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CASE HISTORY—PEER-REVIEWED

Material Selection of an Elastomer Capable of Absorbing Vibrations Actuated by a 4D Movie Theater

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Abstract The objective was to investigate possible vibration isolator solutions for a 4D entertainment theater. The paper focused on resolving a vibration leakage issue experienced by customers of Company A which manufactures tactile motion actuators for 4D theater entertainment purposes. The investigation started by utilizing Cambridge Engineering Selector software to determine the value of the mechanical loss factor for given materials. Elastomers had the best mechanical loss coefficient, specifically polyurethanes. While considering the specifications provided by Company A, certain parameters such as nominal load withstanding and prices were considered. After investigating the materials thoroughly, Sorbothane showed the best performance along with suitable prices. The vibrational system investigated resulted in a frequency ratio of 6, and a transmissibility of 2.86% at normal conditions, which indicates that the material selected was suitable. Sorbothane material at shore 00 and durometer 50 showed its capability to withstand maximum nominal loading at 635 kg (1400 lbs). This was 57% higher than the targeted loading. The mechanical loss factor was 0.52 at 50-Hz excitation frequency, which was high enough to dissipate excessive vibrations.

Keywords Ashby's charts · Polyurethanes · Mechanical loss coefficient · Transmissibility

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Introduction

The objective of this paper was to investigate possible vibration isolator solutions for a 4D entertainment theater. The approach was to conduct a material selection search within the elastomers family to resolve a vibration leakage issue claimed by customers of Company A. This company manufactures a vibratory system that actuates vibrations transmitted from an amplifier in order to provide a 4D experience while watching movies. The device manufactured by Company A operates as a vertical tactile motion actuator that transforms electrical signals into mechanical vibration motion.

The device is placed underneath each leg of a couch. The vibratory system including the vibration actuators responds to specific scenery in the movie and creates vibration responses to mimic the scenery in the seating environment. However, the device is in direct contact with the floor where it exposes vibratory energy that disturbs the surroundings. The vibration losses transfer into the floor and are not damped. Therefore, the issue is vibration leakage into floor. The specification requirements required by Company A for two different geometries are listed in Tables 1 and 2.

Background

The main idea behind this study was to select a material that is high in damping. Highly damped materials have the capability to absorb vibrational energy and damp it thoroughly. The best known vibration isolation materials are elastomers. Those materials have a significant mechanical loss factor coefficient, η, and yet have the least Young's modulus values [1].

Table 1 Specification list by Company A for square pad

Properties	SI units	Imperial units
Resonant frequency	20–80 Hz	20–80 Hz
Geometry	12.7 × 12.7(+5.1–0) cm	5″ × 5″(+2″–0″)
Thickness	0.254–1.27 cm	0.1–0.5 inches
Nominal load for pad	1779 N	400 lbs
Maximum load for pad	3559 N	800 lbs
Maximum price	$15.00 each	$15.00 each

Table 2 Specification list by Company A for circular rubber feet

Properties	SI units	Imperial units
Resonant frequency	20–80 Hz	20–80 Hz
Geometry (diameter)	5.1–10.2 cm	2–4″
Thickness	0.254–1.27 cm	0.1–0.5 inches
Nominal load for pad	445 N	100 lbs
Maximum load for pad	890 N	200 lbs
Maximum price (minimum order quantity 1000 pcs)	$5.00 each	$5.00 each

The Ashby's charts [2] were used in narrowing down the materials that have high mechanical loss factor coefficient, η, and low Young's modulus, E. The system being investigated represents an active application that aims to reduce the vibration from the machine to the ground shown in Fig. 1.

The natural frequency for the system is shown in the following equation:

$$f_o = \frac{1}{2\pi}\left(\frac{K}{M}\right)^{\frac{1}{2}} \qquad \text{(Eq 1)}$$

where K represents the dynamic spring stiffness, and M represents the weight (applied load). The natural frequency range is provided from the specification list. The excitation frequency of the vibration actuator, specifically for the device manufactured by Company A, had a range of 0–600 Hz. The vibrational transmissibility is the ratio of the energy going out of the system to the energy coming into the system. The lower transmissibility means the lower damage to sensitive components. Transmissibility analytical approach is shown in "Appendix" and calculated by the following equation:

$$T = \frac{F}{F_0} = \left|\frac{1}{1 - \left|\frac{N}{f_0}\right|^2}\right| \qquad \text{(Eq 2)}$$

where T represents transmissibility, F is the transmitted force, F_0 is the machine's excitation force, N is the interference frequency, and f_o is the natural frequency. The vibrational transmissibility was compared to the frequency ratio of the system studied. The key is to ensure that the material selected was under the area of isolation where magnification factor is equal to or greater than 1.4. The magnification factor is defined as the point at intersection between an underdamped system to a critical damped system, which is always constant having a value of $\sqrt{2}$. The dynamic stiffness can also be determined using the natural frequency chart by indicating the natural frequency and the nominal loading values [3]. The analytical calculation for frequency ratio is shown in "Appendix" and calculated by using the following equation:

