

12.3.8 Vibrations

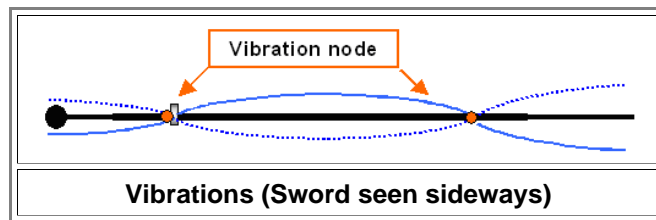
The Basics

In most of the modules in this section your sword was treated as a "rigid body". It could not deform or change its shape in any form. From a Materials Science point of view it was a boring dead object with only 2 boring properties: mass and shape, i.e. mass distribution. Your sword, however, is at least an *elastic* object. It deforms elastically to some extent when forces are applied. Worse, it even may deform plastically or even fracture but this we will still neglect.

The elastic properties we cannot neglect any longer because they are the reasons for the **vibrations** of the blade (and the handle) you may encounter whenever you hit something sufficient hard. You may see the blade actually vibrating and you will feel vibrations in your hand. If your life depends on your sword (and your ability to wield it), you will pay a lot of attention to this subject since it is a major point (and problem) in a sword fight.

So what can I tell you on this subject? Certainly that it is very complex if you want to look at it quantitatively, i.e. derive numbers. That's why I'm keeping this short and qualitative.

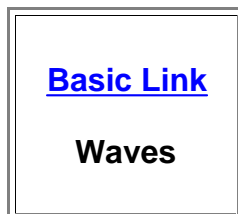
Let's start with an experiment. Hold your sword up and hit the blade on its flat part hard with a hammer or something. Or simply throw it down on the ground. Changes are that you will see the blade vibrating roughly like this



We see what is called a "[second harmonic](#)" and the question is what this means. And why we don't see the first or seventeenth **harmonic**. The we have tow more special points in the sword, called "vibrations nodes" in the picture above. How do they relate to all the other points that we already discussed, e.g. the [percussion point](#)?

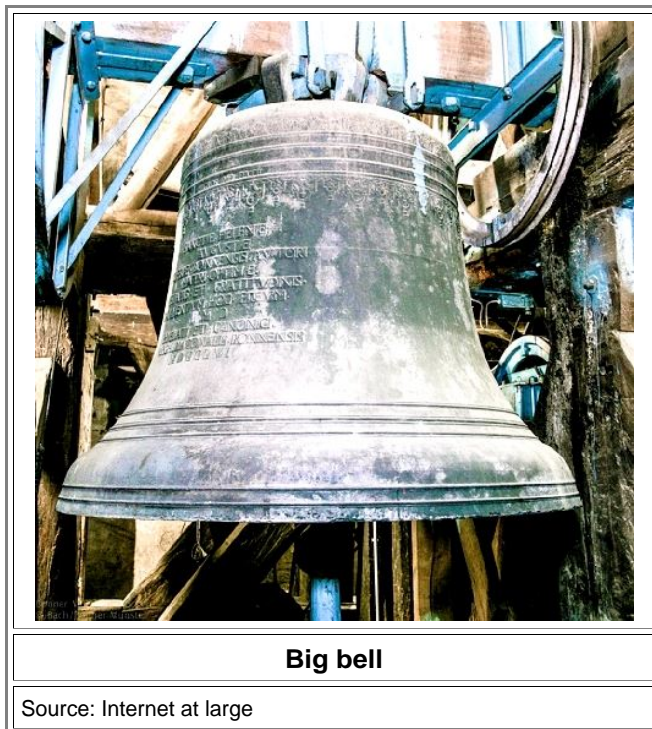
Tough questions. Let's start by considering in a very general way what will happen to (reasonable) objects if they are shaken by something with a given frequency ω . Take your spouse and shake him because he deserved it for one reason or the other. The frequency then is rather low and you spouse will just wiggle with the frequency you employ. The second you stop shaking, he will stop wiggling. This is because the wiggles or oscillations he performed while forced are heavily damped, i.e. decay rapidly without external influences. Every oscillating body will stop oscillating sooner (heavy damping) or later (small damping) when the forces causing the oscillations are stopped. If you're not sure about the meaning of terms like frequency, wavelength, destructive interference and so on, consult the basic module outlined below.

