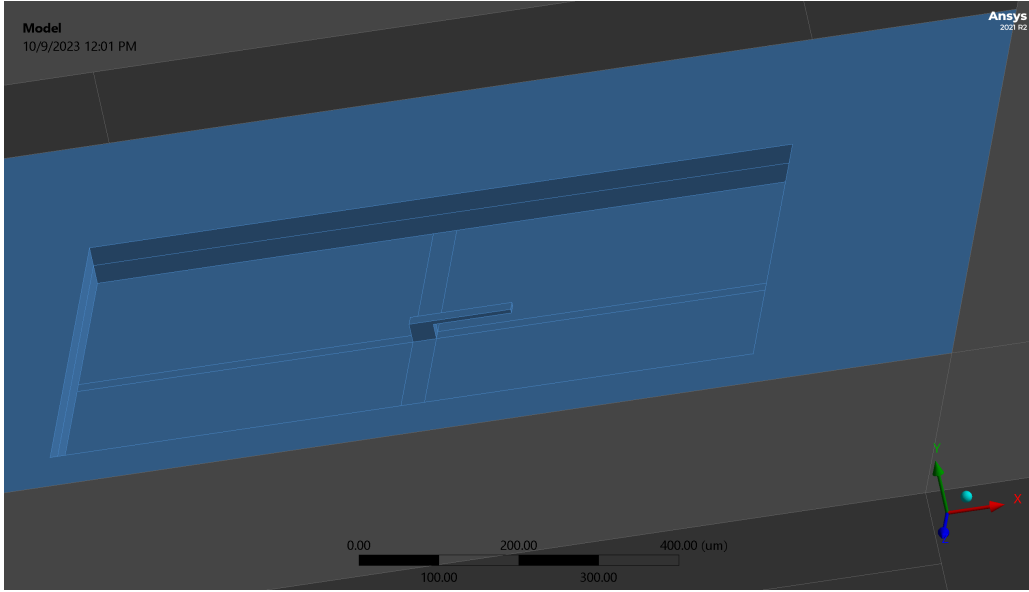


Figure 27: The beam representing a part of the sensor structure. It is located within the gap in the silicon die and is connected to the anchor point. Note, that the top of the mold and the silicon cap is hidden.

The eigenfrequencies of a beam can be approximated with the help of Euler–Bernoulli beam theory [17]. A homogeneous, linear elastic beam is imagined with a fixed left and a free right end. The model is shown in Figure 28. The partial differential equation of the beam is

$$\rho A \frac{\partial^2 y}{\partial t^2} - I_z E \frac{\partial^4 y}{\partial x^4} = 0, \quad (12)$$

where $y(x,t)$ is the displacement of the beam point at coordinate x and time t . The other letters represent constant parameters: $\rho = 2329 \text{ kg/m}^3$ is the density, $E = 169 \text{ MPa}$ is the Young modulus, A is the cross-sectional area of the beam, and I_z is the second moment of area. For a rectangular cross section these are computed as

$$A = ab, \quad (13)$$

$$I_z = \frac{ab^3}{12}, \quad (14)$$

with a and b being the width and height of the cross section, as shown in Figure 28. As it has already been discussed in Section 2.2, silicon in MEMS should be modeled with an orthotropic elastic model. However, for the Euler–Bernoulli beam theory only the longitudinal (x -direction) modulus is needed, as this theory is purely based on bending and normal stresses. So, using the Young’s modulus value $E = E_x = 169$ GPa is sufficient [12].

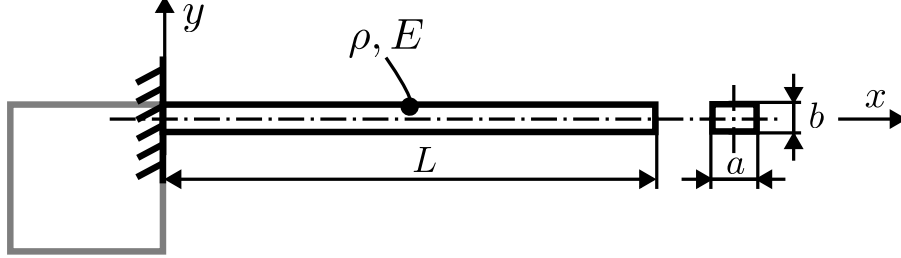


Figure 28: The beam model with a fixed left end and a free right end. The gray box represents the part that connects the beam to the silicon die in the FEM simulation and is not part of this simple model.

