

Experimental Verification of an Instrument to Test Flooring Materials.

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Abstract. The focus of this work is to validate the fluid model with different flooring materials and the measurements of an instrument to test flooring materials and its force attenuating capabilities using mathematical models to describe the signature and coefficients of the floor. The main contribution of the present work focus on the development of a mathematical fluid model for floors. The aim of the thesis was to analyze, compare different floor materials and to study the linear dynamics of falling impacts on floors. The impact of the hammer during a fall is captured by an accelerometer and response is collected using a picoscope. The collected data was analyzed using matlab least square method which is coded as per the fluid model. The finding from this thesis showed that the fluid model works with more elastic model but it doesn't work for rigid materials like wood. The importance of parameters like velocity, mass, energy loss and other coefficients of floor which influences the model during the impact of falling on floors were identified and a standardized testing method was set.

Keyword: Fluid model, coefficients of the floor, linear dynamics, Matlab, least square method.

1. Introduction

Over thousands of people in Sweden pass away every year as a consequence of falling. According to The National Board of Health and Welfare (2016), the number of deaths has doubled since 2000. The risk of falling increases with age due to normally aging which may affect body balance, poor muscle strength and visual and hearing impairments. Usually, women are often in more need of hospitalization after falling, but more men seem to pass away due to a fall (The National Board of Health and Welfare, 2016).

The Swedish workplace expert played out a review at home for elderly in Sweden. The Swedish work authority touched base at a conclusion that the ergonomic issues various agents had experienced were related to floor covering in the building. "The Swedish work authority points out that if the floor covering has got a suitable springiness or not cannot be objectively judged since there are no test methods for this"[1]. When flooring with soft cover floor material i.e. with a greater springiness, it can affect a number of other properties. Some properties will be affected in an undesired way such as rolling resistance, residual indentation, damping effect, shock absorbing properties etc.

Naturally, the problem is more acute for more vigorous types of human activity such as dancing, jumping, accidental falling etc. and therefore designers of buildings featuring a gymnasium or dance studio should take extra care to limit the vibrations in the rest of the building. It is very difficult to modify an existing floor to change its behavior, as only major changes to the mass, stiffness or damping of the floor system will produce any perceptible reduction in vibration amplitudes. It is important therefore that the levels of acceptable vibration should be considered at the design stage, paying particular attention to the main usage of the floors.

There are many mathematical floor models but all models are not compatible with all flooring materials. Among them, the most common and proper model that exist is Maxwell's model.



The Maxwell material is a viscoelastic material having the properties both of elasticity and viscosity [2]. The Maxwell model can be represented by a purely viscous damper and a purely elastic spring connected in series. If a small stress is applied for a long time, then the irreversible strains become high. This model behaves similarly to a fluid. The same concept is used to develop a new model in this thesis work which is compatible with more elastic floor materials.

“To better understanding mechanical responses of materials subjected to deformations or forces, theoretical models are required. These models provide important analytical tools for predicting and simulating material functions” [3]. When a material is subjected to deformations, the stress involved is related to the strain by a mathematical relationship known as the constitutive law. This equation can, thus, provide useful information in determining properties of materials. Since viscoelastic materials show both viscous and elastic material behaviors, their constitutive equation must mathematically reveal stress, strain and their time derivatives. For this purpose, the author considers a model with spring, damper, and a mass connected in series. The model represents the response or impact creates on the hip bone of elderly people during an accidental fall on the floor by losing their body balance. In this thesis work, the author considers it as a linear dynamics case. But actually the mechanical responses of viscoelastic materials are in a general nonlinear case, the well-established linear theory of viscoelasticity must be reasonably replaced by nonlinear theories. Nonlinear models are more difficult to formulate than linear models because these models need to solve nonlinear differential equations that are generally non-integrable [11][12].

And studies says that it is not just elderly individuals who fall, other hazard gatherings are patients remaining at a doctor's facility or human services specialists [4]. The most well-known method for falling is from a bed or seat or dangerous floor. There is a need for more research with respect to the effect strengths when falling in a relationship of the ground surface materials in medicinal services situations [5].

To build up the learning of the speed while falling they performed genuine fall studies in two long haul mind offices. Utilizing cameras falls could be recorded and after that investigated utilizing Matlab and approval in a research facility utilizing a human member. The review reports a normal vertical effect speed of 2.14 m/s, and even affect the speed of 1.16 m/s for the pelvis. Utilizing hands or different unconstrained activities to choose the fall plainly influences the effect speed. Another variable that impacts the effect speed is the method for falling; sideways, forward or in reverse [6].