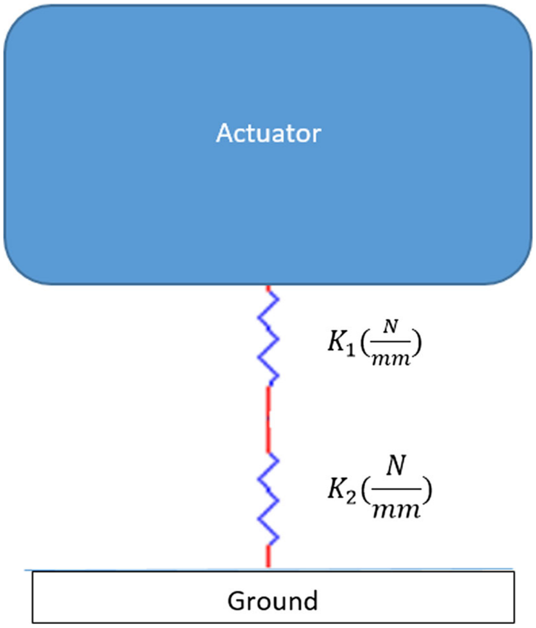

Fig. 1 Active application

$$\text{Frequency ratio} = \frac{N}{f_0} \qquad \text{(Eq 3)}$$

The frequency ratio and the transmissibility were plotted to ensure that the material selected lies under the isolation area, Fig. 2. The system has to impose a frequency ratio that is above the value of magnification factor.

Materials and Methods

The methodology was to use CES [2] in order to examine the relevant properties of the materials such as the mechanical loss factor coefficient, *η*, and Young's modulus, *E*, and updated market price. Figure 3 shows multiple selection options varying from metals having lowest mechanical loss factor coefficient, *η*, to elastomers having the best *η*.

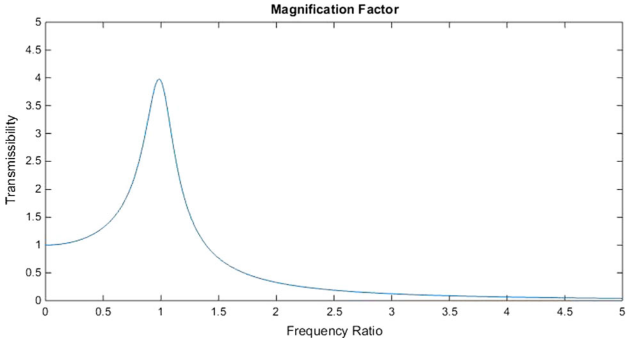

Fig. 2 Magnification factor

In Fig. 3, four different materials polyurethane foam, polypropylene foam, melamine foam and butyl/halobutyl rubber were compared. The first objective was to have a high mechanical loss coefficient and a low Young's modulus *E*. The process of selecting the best material starts by drawing a diagonal line in Ashby's chart. The materials that lie above the diagonal line will be considered and further examined. Since the polyurethane lies above the diagonal line, it has the highest mechanical loss coefficient and lowest Young's modulus; then, it will be selected as the best material for the study. The price is the second objective for the study. Company A indicated that the price should not be higher than five dollars per piece. Table 3 shows that polypropylene, butyl/halobutyl rubber and polypropylene meet the objective, but melamine does not meet the objective due to its high cost. Accordingly, melamine was eliminated.

In Figs. 3 and 4, the elastomer bubbles on top far left have highest *η*. In Figs. 5 and 6, the prices for elastomers selected versus their mechanical loss coefficient are shown.

The materials selected from CES [2] as shown in Figs. 4, 5, and 6 were all polyurethanes having differences in their microstructure. The prices given in Table 4 for the selected materials were relatively economical.