The boundary conditions (fixed end, free end), are formulated as

$$y(0,t) = 0, \quad (15)$$

$$y'(0,t) = 0, \quad (16)$$

$$y''(L,t) = 0, \quad (17)$$

$$y'''(L,t) = 0, \quad (18)$$

where y' , y'' and y''' represent the first, second and third derivatives with respect to x .

The solution for the eigenfrequencies is traditionally given in the form of β values, from which the natural frequencies can be computed as

$$\omega_{n,i} = \frac{\beta_i^2}{L^2} \sqrt{\frac{I_z E}{A \rho}} \quad (19)$$

For the cantilever beam the β values are given by the equation

$$\cos \beta \cosh \beta = -1. \quad (20)$$

The first few solutions are the following.

$$\beta_1 = 1.8751 \quad (21)$$

$$\beta_2 = 4.6941 \quad (22)$$

$$\beta_3 = 7.8548 \quad (23)$$

Other solutions are approximately (for at least 4 decimals)

$$\beta_n = \frac{\pi}{2} + n\pi, \quad n \in \mathbb{N} \quad (24)$$

Frequencies computed from β values of (21)-(23) can be made approximately equal with the peak frequencies of the anchor velocity by choosing adequate sizes a, b and L . Two such combinations are listed in Table 7. These were used in the simulations.

L [μm]	a [μm]	b [μm]	$\omega_{n,2}$ [10^6 rad/s]	$f_{n,2}$ [MHz]	f_a [MHz]
100	20	5	27.09	4.31	4.03
155	20	5	11.25	1.79	1.74

Table 7: Parameters of the beams and the matching resonances. The eigenfrequencies of the beam are ω_n and f_n , whereas f_a denotes the approximately matching anchor velocity peak frequencies.

5.3 FEM model with the beam

The two beams with the appropriate sizes were modeled into the package. A $30 \times 20 \times 25 \mu\text{m}$ block is placed above the anchor point, to which the beam connects. The model geometry in the vicinity of the structure can be seen in Figure 27. The applied material is the already described orthotropic silicon.

Since the structure is much smaller than the silicon die it connects to, the mesh should employ differing element sizes. During meshing with hexahedral elements difficulties were encountered. The transition between the element sizes proved to be irregular, requiring a large region, while also disturbing the conformal meshing on the die boundaries. Several meshing failures necessitated the change to tetrahedral mesh, which produced a seamless transition. However, the element size greatly increased. The tetrahedral mesh on the beam and in its vicinity is depicted in Figure 29.

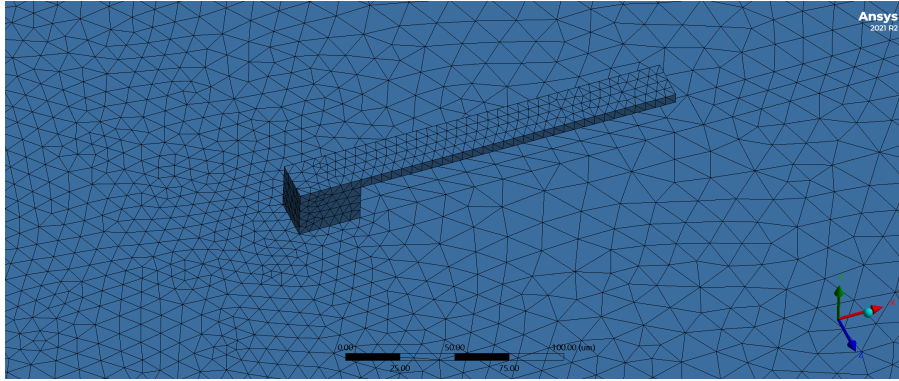


Figure 29: The mesh of the beam and of the silicon die it connects to.

In case of the sensor package, the tetrahedral mesh was compared with the two finest hexahedral meshes from Section 2.4. The mesh characteristics are listed in Table 8.

Element size [μm]	Floor element size [μm]	Element quality (MJR)	Number of elements	Simulation runtime
15	50	0.99854	883,866	7 m 14 s
15 (tetra)	50	AR: 7.68	3,578,748	13 m 18 s
10	30	0.99853	3,169,021	13 m 56 s

Table 8: Parameters and quality of the tetra and the finest hexa meshes. MJR stands for minimum Jacobian ratio, AR is aspect ratio. All meshes are good quality.