The Swedish Work Environment Authority (2015) has in one of their controls a necessity that expresses that "Floors might be firm and stable and should have versatility proper to the action"[1]. In the meantime, they announce that the mechanical properties of the floors can't dispassionately be measured on the grounds that there is no all-around attempted test strategy for this [5]. In a review by Wright and Laing [9] a mechanical drop tower was utilized to gauge top effect and pinnacle direct increasing speed of a head form on nine distinctive floor sorts. Additionally, the Head Injury Criterion (HIC) was connected to assess the effect. The outcome shows that diminishing the firmness of the floor might be a viable technique to lessen fall-related wounds. The test is to create floor properties that will diminish affect strengths and increasing velocities while falling, yet at the same time permit, great adjust for the clients.

In this thesis work, the main aim is to develop a simple linear mathematical model which is compatible with all types more elastic floor materials and that can be used to create an index is based on measurements of flooring materials and their mechanical characteristics. So that the risk of injury caused by sudden fall on hip bones of elderly people can be reduced and Furthermore, the falling injury flooring index is to be used in the research and development process in the flooring industry.

Falls cause 90% of injuries on the hip and waist fracture and 60% of head injuries in older adults [4]. The risk for such injuries depends on impact velocity and time available during fall to generate a protective response. The primary objective of this thesis is to gather information on mechanical properties of different floor coverings. As a part of improving the knowledge about the linear dynamics of vibrations involved during the sudden impact caused on hip bones of elderly people during fall. The project initiated at Halmstad University, Sweden.

2. Materials

A total of 3 different floor materials has been tested. The materials range from a wooden based rigid material to a sport floors.

2.1. Kradal Impact Absorbing Floor.

It is 12 mm thick and comprises closed compact cell adaptable polyurethane/polyurea composite tile. The floor likewise has an outer surface of polyurethane/polyurea elastomers, around 1.5 mm thick. They were mounted specifically onto a solid floor with a layer of 4 mm adaptable grouts in the middle. The floor was at long last covered to seal the top surface. The floor can lessen the vitality by 65-85% contrasted with cement as indicated by the item testing report (Kradal, 2013).

2.2. Kradal Tile

The Floor Tiles give unparalleled solidness and protection from falls in an individual flooring surface material and are reasonable for both business and private establishment. Uniquely formulated utilizing a special polyurethane technology. Each tile is composed of thousands of micro-spheres that increase padding impact. Retains a hardened and resilient character under high activity use. Flooring contributes towards enhanced passive safety while at the same time offering protection from falls in an individual flooring surface material and sudden impact affects the people aged around 65 years and more due to weak bones.

2.3. Wooden Flooring materials

The wooden materials are used to cover the flooring areas for aesthetic look but they impact absorbing capabilities are very less if they are used as a single material for flooring. They have very small resilience and so they cannot be used in elderly care homes. So as the part of my research work the author need to find whether the model is compatible with this material. The author have tried different combination of materials with wooden one and an elastic material e.g. wooden material can be combined with kradal floor materials.

3. Methodology

This study validates a testing method together with the flooring industry, as well as specify other important functions of the future innovation. The method should capture the mechanical properties of floors when subjected to an impact. In order to validate the measurements of an instrument to test flooring materials and its force attenuating capabilities the author have used mathematical models to describe the signature and coefficients of the floor. For this we have an experimental setup to test different floor models and calculate the materials physical properties. A fluid mathematical model had been already developed to describe the signature and coefficients of the floor. The hammer experiment setup have been used to test the impact of falling on different floor material such as wooden, sports floor material and floor materials which are used in houses where elderly peoples live. And a matlab code is used to compare the different impact behaviors on different floors.

Measurements with different floor were collected using hammer experimental setup. By varying different parameters. Those data are collected and saved using PC oscilloscope. The data collected are analyzed and compared using Matlab. The code for Matlab was used to fit the fluid model against measurements. During the impact of the hammer on a floor the collection time is set in the picoscope so that it can capture a number of points to get a clear and accurate graphical representation during analysis. Those points or data can be solved using Matlab to compute the different constants and parameters of the floor.

