

EN4 Dynamics and Vibrations

Design Project

Design and Construction of a Vibration Isolation System

Synopsis

The goal of this project is to design, build and test a system to isolate a sensitive instrument from ground-borne vibrations. The deliverables for this project are:

- (i) A fabricated vibration isolation system
- (ii) A short report that (a) describes your design process; (b) includes a calculated estimate of the natural frequency of your isolation system; and (c) an estimate of the expected reduction in vibration amplitude that your device will achieve
- (iii) An oral presentation describing your design and demonstrating its performance.

Brown Design Workshop will be open for construction between April 11 and April 14 (see the class website for TA and Faculty hours). Project testing will take place between 9am and 5:00pm on April 15.

1. Introduction

People and sensitive instruments need to be protected from vibrations. Buildings are mounted on special pads which isolate them from roadway vibrations caused by traffic; the suspension system on your car, and the padding on its seats, are designed to protect you from uncomfortable vibrations induced by driving over a rough road; and instruments (such as electron microscopes or atomic force microscopes) are always mounted on special vibration isolation tables.

The simplest vibration isolation systems exploit the behavior of a base-excited spring-mass system: as we have discussed in class, if the natural frequency $\omega_n = \sqrt{k/m}$ of the system is much lower than the frequency of base excitation ω , the amplitude of vibration of the mass is proportional to $\zeta \omega_n / \omega$, where $\zeta = c / 2\sqrt{km}$ is the damping factor. This shows that a mass can be prevented from vibrating by mounting it on very soft springs. It also suggests that the system should be as lightly damped as possible, which is true, but some damping is always necessary to make sure that if the system is perturbed from its

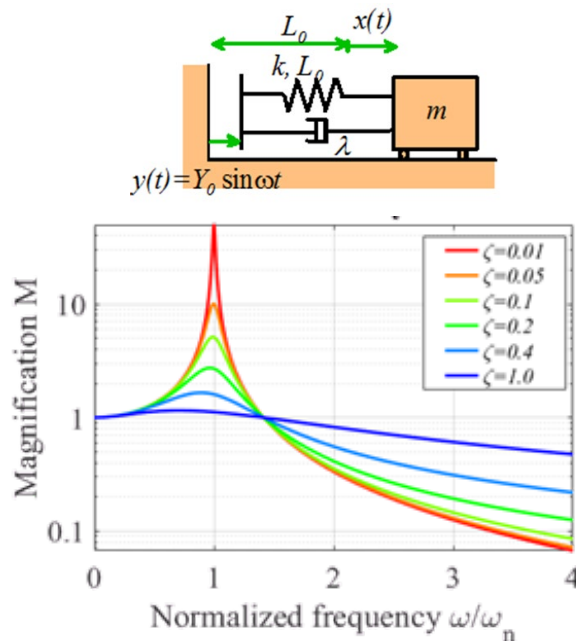


Figure 1: Amplitude of vibration of a base-excited spring mass system as a function of frequency

equilibrium position the subsequent transient vibrations die out quickly; and to avoid a large vibration amplitude if the system is accidentally excited at its resonant frequency.

A large number of clever ways to make very soft vibration isolation springs have been invented – these include conventional suspension springs; special elastomeric pads; foams; pendula; air springs, and many others. Some designs even claim to achieve zero or negative stiffness.

Other approaches to preventing vibrations include tuned vibration absorbers (which exploits the observation that a two spring-mass system has an anti-resonance); or active suspensions, which use actuators and sensors to apply forces to the system that is being isolated so as to cancel out any external forces. Most of these cannot be made with the materials and parts provided for this project, but you can certainly come up with creative and very effective designs that are more sophisticated than a simple spring-mass system.

In this project, you will design a small-scale vibration isolation system. The system should protect an object from horizontal ground-borne vibrations. Your design will be tested by attaching it to a vibration test-stand that will subject its base to horizontal vibrations with known amplitude and frequency. The vibration of an object supported by your test-stand, together with that of the table, will be measured using a pair of three-axis accelerometers to determine the effectiveness of the vibration isolation.