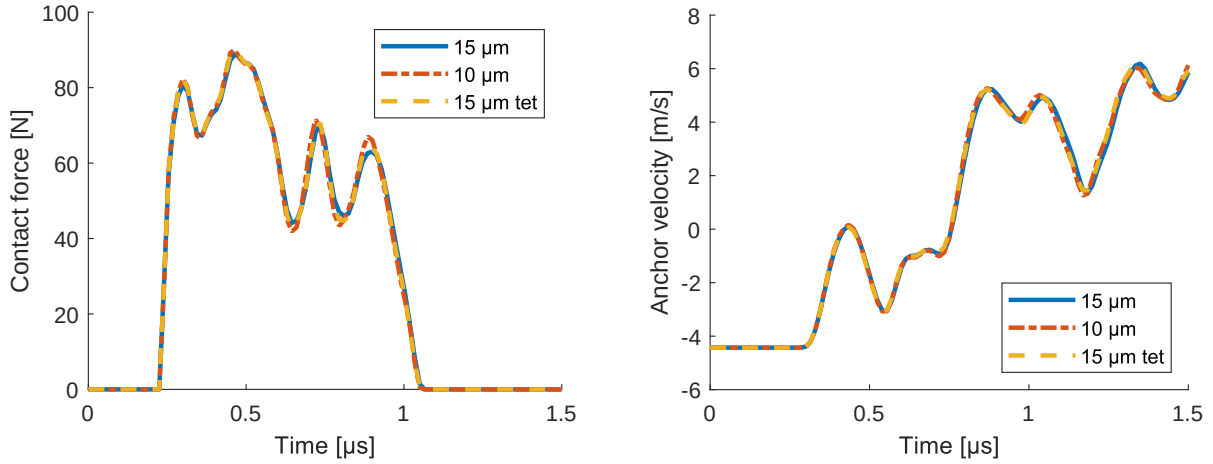


Figure 30: Validation of the tetra mesh with two fine hexa meshes. In both the case of the contact force (left) and the anchor velocity (right) the differences are hard to see.

Comparing the curves in Figure 30, the $15\text{ }\mu\text{m}$ tetrahedral mesh can also be accepted as a good mesh, its use in this combined package and structure part simulation is justified.

5.4 Simulation results

The drop of the sensor package with the beam modeled in it was simulated in LS-Dyna. The resulting displacement and velocity curves for the anchor point and the free end of the beam show the amplification and thus, whether resonance occurs. In Figure 31 for the case of $L = 100\text{ }\mu\text{m}$, whereas in Figure 32 for the $L = 155\text{ }\mu\text{m}$ variant were the curves plotted.

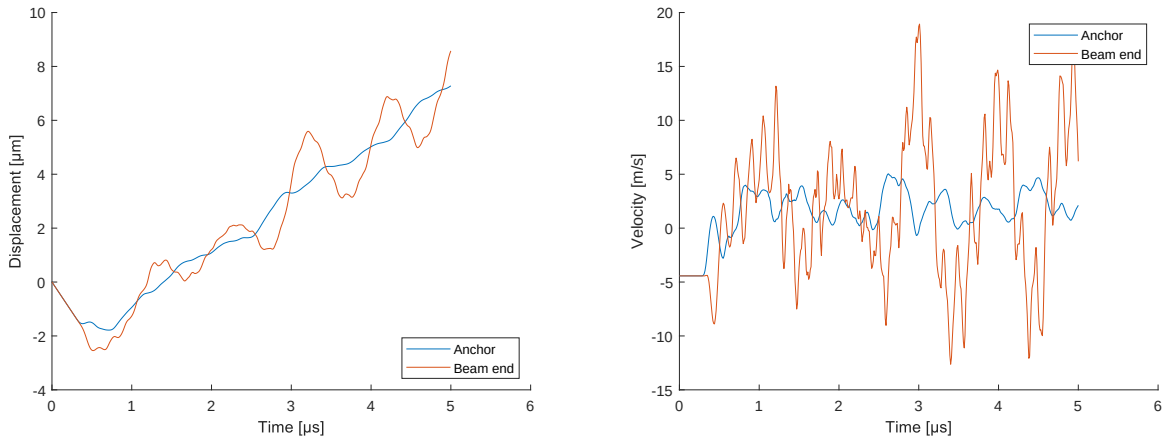


Figure 31: The displacement and velocity curves for $L = 100\text{ }\mu\text{m}$ beam.