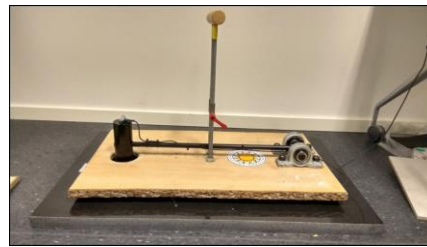


Figure 1. Experimental setup

3.1. Impact testing

A hammer is dropped from different heights and allowed to hit on the test floor. The impact is absorbed by floor and part of the energy is absorbed by the hammer is sensed by piezoresistive accelerometer attach to the hammer. The model ASC 66C1 is a uni-axial accelerometer based on piezoresistive technology. The model ASC 66C1A is a signal amplified uniaxial accelerometer. Instead of real fall of elderly people, a hammer is dropped on the floor to know the impact on hips and to describe the signature and coefficients of the floor. The impact on hammer sensed by the accelerometer is sent as signals to an oscilloscope. From oscilloscope, it is fed to Picoscope 6. And with the use of matlab we check whether the model fits with measured floor behaviour.

3.2. Impact velocity

To develop the knowledge of velocity when an impact was made by the hammer on floor. The falls could be recorded and then analysed using Matlab and validation in a laboratory. The study reports an average vertical impact velocity of 2.14 m/s can cause serious injury [13]. So in order to know the influence of velocity on the new fluid model the hammer is dropped from different heights. Descriptive results for vertical impact velocity of the hip bone. We focused more on vertical impact velocity, as a strong indicator of risk for serious injury. The author calculated the impact velocity based on free fall of a mass (where impact velocity= $\sqrt{2gh}$), where $g=9.81\text{m/s}^2$ and h is the vertical distance of fall). With the experimental setup, we can measure maximum velocity up to 3m/sec and minimum velocity to create response is 2m/sec.

3.3. Variation of mass

As the mass varies the impact cause on hip also varies. In the experiment setup we have a hammer of mass 0.6 kg and unfortunately, we were in a situation that mass of hammer cannot be increased. But then the author come across a new idea that by reducing the contact area of the hammer where it hits the floor we can create the same impact when mass is increased. As the area of contact is reduced mass will increase ($\text{mass} \propto 1/r^2$, where r is the radius of contact area). To reduce the area of contact we attach small thickness plates on hammer bottom part. The actual radius of the contact area of the hammer was 5cm but in order to reduce the contact area a plate of 2.5cm, 3.54cm, 2.88cm plates were used to increase the mass by twice, thrice and four times the original mass of hammer. To know whether the recorded data is accurate we checked plates of different thickness and fall height was set to minimum velocity which is enough to cause injury to hip. We get an accurate result for all thickness plate but when the mass is increased to four times we were not able to get the exact curve for 2mm thickness plate. There was a double peak on the curve which is caused due to hammer making more than two contact surface on the floor.

4. Theory

During this chapter of the thesis all the theoretical aspects of the study will be presented. It starts with a short summary of the state-of-the-art literature used during the thesis and an introduction of the fluid model.

4.1. Theoretical Framework

According to the fluid model, the hammer is represented as mass m and spring and damper represent the floor material. There is also a small mass which represents as the mass of floor material but it's negligible when compared to the mass of hammer so it was neglected. The free body diagram shows the forces acting on the hammer when it hits on floor and direction of action of force on spring and damper at equilibrium. The floor material is represented by damper and spring connected in series.

Analysis of new fluid model of motion

$$\sum F_x = -k(x - z) = m\ddot{x} \Rightarrow m\ddot{x} + k(x - z) = 0 \quad (1)$$

$$\sum F_z = k(x - z) - c\dot{z} = 0 \Rightarrow c\dot{z} = k(x - z) \quad (2)$$

Fluid model free body diagram

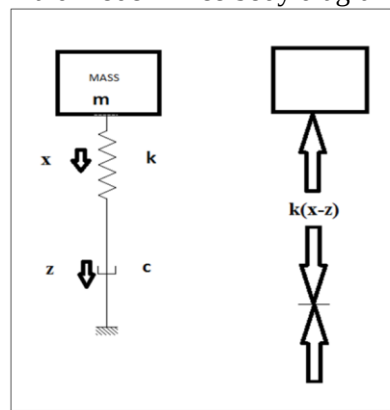


Figure 2. Fluid model

Substitute (2) in (1) gives

$$m\ddot{x} + c\dot{z} = 0 \quad (3)$$

Integrating equation (3) at $t=0$ gives

$$m(\dot{x} - v_0) + cz = 0 \Rightarrow z = -\frac{m}{c}(\dot{x} - v_0) \quad (4)$$