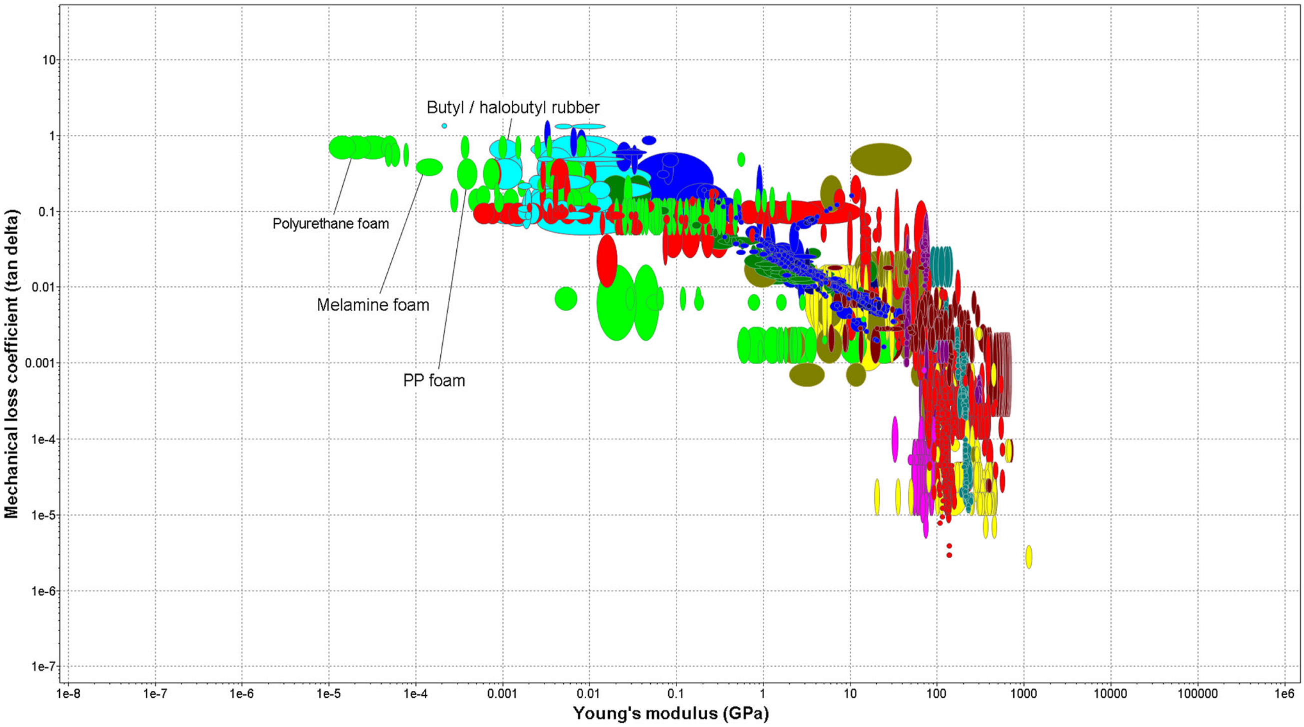

Fig. 3 Ashby's chart for mechanical loss coefficient vs. Young's modulus for all materials [2]

Table 3 Various elastomer prices and mechanical properties [2]

Material	Price (USD/lb; USD/Kg)	Young's modulus (psi; Kpa)	Mechanical loss coefficient
Polyurethane	(2.82–3.76 USD/lb) (6.2–8.3 USD/Kg)	(2.9–7.25 psi) (19.99–49.98 Kpa)	0.5–1.0
Polypropylene	(0.898–0.988 USD/lb) (1.979–2.178 USD/kg)	(43.5–72.5 psi) (299.92–499.87 Kpa)	0.2–0.5
Butyl/halobutyl rubber	(1.71–1.88 USD/lb) (3.769–4.144 USD/kg)	(102–218 psi) (703.27–1503.06 Kpa)	0.5–0.9
Melamine	(4.7–6.58 USD/lb) (10.36–14.506 USD/kg)	(14.5–29.0 psi) (99.97–199.95 kPa)	0.3–0.5