If strong or weak damping is experienced depends on the oscillation frequency, the objects geometry and the material properties of the object. In the case of your spouse, the material properties dominate by far and cause heavy damping at all (reasonable) frequencies. The reason for this is simple: your husband is a slime bag! You knew that all along but now you have the irrevocable proof. There is no stiffness or hardness in his body (at least most of the time and in



most of the body),
and that always
causes heavy
damping.

So let's look for something more rewarding than your spouse when you shake it. A bell, for example. Something like this:



In order to save time, we don't just shake it with one frequency, then with another one and so on to figure out its response, we shake it with many superimposed frequencies in parallel. Any physicist will tell you that this amounts to hitting it with a hammer. If you watch closely (very closely) you will see that the bell vibrates with all frequencies while you hit but that right after the hit, vibrations with most frequencies "die out", i.e. are heavily damped and disappear, while a few with some particular frequencies last for quite a while.

You know that because you hear it. The bell rings with a well-defined pleasant tone after being hit with a hammer or something (in contrast to your spouse who won't ring or produce pleasant tones of any kind upon being hit with a hammer). The vibrating bell makes the air around it vibrate too, and that is what you hear as long as the frequencies are in the auditory region of roughly 20 Hz to 20.000 Hz. The bell rings with a clear tone or basic frequency (plus a few "harmonics") and not with all the frequencies that were contained in whatever caused the vibrations. The reason behind this phenomena is that only some particular and special frequencies, the "**Eigenfrequencies**" of the bell, can "live" in there for a long time (several seconds instead of just milliseconds for all the other frequencies). You might say that all frequencies except a few Eigenfrequencies are heavily damped. Two questions emerge:

1. What determines the Eigenfrequencies of the bell (or any other object, in particular musical instruments)?
2. Why are all other frequencies heavily damped?

It's actually only one question, just asked in different ways. The answer is simple in principle:

1. Besides Young's modulus of the material (and a few other minor material contributions), it is the *shape*, the geometry of the object, that determines the Eigenfrequencies.
2. All frequencies besides the Eigenfrequencies cancel themselves by "destructive" interference and therefore disappear very quickly

Easy enough in principle and devilishly difficult to calculate for non-trivial geometries in more than one dimension.

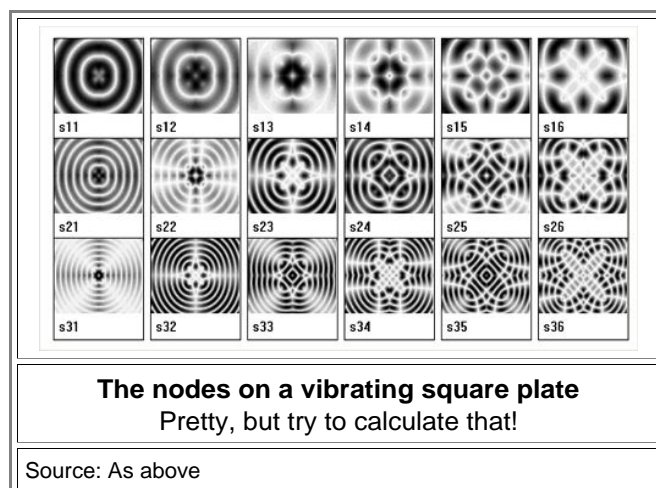
Now we know that all "elastic" or "hard" objects, including your sword but not your slime-bag spouse, can vibrate with some special Eigenfrequencies. They do so in what is called "**Eigenmodes**". A vibration means that *some* points on the objects are moving back and forth with the Eigenfrequency of the Eigenmode but not necessarily that *all* points do this. In fact, some points will not move at all - we have "**nodes**" of no movement.

Another strange word. "*Eigen*"-frequency, "*Eigen*"-mode (not to mention Eigenvector, Eigenvalues, and so on. Well, you just experience mixed German - English words. "*Eigen*" is German and means "own" in both sense of the english word: it's your own and you own it. Just a little historical reminder that large parts of modern Math and Physics were originally conceived in the [true language](#).