Substitute (4) in (1) gives

$$m\ddot{x} + \frac{mk}{c}\dot{x} + kx = \frac{mk}{c}v_0 \Leftrightarrow \ddot{x} + \frac{k}{c}\dot{x} + \frac{k}{m}x = \frac{k}{c}v_0 \quad (5)$$

$$\omega_n^2 = \frac{k}{m} \text{ and } \zeta = \frac{\sqrt{mk}}{2c}$$

And introduce in (5)

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2x = 2\zeta\omega_nv_0 \quad (6)$$

$$x(0) = 0 \quad (7)$$

$$\dot{x}(0) = v_0$$

Solution

$$X = X_h + X_p \quad (8)$$

$$X_p = \frac{2\zeta v_0}{\omega_n} \quad (9)$$

$$X_h = e^{-\zeta\omega_nt} [A \cos(\omega_d t) + B \sin(\omega_d t)] \quad (10)$$

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} \quad (10)$$

$$x = \frac{2\zeta v_0}{\omega_n} + e^{-\zeta\omega_n t} [A \cos(\omega_d t) + B \sin(\omega_d t)] \quad (11)$$

Substituting (7)

$$x(0) = 0 = \frac{2\zeta v_0}{\omega_n} + A \Rightarrow A = -\frac{2\zeta v_0}{\omega_n} \quad (12)$$

$$\dot{x}(0) = v_0 = -\zeta\omega_n A + \omega_d B \Rightarrow B = \frac{v_0(1 - 2\zeta^2)}{\omega_d} \quad (13)$$

$$x = \frac{2\zeta v_0}{\omega_n} [1 - e^{-\zeta\omega_n t} \cos(\omega_d t)] + \frac{v_0(1 - 2\zeta^2)}{\omega_d} e^{-\zeta\omega_n t} \sin(\omega_d t) \quad (14)$$

By differentiating equation 14 twice we will get acceleration.

$$\ddot{x} = -\frac{\omega_n v_0 e^{-\zeta\omega_n t}}{\sqrt{1 - \zeta^2}} \sin(\omega_d t) \quad (15)$$

4.2. Software used

The software used is Picoscope 6 and Matlab. Picoscope 6 is a software application for Pico Technology oscilloscopes. Used with a picoscope hardware device, it creates an oscilloscope and spectrum analyzer on the computer. The picoscope collect voltage signals from the piezoelectric sensor. It also provides a graphical representation of the impact of the hammer on the floor when dropped from a height and provides the impulse time against voltage graph. The data collected by picoscope are saved as CSV files and computed by Matlab using the least square method where it is coded according to the fluid mathematical model.

5. Results and Discussions

5.1. Match with the fluid model

The curve obtained or plotted using Matlab from the data collected during the impact of the hammer on the two different floors. The data points collected by picoscope is computed with Matlab and a curve is plotted with acceleration against time when hammer first touches the floor till the contact is lost. The figures 3 and 4 the red curve is the new model and the blue color is the measured curve of floors. It clearly shows that the new model clearly matches or fits with two floors. The new model behaves exactly same as the two tested floors. Thus, we can validate the fluid model.

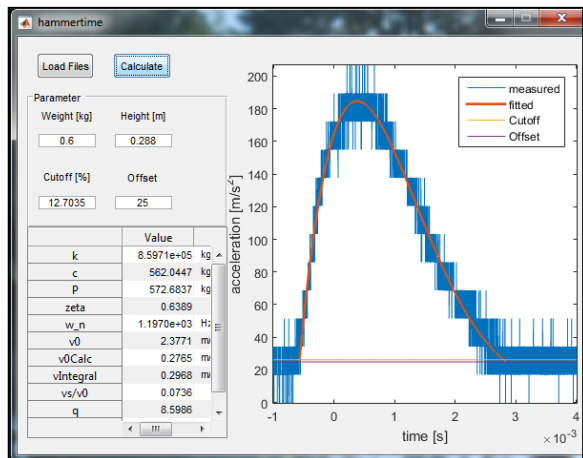


Figure 3. Kradal shock absorbing floor impulse response for an Impact velocity 2.4m/s