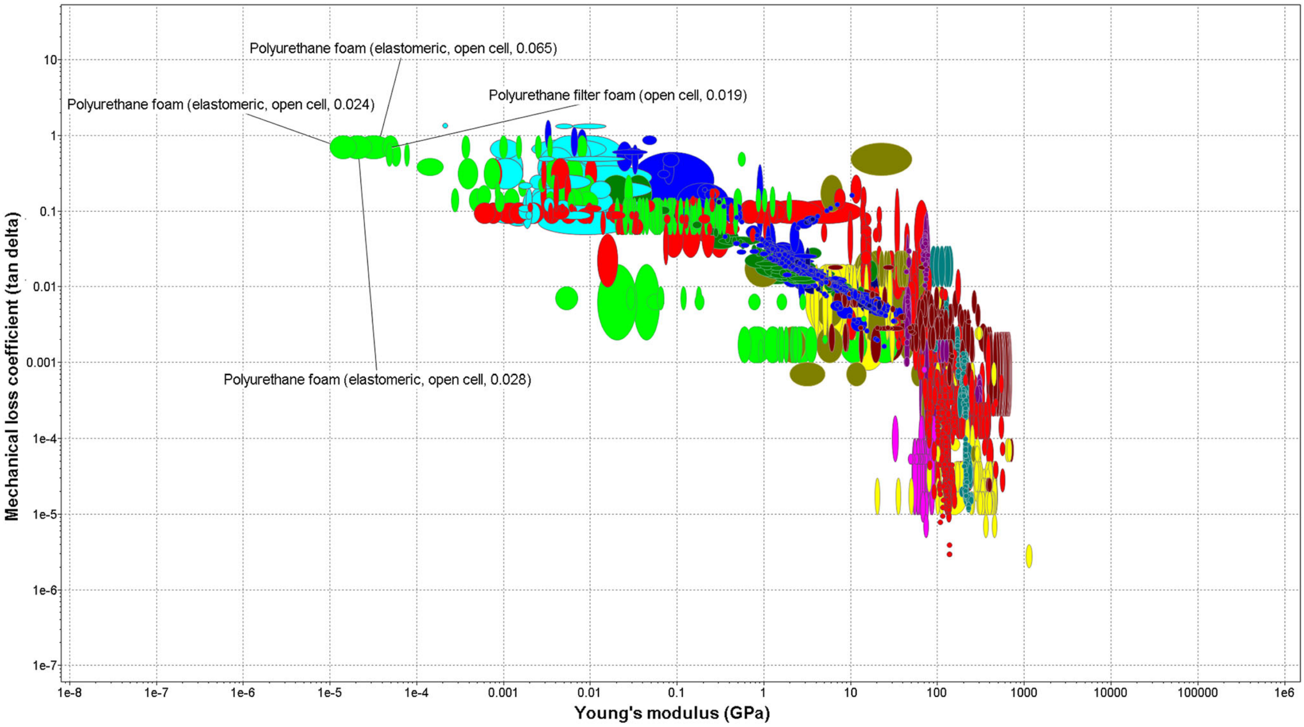

Fig. 4 Ashby's chart (η vs. E) for all materials [2]

The polyurethanes shown in Table 4 illustrate the best possible solutions for the selection. An initial selection has been made on the polyurethane foam (elastomeric, open cell, 0.024) based on its relatively low Young's modulus and low cost compared to other polyurethanes shown in Table 4. Hence, the 0.024 in the polyurethane name means the relative density value of the material. Once polyurethane foam (elastomeric, open cell, 0.024) was selected, the selection was suggested to Company A to find the raw material in the market, to create a mold design and to find a supplier. However, Company A was unable to find a supplier for the raw materials as well as a mold design creation. Therefore, Company A requested to research other possible sources besides Ashby's charts in order to find a supplier willing to provide a rubber molded by their unique design. A research online has been conducted to find a rubber that is specifically suitable for vibration isolation applications. The research resulted in finding out that there was a modified polyurethane composition owned by Sorbothane Company, which carries the same name, but shows a better performance than unmodified polyurethane in controlling mechanical vibrations and is suitable for vibration damping operations. Sorbothane is a viscoelastic polymer (polyurethane) that has low transmissibility verifying its damping superiority over other elastomers [3].