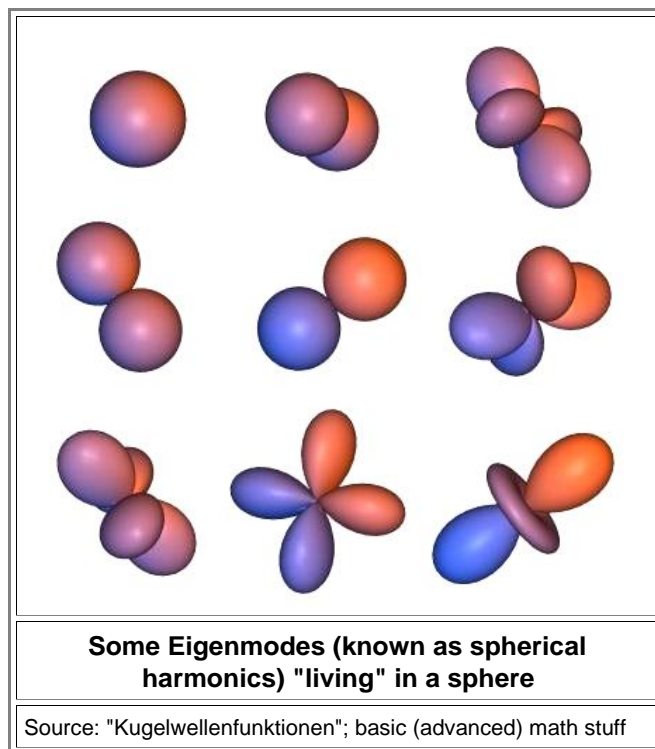
For one-dimensional systems like strings the nodes correspond to *points* on the string; this can be seen in the [picture above](#). For two-dimensional objects like the drumhead of drums, the nodes are lines. It looks like this:



Looks complicated, is complicated. But you have seen nothing yet. Look at the picture below, showing the nodes for a lot of Eigenmodes of a vibrating square blade:



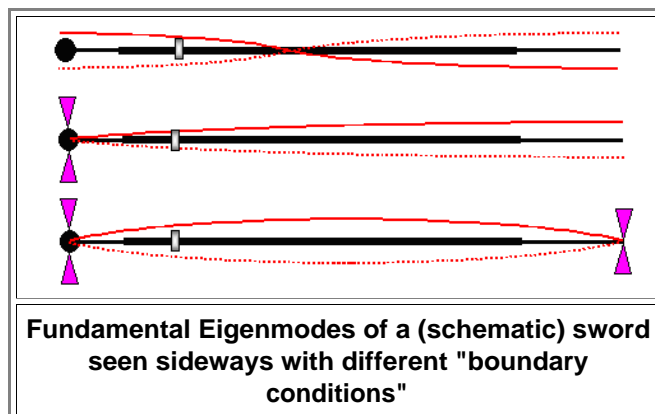
The real fun, however, starts when you look at three-dimensional objects like your sword. Before we do that we give something much simpler a quick look: A hollow sphere. Think of an ocarina if you like to consider musical instruments. Its Eigenmodes now produce *surfaces* of no vibrations (or alternatively maximal amplitudes of the vibrations). It look like this:



Some of you now might feel that they have seen a picture like this before, just in a completely different context. Well, yes. Above you actually get a glimpse into the basics of quantum mechanics. Look it up [here](#).

Three last words before we look at the vibrations of a sword.

1. There is always an Eigenmode with the lowest frequency. We may call that the **fundamental mode** or frequency. It defines often (but not always) the musical note or pitch you hear. The Eigenmodes with higher frequencies we sort according to frequency and call them first, second, third, ... harmonics. In simple systems like vibrating strings their frequency is doubled, trebled and so on relative to the fundamental frequency.
2. The Eigenmodes of a given body depend to some extent on the confinements (boundary conditions in math lingo) of this body. You might hold the hilt of your sword in a vice to study its vibration modes, i.e. forcefully reducing the amplitude of any vibrations to zero at this defined point. You might also "clamp" the tip, any point in the blade, or nothing at all. You will get different Eigenmodes and different Eigenfrequencies. The picture below gives an idea for this. In the middle you have a mode sometimes called "diving board" mode.



3. Vibrations are not restricted to "up and down" as shown in all those pictures. The blade could also rotate rhythmically (torsion vibrations) or get periodically shorter and longer. This is not really going to happen in any appreciable way with a real sword -but it is a possibility.