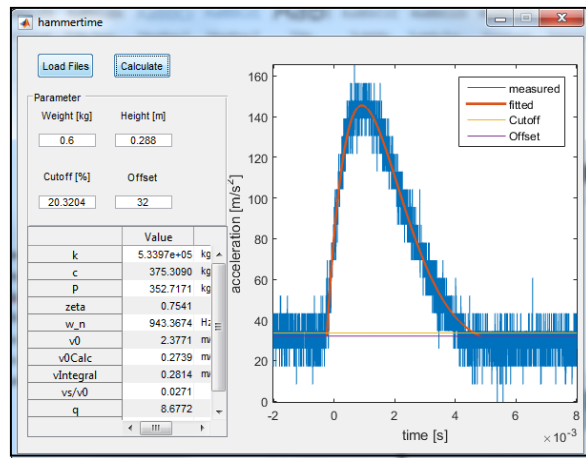


Figure 4. Kradal Tiles impulse response for an Impact velocity 2.4m/s

5.2. Stability for different velocities

The fluid model is stable or independent of different impact velocity. The k , c and ζ values do not change with different velocity. The below figures clearly describe the two-floor materials are independent of impact velocity. The parameters of model do not change with the change in impact velocity. So it proves the model's stability for different impact velocity.

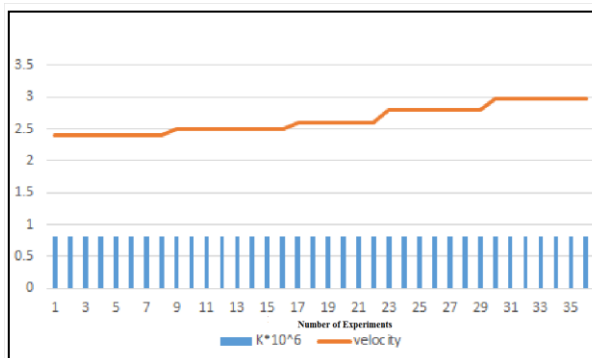


Figure 5. K vs Velocity for kradal shock absorbing floors

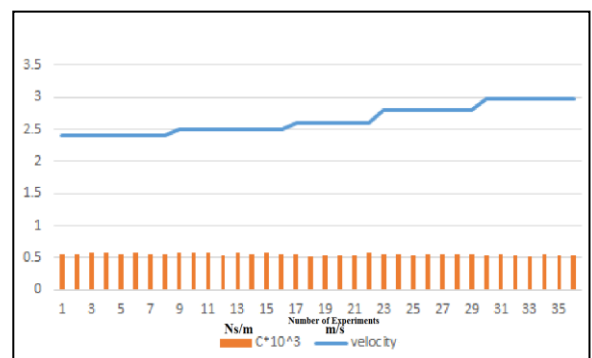


Figure 6. C vs Velocity for kradal shock absorbing floors

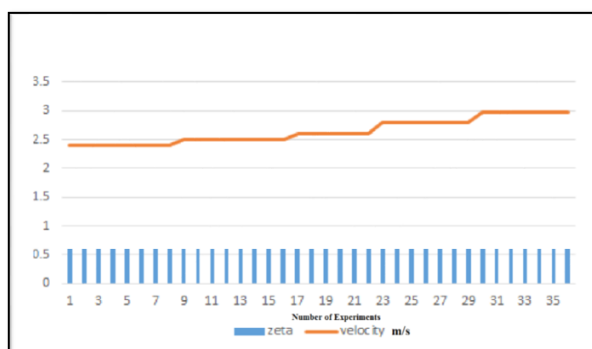


Figure 7. Zeta vs Velocity for kradal shock absorbing floors

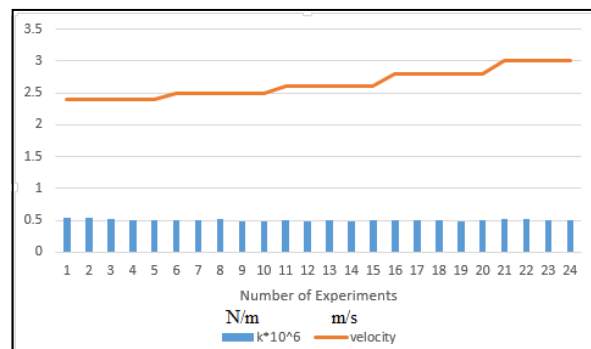


Figure 8. K vs velocity for kradal tiles

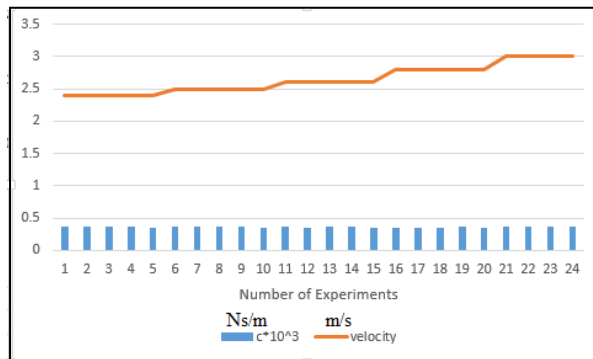


Figure 9. C vs Velocity for kradal tiles

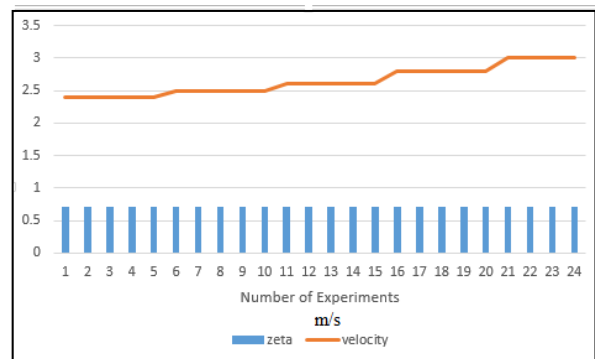


Figure 10. Zeta vs Velocity for kradal tiles

5.3. Mass Dependency