2. Design Specifications

Your vibration isolation system should provide a flat platform with dimensions at least 5”x5” on which the user can support a mass between 100 and 400 grams. The isolation system should meet the following specifications:

1. It must be capable of isolating horizontal ground-borne vibrations (which you can assume to be in one direction only) with frequencies ranging from $8 < f < 45$ Hz (see Section 5 for details of how your design will be tested). You should aim to reduce the horizontal vibration amplitude as much as you can. If you are able, you should also try to design your system to isolate vertical vibrations with frequencies in the same range as the test stand also exerts a smaller vertical base excitation (particularly at higher frequencies).
2. The total mass of your system (excluding the additional mass) must not exceed 300 grams (**be sure to think about the weight of your design – you will not be able to make the support structure out of a big solid piece of Al sheet because this will exceed the weight limit**)
3. Your device should be designed so that it can be bolted to the perforated aluminum platform of the vibration test-stand described in Section 4.
4. Your device should contain an attachment point to mount a 3 axis accelerometer for testing.
5. Your device should fit inside a 8”x8”x8” cube (but note that the base of the vibration test-stand is 7.5”x12” and cannot accommodate an 8” base).
6. Your design may be adaptable if you wish (so you can make changes to support a larger or smaller mass, or to isolate a different frequency) but it must be possible to change the device from one configuration to another in less than 3 minutes.

When you design your vibration isolator, you will need to try to (i) find a way to mount the platform on some form of soft spring (note that this does not actually need to be a spring - horizontal vibrations can be isolated using a pendulum, for example); (ii) if necessary, find a way to damp the system (you can use friction; or air drag; or come up with your own idea); (iii) make

sure that your system has no vibration modes with natural frequencies close to the 8Hz - 45Hz range.

When considering candidate designs,

- Make sure that the static deflection of your isolation platform will not be excessive.
- Try to anticipate the vibration modes of the structure. You want the horizontal vibration mode (and possibly the vertical mode) of the isolation platform to have a low frequency, but any other modes (rocking, vibration of the support structure, etc) to have a natural frequency higher than 45Hz.
- Don't forget the factor of 2π relating angular frequency to cycles/sec!.
- Try to keep the design simple, so you can predict how it will work with simple calculations (you will probably find the energy method for estimating natural frequencies to be quite helpful). If your design contains a hundred springs, it will be difficult to control (the springs themselves can vibrate in unexpected ways).

You will probably find you have to modify your design a few times to fix problems (this is normal – the most successful engineers get their designs to fail as quickly as possible so they can redesign them before their competitors). Make sure you leave some time in your construction/test schedule to fix problems.

3. Materials and supplies

You will be provided with the following materials and supplies with which to construct your design:

The following assortment of extension springs (the part numbers are from McMaster-Carr)

Stiffness (lb/in)	Spring OD (in)	Un-stretched length (in)	Min load (lb)	Max load (lb)	Part Number
0.04	0.281	2.5	0.04	0.51	9654K49
0.06	0.25	1.875	0.04	0.51	9654K512
0.2	0.188	1.875	0.08	0.86	9654K816
0.5	0.188	1	0.11	0.75	9654K969
1.01	0.344	1.5	0.31	2.03	9654K912
1.59	0.125	1	0.26	1.1	9654K966

The following assortment of compression springs (the part numbers are from McMaster-Carr)

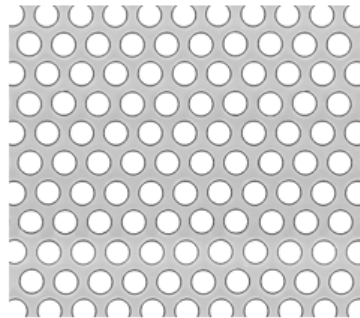
Stiffness (lb/in)	Spring OD (in)	Un-stretched length (in)	Max load (lb)	Part Number
0.29	0.187	1.75	0.36	9657K45
0.46	0.187	1	0.32	9657K43
0.9	0.25	1.75	0.97	9657K42
1.43	0.156	1.75	1.40	9657K62

In addition, the following materials and supplies will be provided

16 gage Perforated Al sheet (0.05" thick) (can be cut to size and bent into L or U sections)	McMaster 9232t181
14 gage Perforated Al sheet (0.06" thick) (can be cut to size and bent into L or U sections)	McMaster 9232t191
3/32" diameter TIG welding rod, 36" long (fits in holes in perforated sheet)	McMaster 7972A439
Foam-core board	
String	
3/16" Collars	McMaster 9414T5
Pop rivets	
4-40 Machine Screws; length between 1/4" and 2"	McMaster 91792AXXX
4-40 Nuts	McMaster 9048005
Star washers	McMaster 91114A005
Washers	McMaster 98023A111
Nylon Spacer, 1/4" OD, 1/2" length	McMaster 94639a295
Nylon Spacer, 1/4" OD, 1/4" length	McMaster 94639a293
Nylon Spacer, 1/4" OD, 3/4" length	McMaster 94639a297
Nylon Spacer, 1/4" OD, 1" length	McMaster 94639a298

Lightweight Alloy 3003 Aluminum Perforated Sheet

36" x 40", .125" Hole Diameter, 40% Open Area, .05" Thick



☐ Each

In stock
\$52.56 Each
9232T181

ADD TO ORDER

Hole Diameter	0.125"
Open Area	40%
Center-to-Center Spacing	0.188"
Additional Specifications	36" x 40" 0.05" Thickness (16 Gauge)

Lighter in weight than steel and stainless steel, Alloy 3003 aluminum has good corrosion resistance, weldability, and formability. Holes are staggered.