All these possible vibration states are Eigenmodes with some Eigenfrequency. And yes, it is fairly complicated. It gets even more complicated when you ask which of these many possible modes actually get "excited" and live for some time when you do something to your sword, like hitting something with it. But now to the two good news: .

1.
**Forget most modes. The important ones
are the fundamental modes
and a few low-order harmonics**

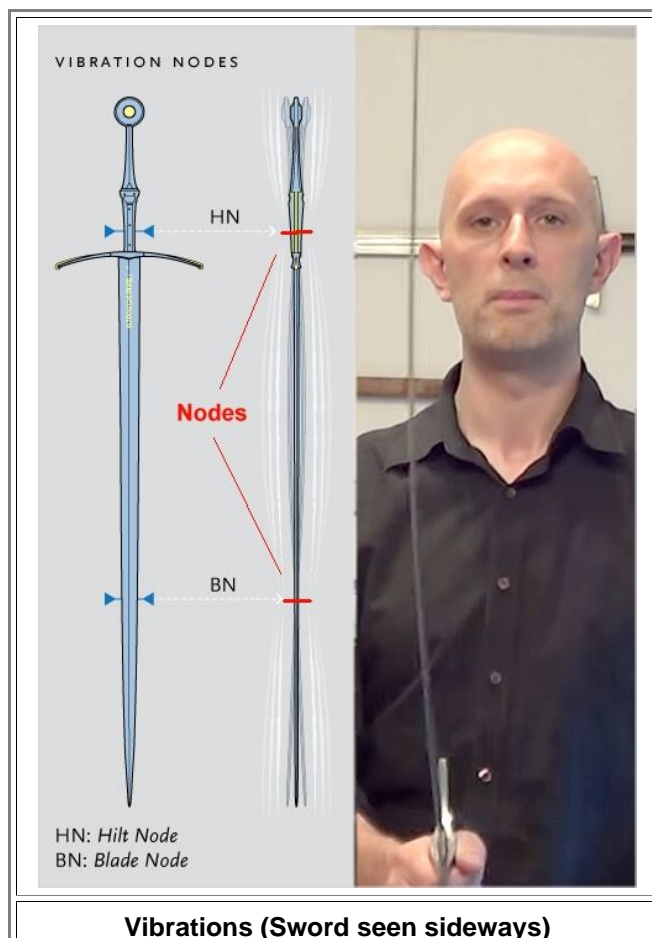
2.
**It is sufficient to treat swords as
one-dimensional objects**

Vibrations of Your Sword

What can I tell you about the vibrations of your sword? Not all that much. First of all it is rather complicated as all the stuff above should have made clear. Second, doing the full theory of your sword's vibration modes and so on is possible but involved. You need a computer and powerful software. Vincent Le Chevalier can do it [4](#); an example of his work is shown below. If the results help you very much in your day-to-day experience of wielding your sword is open to question. Not only does the way you move and hold your sword influence what is going on vibration-wise, what you perceive is highly subjective and thus cannot be predicted by theory. The rather heated ongoing discussion in various forums bears witness to this.

In what follows I just run you through some points that are important to understand the topic and to put it into perspective with the other properties of a sword.

The first point to notice is that usually just the basic modes of vibration *perpendicular to the blade* are considered, as shown in the picture below on the left. Let's call that **side-to-side oscillations** or simply *blade oscillations*. It is easy to make your sword vibrate that way: Hold it around the cross guard and hit the pommel hard with your hand. It will vibrate as shown in the right-hand side of the picture below. This is a screen-shot from a very useful Youtube Video [2](#), one of many posted by **Matt Easton**. You should definitely see it