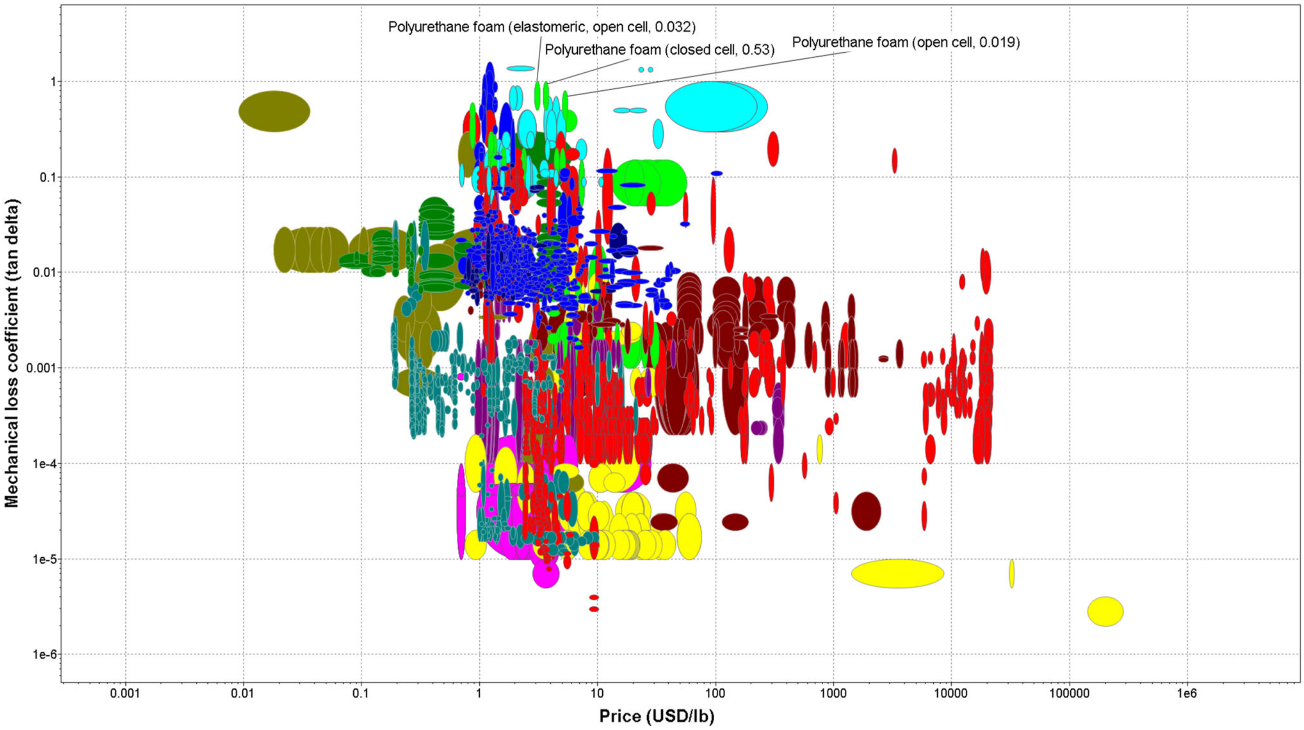

Fig. 5 Ashby's chart (price vs. η) for all materials [2]

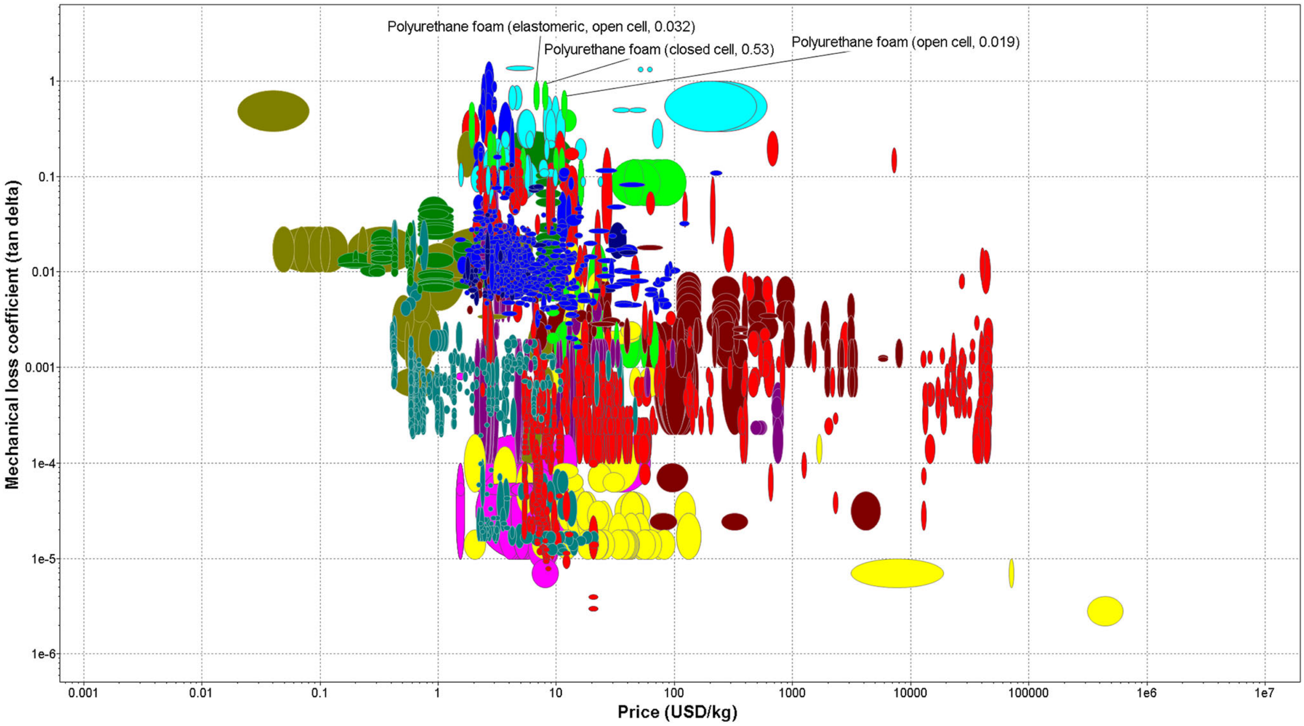

Fig. 6 Ashby's chart (price vs. η) for all materials [2]

Table 4 Materials selected based on price and mechanical loss coefficient from CES [2]