Figure 2: Specifications for Al perforated sheet. The base of the vibration test-stand is constructed from this material. You can cut and bend it to construct structural members for your test stand. 'L' or 'U' shaped structural members will have the greatest bending stiffness.

4. Design Report

Your report should include

1. A description of the final design, with important specifications and any instructions necessary for its use;
2. Technical drawings that would be sufficient for someone to construct the device;
3. A calculation estimating the lowest natural frequency of your isolation system (if you can estimate natural frequencies for both horizontal and vertical vibration that would be even better). To do this calculation you will need to idealize your test-stand somehow (as a pendulum, spring-mass system, or spring-rigid body system as appropriate), derive the equations of motion, and arrange the equation in the standard form to read off the natural frequency. Don't worry if you need to make assumptions to do this calculation that might make you uncomfortable – that often happens in engineering and we just do the best we can. If you want to analyze a more challenging design there are some notes on forced vibrations of systems with many degrees of freedom [here](#);
4. An experimental measurement of the natural frequency of vibration for your platform (you could measure the damping as well, e.g. by using a free vibration experiment. You won't be able to measure the free vibration of your system with the accelerometers, but you could put a tracking marker on your platform, and take a video. You can modify the tracking code you used in the mass launcher project to plot the displacement as a function of time (you will need to change the frame rate in the code to match your video source).
5. An estimate of how much you expect your system to reduce vibrations (i.e. its transmissibility) at $f=8\text{Hz}$ and at $f=45\text{Hz}$.
6. An experimental measurement of the transmissibility.
7. A short description of candidate design solutions that your team considered, with an explanation of why the final design was selected;

5. Testing

Your isolation system will be tested on a purpose-built test-stand, shown in Figure 3. The table consists of a platform with dimension 7.5"x12" made from perforated aluminum sheet, which is mounted on a linear bearing. An electromagnetic shaker causes the table to vibrate horizontally along one direction at a prescribed frequency that can range from 1 to 800 Hz. The motion is approximately harmonic. At frequencies exceeding 20Hz the table will also subject your design to a vertical vibration with smaller amplitude. The base of the table is fairly stiff, but will bend if you attach something heavy to it, which may result in unexpected vibration modes. It is best to keep your design as light as possible to avoid this.

The amplitude of vibration is adjustable, and varies with the vibration frequency. At 1Hz the maximum possible vibration amplitude is of order 2.5cm; at 50Hz it is about 0.75mm. Representative acceleration histories measured at two frequencies by a 3-axis ADXL362 accelerometer attached to the

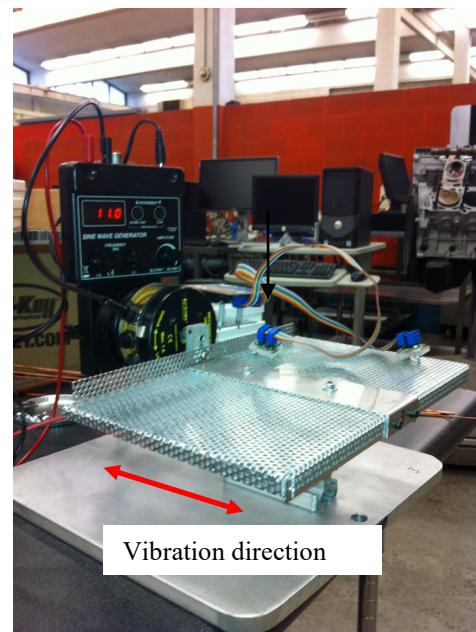


Fig 3: Vibration test-stand, with two 3-axis accelerometers. The table has dimensions 7.5"x12" and has holes compatible with 16 gage Al sheet

table are displayed in Figure 4.