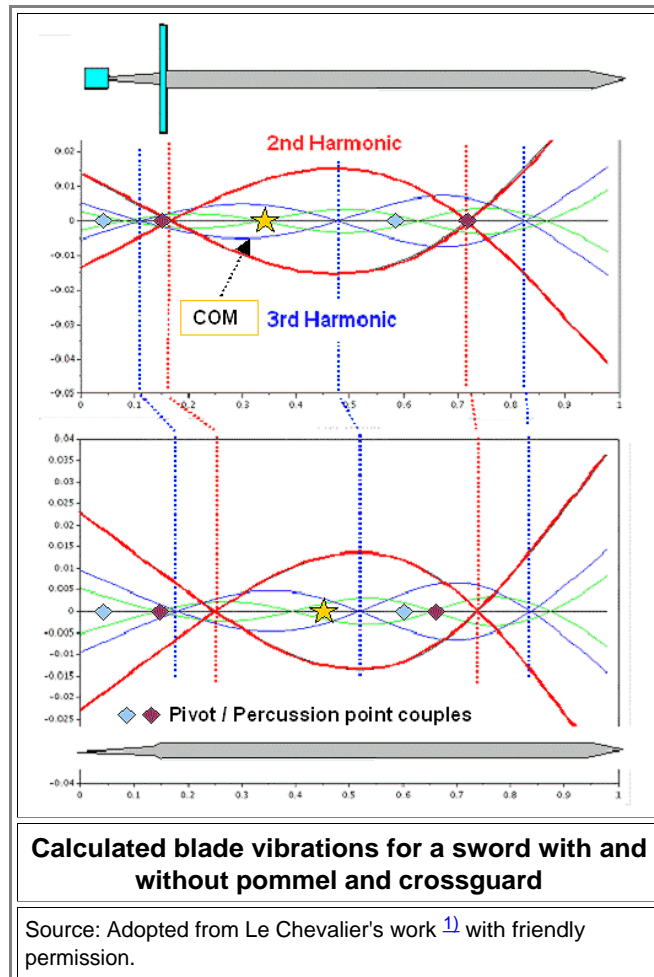
Part of a picture from Peter Johnsson / Le Chevalier's work [1](#)
Reproduced with gracious permission of the authors.

Matt Easton of Schola Gladiatoria in one of his Youtube videos [2](#)

The drawing illustrates what is known as the **"second harmonic"**. It is "second" because it has two nodes. It is also considered to be the major vibration mode in swords. Matt Eaton's sword in the picture seems to be doing a "diving-board mode" but in the video you see second harmonics too. Note that modes can coexist; you typically may find several modes superimposed.

The frequency of side-to-side or blade vibrations in low-index modes like the **second** harmonic is rather low, at best around 10 HZ or so. Definitely far below anything that would make a kind of musical noise. No singing sword ³⁾ here. You induce these modes by any (sudden) force with a component vertical to the blade, for example when you hit something not exactly at a right angle relative to the blade and away from the two nodes. Of course, when you deflect your opponent's swing with the flat of your blade, you will excite these modes too.

What these modes really look like can be seen very nicely in some computer simulations done by Vincent Le Chevalier [4](#):



Shown are the vibration maximums for the 2nd, 3rd and 4th mode (somewhat exaggerated). You see that the nodes for the 2nd mode of the pure blade are very roughly at about 1/4 and 3/4 of the blade length and that adding cross guard and pommel changes the location of the hilt nodes more than that of the blade modes.

The simulation also shows how the positions of the center of mass (COM) and of the percussions points (for two fixed hilt pivot points) changes. Quite a bit! With a "proper" pommel and cross guard, the COM moves appreciably closer to the hilt, increasing the agility of the sword, while the blade percussion point move out to a position pretty much identical to the blade node. That is a bit fortuitous but exactly what you want.

We get a first impression that the kind of hilt you supply is of prime importance to the dynamic performance of your sword. I will get back to this later in more detail.

The major point is that we now have **two** more major points on our sword (besides the two trivial ones giving the beginning and end of the sword). We have the position of the hilt node and of the blade node addition to the three points discussed before (pivot point, center of mass, percussion point). The claim is that any stick or sword has these five important points! Can that be true? That's where a lot of confusion starts. So let me clarify:

For a simple homogenous stick, three out of the five points are "trivial". The center of mass is exactly in the middle, and the nodes of the second harmonic are found at 1/4 and 3/4 of the length. That leaves two "special" points: An arbitrarily located pivot point of your choosing and the corresponding percussion point.

For a real sword this is different. All five points are special. They are related, of course, because the defined geometry of a sword determines most of the calculations. There is, however, no obvious relation.

Yes, you got it, I do actually claim

Vibrations nodes are generally **not** at the position of the percussion point!

This is often claimed or somehow mixed up because it is desirable that the percussion point and the blade vibration node coincide. That has caused sword makers to design their swords in such a way that these points actually **are** close to each other. This is possible (see the picture above) but not necessarily an easy thing to do. Producing such a "**harmonically balanced**" sword, as it is sometimes called, needs either centuries of experience and "know-how" or a powerful computer plus somebody who can program it with the required physics.