Material	Price (USD/lb)	Young's modulus (psi; Kpa)	Mechanical loss coefficient
Polyurethane filter foam (open cell, 0.019)	(4.7–7.52 USD/lb) (10.36–16.58 USD/Kg)	(6.38–7.52 psi) (43.99–51.84 Kpa)	0.5–1
Polyurethane foam (elastomeric, open cell, 0.065)	(2.82–3.76 USD/lb) (6.17–8.29 USD/Kg)	(2.9–7.25 psi) (19.99–49.98 Kpa)	0.5–1
Polyurethane foam (elastomeric, open cell, 0.028)	(2.82–3.76 USD/lb) (6.17–8.29 USD/Kg)	(2.03–4.35 psi) (13.99–29.99 kPa)	0.5–1
Polyurethane foam (elastomeric, open cell, 0.024)	(2.82–3.76 USD/lb) (6.17–8.29 USD/Kg)	(1.45–2.9 psi) (9.99–19.99 kPa)	0.5–1

Table 5 Sorbothane material properties [3]

Durometer	Shore 30	Shore 50	Shore 70
Tensile strength at break	(110 psi) (758 Kpa)	(172 psi) (1186 Kpa)	(173 psi) (1193 Kpa)
Elongation at break	645%	653%	395%
Tear strength	(16 lb/in) (286 kg/m)	(20 lb/in) (357 kg/m)	(31 lb/in) (554 kg/m)
Bulk modulus	(4.71 Gpa) (683 Kpsi)	(3.84 Gpa) (557 Kpsi)	(4.14 Gpa) (601 Kpsi)
Poisson's ratio	0.4066	0.4856	0.4947
Density	(81.91 lb/ft^3) (1312 kg/m^3)	(81.78 lb/ft^3) (1310 kg/m^3)	(82.28 lb/ft^3) (1318 kg/m^3)

Results

Table 5 represents the properties for Sorbothane provided by Sorbothane Company. The durometer shore 00 indicates the hardness scale for the rubber. The durometer values at which the selection is made have to be stiff appropriately that it does not affect the 4D experience. The rubber durometer has to be stiff enough that it is statically fixed at normal conditions. That is, shore 00 offers durometer 30, 50, 70, where the less durometer value implies less stiffness. At shore 00 grades 30 and 50, they fall under the extra soft rubber criteria, but shore 00 grade 70 falls under medium soft rubber, which is slightly stiffer than grades 30 and 50.

The mechanical loss coefficient for Sorbothane is represented in Table 6. At given resonant frequencies, the Sorbothane responds with different loss factor coefficients. The less the durometer, the more the mechanical loss coefficient. However, accounting for an appropriate stiffness for the application, if the least durometer is selected, even though it has the highest mechanical loss coefficient, the rubber will create undesired motion itself under the loadings. This will affect the desired mimicking motion created by the vibration actuator. Ultimately, the 4D experience will not be pleasurable.

In Figs. 7 and 8, Sorbothane was being compared to various types of common vibrational isolators used such as natural rubber and neoprene. Sorbothane was compared to natural rubber and neoprene to verify its performance in damping effectiveness. In Fig. 7, Sorbothane shows its capability to damp vibrations with a faster response by having smaller oscillations at given impact forces (G-force). Also, Sorbothane exhibited very low rebound when compared to other materials [5]. In Fig. 8, Sorbothane has the least transmissibility while maintaining a relatively similar frequency ratio to neoprene and natural rubber [5]. Low transmissibility means less damage to sensitive components [5].

Table 7 shows transmissibility analyzed for the vibrational system using Eq 2. The natural frequency is given by the range specified by Tables 1 and 2 for Company A. The driving frequency is averaged for the vibrational actuator, and the frequency ratio is calculated using Eq 3. The interference frequency is for the vibration actuator.

Figure 9 represents a square rubber pad that will be placed underneath the couch isolating it from the floor ground. Figure 10 represents circular rubber feet that will be placed underneath each chair leg.

Tables 8 and 9 show the general properties of the Sorbothane, which have been conducted by Sorbothane. The prices and the loading capability of the product are the market off-shelf price.