The mass of the body or people vary from people to people. So that the impact on hip bones during a fall may vary from people to people. It is necessary to check the mass dependency of the model. The mass of the hammer setup is fixed i.e. 0.6kg so to vary the mass in order to study the dependency of mass. The contact area of the hammer which comes in contact with the floor was reduced so that by reducing the contact area of the hammer where it hits the floor we can create the same impact when mass is increased. Thus, mass can be varied without adding mass to the experimental setup. With minimum velocity which is enough to make injury on the hip bone of elderly people i.e. 2.14m/sec was used to test the mass dependency of the new model on floors.

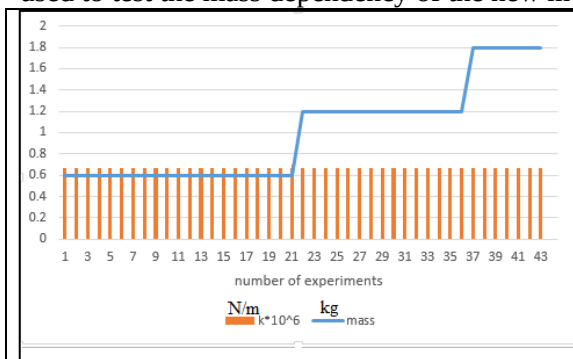


Figure 11. K vs mass kradal shock absorbing for an Impact velocity 2.4m/s

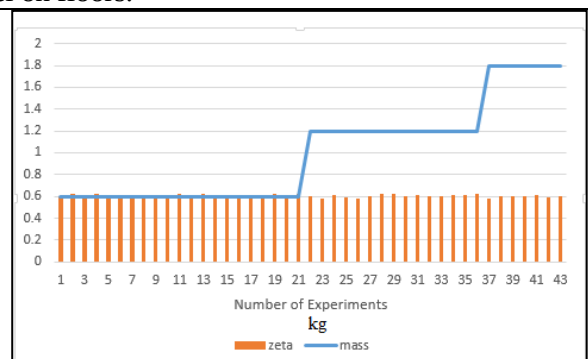


Figure 12. Zeta vs mass kradal shock absorbing for an Impact velocity 2.4m/s

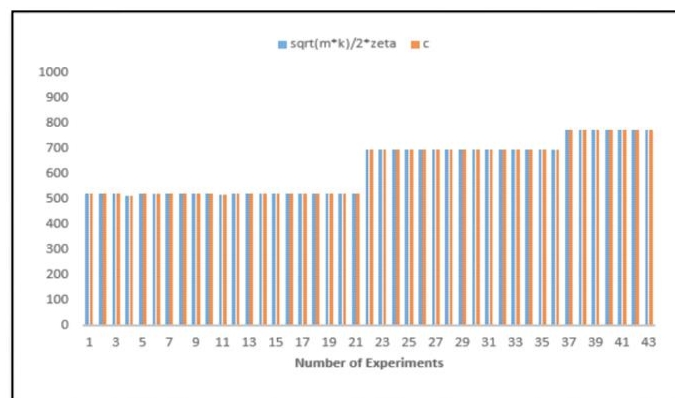


Figure 13. Measured damping constant (c) vs theoretically calculated C value for an Impact velocity 2.4m/s