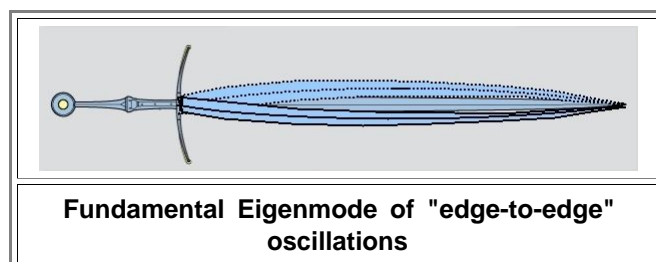
Why would we want these two points to be close together (and not too far from the sword tip)? Because if you hit your target at the percussion point you feel no force in your hand and deliver substantial if not maximum impact. When you hit your target at the position of the node you do not excite (second order) vibrations of the blade, hurting your hand and diminishing impact force. So having the points coincide is often a very good idea. But you have to do this by optimizing the sword design. There is no natural and unavoidable coincidence of these points.

As Michael Tinker Pearce (Sword Maker) puts it in a "Sword Forum International" contribution: [What harmonic Balance does for a sword - prevents shock from being transmitted to the users hand when striking with the sword. This conserves energy- the sword doesn't 'waste' energy shaking the user even when the strike lands off of the COM. It also prevents the user from losing control of the sword because of vibration transmitted to the user's hand. It also minimizes the sword's tendency to damage it's hilt assembly through vibration. All good things! A sword that is not 'harmonically balanced' is not, in my opinion, a 'good' sword.](#)

Modern experts (like Matt Easton and in particular [George L. Turner](#)) who have given old swords a close look find that pretty much all of them are harmonically balanced while that is not true at all for many modern "replicas". They may **look** like the original but their balance is off. Their percussion point may even be off the blade, e.g. some cm in front of the tip (perfectly possible: look at the [math](#)!) I

Now I want to promote a new and somewhat disturbing idea. If you excite side-to-side or blade vibrations as discussed above and then quickly put your ear on the blade, you might actually hear a tone. Maybe you can even produce a directly audible tone with your particular "singing" sword. That can only mean that you have some "high-frequency" (e.g. around 100 - 400 Hz) Eigenmodes that can live in your sword **in addition** to your very low frequency blade oscillation modes.

The only contender for these modes are "**edge-to-edge**" vibrations. Something like that:



You excite these modes when you hit something with the edge of your blade. They thus may come more naturally than the side-to-side oscillations from above - but are rarely mentioned! Perhaps because their amplitude is so small that you don't see it easily - in contrast to the blade oscillations where the amplitude can easily exceed several centimeters!

Now to my last point. Maybe you should forget most of what I have written above!?

The claim is: While side-to-side oscillations are showy and bothersome, what you really should worry about are the edge-to-edge oscillations. They are the ones that "sting" your hand or otherwise impede your performance.

That's the viewpoint of [George L. Turner](#), who so far has written the most detailed treatise about sword dynamics. Look up [chapter 11](#); pp 130 - 137pages. While his viewpoint is still open to some doubt; I do believe that he makes a good and valid point.

● So you should worry about the nodes for the second harmonics of the edge-to-edge vibrations and not about the nodes of the blade vibrations? Yes you should. But not too much, because the positions of the nodes is likely quite close for most sword geometries.

▮ I'm stopping here. Much more could be said (for example that so far we treated a sword essentially as a one-dimensional object).

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- 1) Peter Johnsson and [Vincent Le Chevalier](#): Documenting the dynamics of swords; Vincent Le Chevalier' blog "[Ensis Sub Caelo](#)".
 - 2) The link to the video is: <https://www.youtube.com/watch?v=j4zwyVw4NdA> It worked in Feb., 2019 but I can give no guarantee
 - 3) The Singing Sword is the primary weapon of the fictional character Prince Valiant, a Knight of the Round Table in the service of King Arthur, in the long running comic strip Prince Valiant, created by Hal Foster in 1937.
 - 4) Vincent Le Chevalier; : [Simulating Sword Properties](#). Explaining how the simulation program works and in particular some information about vibration modes computation.