Table 6 Mechanical loss coefficient (tan delta) for Sorbothane [3]

	Durometer (shore 00)		
Mechanical loss coefficient	30	50	70
Mechanical loss coefficient at 5-Hz excitation	0.58	0.4	0.2
Mechanical loss coefficient at 15-Hz excitation	0.64	0.46	0.28
Mechanical loss coefficient at 30-Hz excitation	0.68	0.5	0.33
Mechanical loss coefficient at 50-Hz excitation	0.69	0.52	0.36

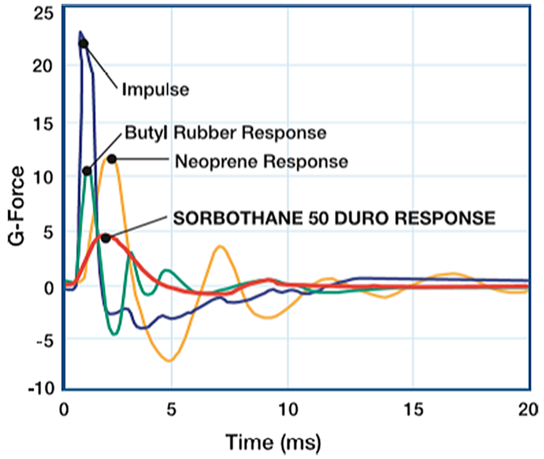

Fig. 7 Controlling shock [5]

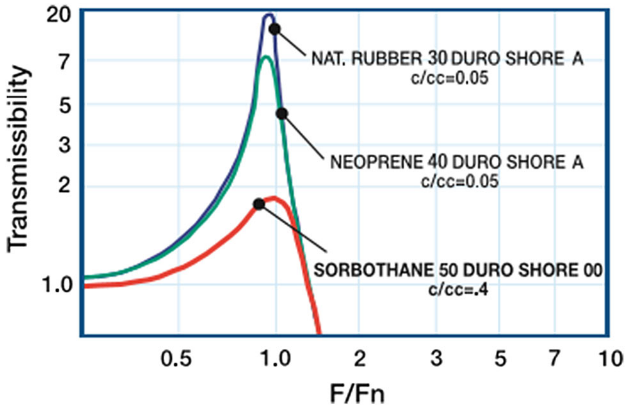

Fig. 8 Controlling vibration [5]

Table 7 Data analysis

Natural frequency (Hz)	50
Interference frequency (Hz)	300
Transmissibility	2.86%
Frequency ratio	6

Fig. 9 Square rubber pad [6]

Fig. 10 Circular rubber feet [7]

Discussion

Based on the results found, the selected polyurethane rubbers from Ashby's charts met the criteria of selection by evaluating their mechanical loss coefficient and price initially. Yet, the best possible solution was to consider far more factors than the material properties themselves. Company A is aiming to find a supplier that can supply rubber material in an off-shelf product or a unique mold designed by Company A. In addition, the company is aiming to establish a professional contract with the supplier for future business. Sorbothane as a vibration isolation solution company has a unique composition polyurethane rubber that is made specifically for vibration isolation tasks. Also, Sorbothane has a stock rubber pad that matches the exact dimensions given by the specification lists with ability to withstand excessive nominal loadings ranging between 900 and 1200 lbs (408–544 kg) for shore 00 durometer 30 and 1200–2400 lbs (544–1089 kg) for shore 00 durometer 50 [10]. Moreover, Sorbothane has circular rubber feet shape that has a similar performance and price of $2.5 for each. The mechanical loss coefficient and price

Table 8 Sorbothane prices [6–9]

Shape	Dimensions (inches; cm)	Quantity	Durometer shore 00	Price (USD)	Total price (USD)
Hemisphere	(1 × 1 × 0.5 inches) (2.54 × 2.54 × 1.27 cm)	8	50	1.87	14.99
Circular	(2.2 × 2.2 × 2.0 inches) (5.59 × 5.59 × 5.1 cm)	8	50	2.49	19.99
Square	(5 × 5 × 0.5 inches) (12.7 × 12.7 × 1.27 cm)	2	50	12.245	24.49
Small square pad	(0.5 × 0.5 × 0.2 inches) (1.27 × 1.27 × 0.51 cm)	36	50	0.6375	22.95

Table 9 Sorbothane loading capability [8, 9]

Shape	Dimensions (inches; cm)	Durometer shore 00	Load (lbs; Kg)
Square	(5 × 5 × 0.5 inches) (12.7 × 12.7 × 1.27 cm)	30	(900–1200 lbs) (408–544 kg)
Square	5 × 5 × 0.5 inches (12.7 × 12.7 × 1.27 cm)	50	(1200–2400 lbs) (544–1089 kg)
Square	(5 × 5 × 0.5 inches) (12.7 × 12.7 × 1.27 cm)	70	(2400–4800 lbs) (1089–2177 kg)
Small square pad	(0.5 × 0.5 × 0.2 inches) (1.27 × 1.27 × 0.51 cm)	30	(0.7–1.5 lbs) (0.31–0.68 kg)
Small square pad	(0.5 × 0.5 × 0.2 inches) (1.27 × 1.27 × 0.51 cm)	50	(1.4–3 lbs) (0.65–1.36 kg)
Small square pad	(0.5 × 0.5 × 0.2 inches) (1.27 × 1.27 × 0.51 cm)	70	(2.2–5.5 lbs) (1–2.5 kg)

were the most valuable parameters in the study. Sorbothane had a relatively high mechanical loss coefficient. The transmissibility analyzed for the viboratory system showed that the rubber lied under the isolation area having 2.86% transmissibility and a frequency ratio of 6 at occasional loadings. Also, the price if ordered by minimum order quantity is managed to be compromised if ordered in large quantities.