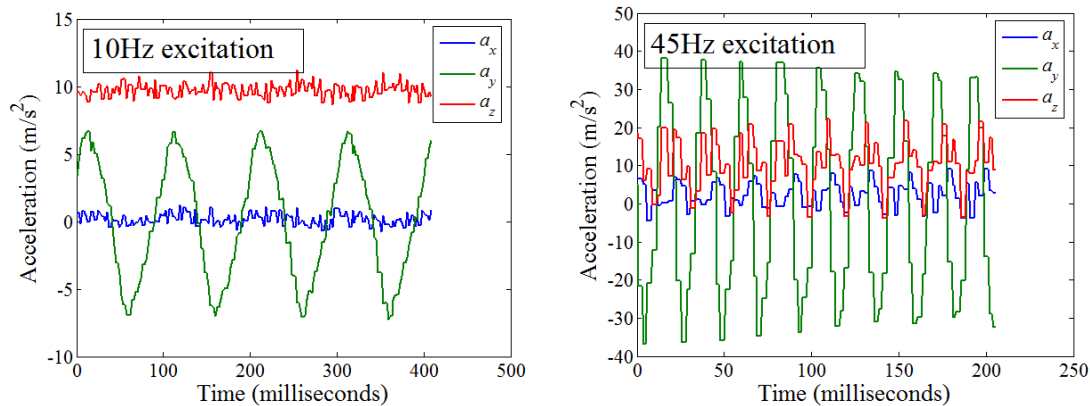


Figure 4: Representative accelerations of the platform. Note that the accelerometers have a maximum data rate of 400Hz, which causes the steps on the accelerations at higher frequencies.

Your design will be tested by attaching an accelerometer to your isolation system, and measuring simultaneously the acceleration of isolation platform and the shake-table. You can use data from the test to demonstrate the performance of your device during the final presentations.

The test-stands will also be available for you to test your designs during the construction period. We only have five vibration tables, however (they are custom made and surprisingly expensive), so you will only be able to use them for a short period of time, and at busy times may have to wait for them to become available.

6. Evaluation

The design testing will take place in Brown Design Workshop on Friday April 15, from 9 am-5:00pm. Four simultaneous 30 minute test time slots will be offered throughout the day.

Each group will

- (1) Test the performance of their design by measuring its ability to isolate vibrations at a few frequencies with a few different objects on the isolation platform;
- (2) Give a brief (10 minute max) oral presentation, showing design drawings and design parameters, and explaining the basis for the final design.

The design report is due at 9am the day of the presentation.

Design and performance will be assessed according to the following guidelines:

Design concept, construction	10 points
Performance (ability to isolate vibrations)	10 points
Oral presentation	10 points
Report and calculations	15 points
Peer evaluation (confidential)	5 points

Appendix: Using the accelerometers

The accelerometer measurements will be made using an Arduino board that will connect to your laptop through a USB port. You can read data from the board using Matlab. On the project website you will find

1. A Matlab code that will communicate with the Arduino board and plot graphs of acceleration –v- time measured by both accelerometers (on the same graph). The code will also save the acceleration-v-time data into a comma separated value file at the end (after you press ‘stop’ on the plot window). You can use the MATLAB script as-is, if you wish, but if you like tinkering with Matlab you can edit it to present the performance of your device in a more creative and effective way.
2. We have also provided the Arduino code (‘sketch’) that runs on the Arduino board and communicates with the accelerometers and your laptop. You should not need to use this, but if you know how to program Arduino boards and want to do something fancy you are welcome to edit the code or write your own. Note that we are using Arduino Uno boards which have only 2k of internal memory for data storage so it is difficult to do anything very sophisticated with the data on the Arduino board itself.
3. The specification sheet for the ADXL362 is also posted on the website. This will tell you how you can use the Arduino to change the settings on the accelerometer (but you will need to know a bit about computer architecture to be able to follow the spec).

The Arduino boards with accelerometers connected to them are pre-loaded with the software that communicates with MATLAB, and you should be able to use them without writing or uploading your own Arduino code. But if you like, you can modify the code: if you would like to program the Arduino boards you will need to first install the Arduino IDE on your computer (you may have done this in EN30). The Arduino IDE can be downloaded [here](#).

To connect the Arduino to MATLAB, you will first need to find out the COM port address for the USB port that has the board connected to it. Open the Matlab code and edit the line that has ‘COM5’ in it (line 14 in the script) and replace the ‘COM5’ with the correct COM port address (on a Mac it will be something that looks like /dev/cu/xxxxx).

Then you should be able to run the Matlab script by pressing the green ‘run’ arrow. If Matlab connects to the COM port successfully a button will come up that says ‘press OK to begin measurement’ – once you are ready to view your data press OK – a figure window should open, and start showing graphs of acceleration –v- time for each accelerometer. The RMS values of each acceleration component are also displayed, and the window has some buttons that let you change the time interval between data points (the ‘delay time’) and the sensitivity of each accelerometer, if you wish. Once you are done taking measurements press the ‘stop’ button – this will close the serial communication with the Arduino board.