From the above figures, it is very clear that the model is dependent on mass the k and zeta values are stable but the damping constant varies with mass. The damping constant is proportional to the square root of mass. The dependency of mass and zeta can be clearly seen in the figure: 13. It depends on

$$\Rightarrow c = \frac{\sqrt{mk}}{2\zeta} \quad (16)$$

5.4. Comparison of Test Floor with New Model

For comparison data are collected for mass 0.6kg and standard velocity of 2.4m/sec for the two types of floor which are mentioned earlier. And the average of all the parameters is presented in the table -1 below. Almost 50 readings were taken to validate it.

Table 1. Comparison of 2 -different floors

Floor	$K \cdot 10^6$ (Kg/s ²)	C (Kg/s)	ω_d (Hz)	Zeta ζ
Kradal shock absorbing floor	0.84 ± 0.04	0.55 ± 0.05	900 ± 5	0.65 ± 0.02
Kradal tiles	0.51 ± 0.04	0.36 ± 0.05	596 ± 5	0.76 ± 0.02

5.5. Floors that are not compatible with the fluid model

It shows that the fluid model does not fit for all types of floor. The curve doesn't fit with the measured curve of some floors like wooden floor material. It shows that model is accurate with the more elastic floors that are used in elderly homes.

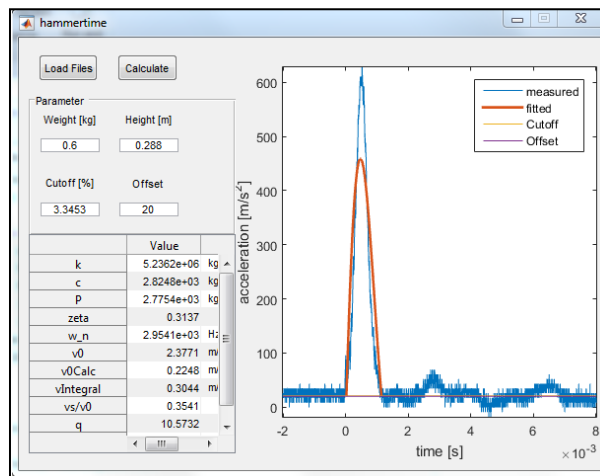


Figure 14. wooden floor material curve fit impulse response for an Impact velocity 2.4m/s

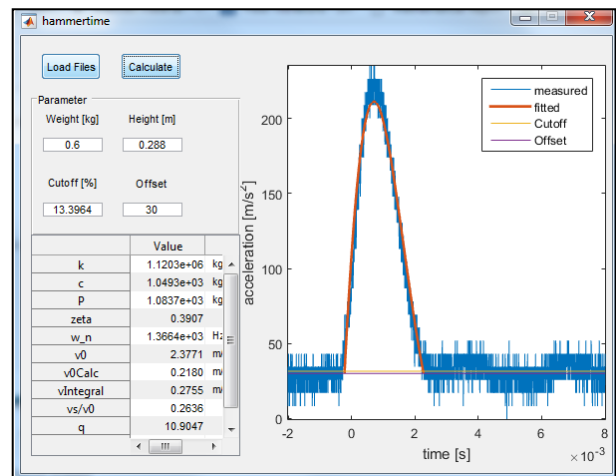


Figure 15. curve fit for combination of floors for an Impact velocity 2.4m/s

The figure 14 shows that measured curve is not at all fits the new model and the shock rate is too high with the wooden floor material alone. So it can cause serious injury during fall. Later by combining the wooden floor material with kradal shock absorbing floor material as shown in figure 15. The impact and shock rate were able to reduce. Figure 15 is obtained when the wooden and kradal shock absorbing floor materials are combined. From the figure 15 the rate acceleration during fall is around 600m/s² but after combining the floor material the rate of acceleration reduced to 200m/s². The new model curve fits exactly with the measured curve. But when those wooden floor materials are combined with the more elastic floor material they fit accurately with the fluid model. So that by this way we can reduce the impact on hip bones during fall. Those rigid surface of wooden materials can help the elderly people to walk properly and makes easy for the wheels of wheelchair and stretchers things to roll with less resistance at hospitals and elderly care homes