Summary

- Material selection for a suitable vibration isolation application was found to be an elastomer.
- Ashby's charts were utilized in searching for elastomer based on three main parameters: mechanical loss coefficient, Young's modulus and price.
- Transmissibility of the vibrational system is calculated to be 2.86%, whereas the frequency ratio was determined to be 6, yielding a rubber material that lies under isolation area.
- Sorbothane is selected based on its rapid performance in controlling shock and vibration compared to other elastomers.
- For pad selection, Sorbothane with shore 00 durometer 50 was available at Sorbothane with dimensions matching the specification list of 0.127 × 0.127 m (5″ × 5″) and 0.0127 m (0.5″) thickness for a price of $12 for a singular pad; total savings are 19%.
- For circular rubber feet selection, Sorbothane offers them with shore 00 durometer 50 with a price of $2.50 for each, saving up to 50% for specification list maximum price.

Appendix

Natural Frequency Calculations

$$f_o = \frac{1}{2\pi}\left(\frac{K}{M}\right)^{\frac{1}{2}}$$

where

K Stiffness in Newton's per meter
M Mass in kilograms

Vibration Isolation Calculation

$$T = \frac{F}{F_o} = \left|\frac{1}{1 - \left|\frac{N}{f_o}\right|^2}\right|$$

where

F Transferred force to the ground (N)
F_o Machine's excitation force (N)
N Interference frequency (Hz)
f_o Natural frequency (Hz)

$$T = \left|\frac{1}{1 - \left|\frac{300}{50}\right|^2}\right| = \frac{1}{35} = 0.0286$$

$$T = 2.86\%$$

Frequency Ratio

$$\text{Frequency Ratio} = \frac{N}{f_0}$$

where

N Interference frequency (Hz)
f_o Natural frequency (Hz)

$$\text{Frequency Ratio} = \frac{300}{50} = 6$$

References

1. M. Ashby, *Materials Selection in Mechanical Design*, 4th edn. (Butterworth-Heinemann, Burlington, MA, 2011)
2. Granta Material Intelligence. Cambridge Engineering Selector (CES EduPack). Cambridge, UK. Retrieved on 2015 (2015) http://www.grantadesign.com
3. Sorbothane. Data sheet 101, Material Properties of Sorbothane, Retrieved on January 27, 2015. (2015) http://www.sorbothane.com/Data/Sites/31/pdfs/data-sheets/101-sorbothane-material-properties.pdf
4. Durometer shore hardness scale, Smooth-On Make it Now: Retrieved on 2015. (2015) http://www.smooth-on.com/Documents-Duromete/c1351_1370/index.html
5. Sorbothane. Data sheet 102. Performance Curves. (2015) http://www.sorbothane.com/Data/Sites/31/pdfs/data-sheets/102-Sorbothane-performance-curves.pdf
6. Isolate It: Sorbothane Vibration Isolation Square Pad 50 Duro (.50″ Thick 5″ × 5″) 2-Pack, Amazon, Retrieved on December 3, 2015. (2015) http://www.amazon.com/Isolate-Sorbothane-Vibration-Isolation-Square/dp/B0042U92TE/ref=sr_1_4?ie=UTF8&qid=1449864991&sr=8-4&keywords=sorbothane
7. Isolate It: Sorbothane Vibration Isolation Circular Pad 50 Duro (.25″ Thick 2.25″ Dia.) - 8 Pack, Amazon, Retrieved on December 3, 2015. (2015) http://www.amazon.com/Isolate-Sorbothane-Vibration-Isolation-Circular/dp/B0042U8P9C/ref=sr_1_2?ie=UTF8&qid=1449864991&sr=8-2&keywords=sorbothane
8. Sorbothane Hemisphere, IsolateIt: Material Property Data, Retrieved on December 3, 2015. (2015) http://www.isolateit.com/hemispheres/sorbothane.html
9. Sorbothane Sheets & Pads, (0.5″ × 0.5″), IsolateIt: Material Property Data, Retrieved on December 3, 2015. (2015) http://www.isolateit.com/vibration-isolating-sheets-pads-16/0-50-0-50-sound-vibration-isolating-materila.html
10. Sorbothane, Isolation Pads, Sorbothane, Material Property Data, Retrieved on December 3, 2015. (2015) http://www.sorbothane.com/Data/Sites/31/pdfs/product-guides/sorbothane-spg-isolation-pads.pdf