In both cases, the frequency of the anchor velocity happens to be close to resonance and the amplification in the displacement and velocity curves is accordingly large. The frequencies of the anchor velocity are dependent on the sensor package, so it is advisable to take the package into consideration when designing the sensor structure.

It must be noted, that this demonstration has several limits. First, the discretization of the beam (element size $5\text{ }\mu\text{m}$) is coarse. A finer mesh could result in simulations with more

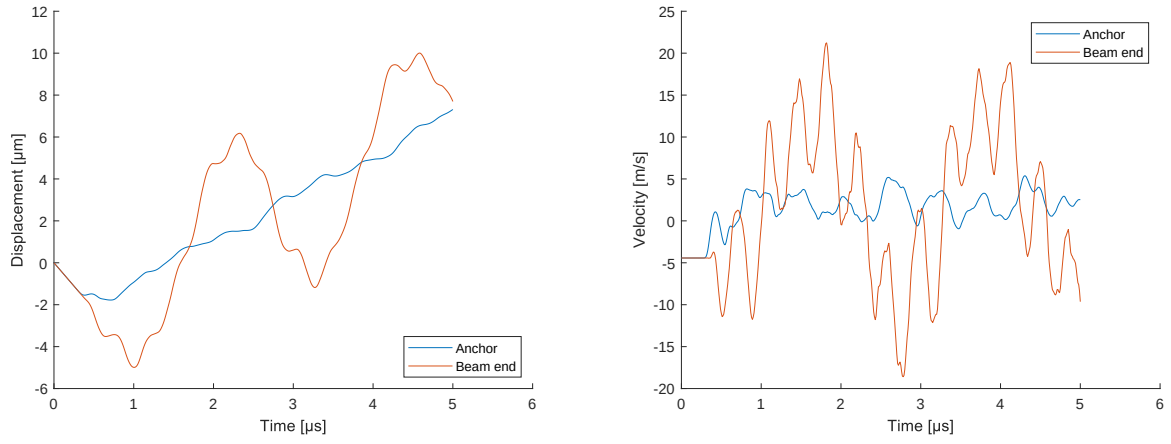


Figure 32: The displacement and velocity curves for $L = 155 \mu\text{m}$ beam.

pronounced resonance curves. Moreover, this analysis should also be extended in the future with a numerical parameter study of the oscillation amplitude with respect to the beam length.

Nevertheless, it can be stated, that because of the possible resonance after impact, it is all the more important to carry out structure simulations with anchor excitation obtained from package simulation or the discussed transfer function model.

6 Conclusion

This study focused on the impact of MEMS sensor packages. During an impact, the sensor structure in the package can break, which renders the device useless. In order to learn when and how the structures can fail, it is necessary to understand how the impact shock propagates in the package. This in turn helps reducing the time needed for designing and increases sensor robustness.

To simulate the impact of a simplified MEMS sensor package with the floor, I used the explicit finite element software LS-Dyna. A mesh dependency study was made and a search for the optimal size of the floor block was also conducted.

The simulation was found to behave linearly with respect to the initial velocity and thus drop height. The contact friction coefficient showed no great influence. A few characteristic impact configurations were simulated: package bottom face, side face, and edge contact. The case of bottom face contact was found to be the most dangerous to the structure because it has the largest peak contact force and largest accelerations.

To model the shock propagation in the sensor package, a transfer function fit was carried out. The output was the velocity of the so-called anchor point, which connects the structure and the package. For input, three quantities were evaluated, from which the average velocity of the bottom face was clearly the most adequate choice. The fitted model was found to perform well for different drop heights, but was more inaccurate for a longer interval and for differing floor materials. Fitting for simulation data from cases of three distinct floor materials was also carried out and found to provide consistent but lower quality fits. The conclusion was drawn that the linear floor materials introduce nonlinear effects into the package transfer function.

Finally, a beam model was created representing part of a sensor structure with eigenfrequencies matching the peak frequencies of the package transfer function output. The package impact was simulated with the beam incorporated into the finite element model. The resulting displacement and velocity curves showed large amplifications, demonstrating that the after-impact oscillations of the package can excite resonance frequencies of the sensor structure.

To sum up, a good understanding of the sensor package impact problem and the most important parameters has been reached. I created a simply applicable transfer function model for the shock propagation in the package and also demonstrated the large effect an impact can have on a sensor structure with resonance frequencies matching those of the package during impact.

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