6. Conclusion

The parameters which describe the behavior of the various floor materials are important to look at when comparing the different variants are Impact velocity, mass dependency, shock rate, impact time, damping coefficient. These parameters help to distinguish various floor by their actual use. The tested floors are independent of the impact velocity. The kradal floor was found to be mass dependent. The damping constant is the only parameter which varies with mass. C is directly proportional to the square root of mass. To reduce the impact on hips during a fall the rebound time or the resilience of the floor must be high. If the rebound time is more it will reduce the magnitude of impulsive force on hip bones. The fluid model is not compatible with the floor material like wooden, concrete etc. which are more rigid. Rigid floor materials and more elastic floor materials should not be used in elderly care homes and hospitals. Rigid materials like wooden floor alone are used the impact on falling can cause serious injury and if only a more elastic floor material is used it can cause difficulty in walking and creates more resistance for rolling of wheels of the wheelchair and stretchers in hospitals. So it is recommended to use as a combination of both to encounter both the above-mentioned barriers. The impact during fall on these floors is not a linear vibration phenomenon. It is a non-linear vibration phenomenon.

After testing various floor materials it is clear that the fluid model is not compatible with all floor materials. To convert the model into a universal model there need to introduce some more components to the fluid model. As the impact force acting on the hip bones are sudden it is not only a linear vibration scenario it involves non-linear vibration phenomenon. Vibration caused by sudden contact or loss of contact is a non-linear vibration phenomenon. Due to the time limit, we have not described anything regarding non-linear vibration. But for the future work, we assume that it's necessary to look the situation in non-linear vibration perspective. So that a new universal model for floor can find out and all floor materials can be classified with that single model.

7. References

- [1] Demker, I. (2009). Determination of mechanical comfort properties of floor coverings. *SP Report, 4*.
- [2] Drozdov, A. D. (1996). *Finite elasticity and viscoelasticity: a course in the nonlinear mechanics of solids*. World Scientific.
- [3] Marc Delphin, M. (2011). A Simplified nonlinear generalized Maxwell model for predicting the time dependent behavior of viscoelastic materials. *World Journal of Mechanics, 2011*.
- [4] Bathelier, X., & Deconinck, B. A. (2011). *U.S. Patent No. 7,892,617*. Washington, DC: U.S. Patent and Trademark Office..
- [5] Harris, D. D., & Detke, L. A. (2013). The role of flooring as a design element affecting patient and healthcare worker safety. *HERD: Health Environments Research & Design Journal, 6*(3), 95-119.
- [6] Choi, W. J., Wakeling, J. M., & Robinovitch, S. N. (2015). Kinematic analysis of video-captured falls experienced by older adults in long-term care. *Journal of biomechanics, 48*(6), 911-920.
- [7] Wright, A. D., & Laing, A. C. (2012). The influence of headform orientation and flooring systems on impact dynamics during simulated fall-related head impacts. *Medical engineering & physics, 34*(8), 1071-1078.
- [8] Gustavsson, J., Bonander, C., Andersson, R., & Nilson, F. (2015). Investigating the fall-injury reducing effect of impact absorbing flooring among female nursing home residents: initial results. *Injury prevention, injuryprev-2014*.

- [9] Bertocci, G. E., Pierce, M. C., Deemer, E., Aguel, F., Janosky, J. E., & Vogeley, E. (2003). Using test dummy experiments to investigate pediatric injury risk in simulated short-distance falls. *Archives of pediatrics & adolescent medicine*, 157(5), 480-486.
- [10] Bhan, S., Levine, I., & Laing, A. C. (2013). The influence of body mass index and gender on the impact attenuation properties of flooring systems. *Journal of applied biomechanics*, 29(6), 731-739.
- [11] Santhosh, B., Narayanan, S., & Padmanabhan, C. (2015). Nonlinear Dynamics of Shrouded Turbine Blade System with Impact and Friction. In *Applied Mechanics and Materials* (Vol. 706, pp. 81-92). Trans Tech Publications.
- [12] B. Santhosh, Narayanan, S., and Padmanabhan, C., "Nonlinear Dynamics of a two degree of freedom Oscillator with a Snap Through Mechanism", in 8th European Nonlinear Dynamics Conference (ENOC 2014), Vienna, Austria, 2014.