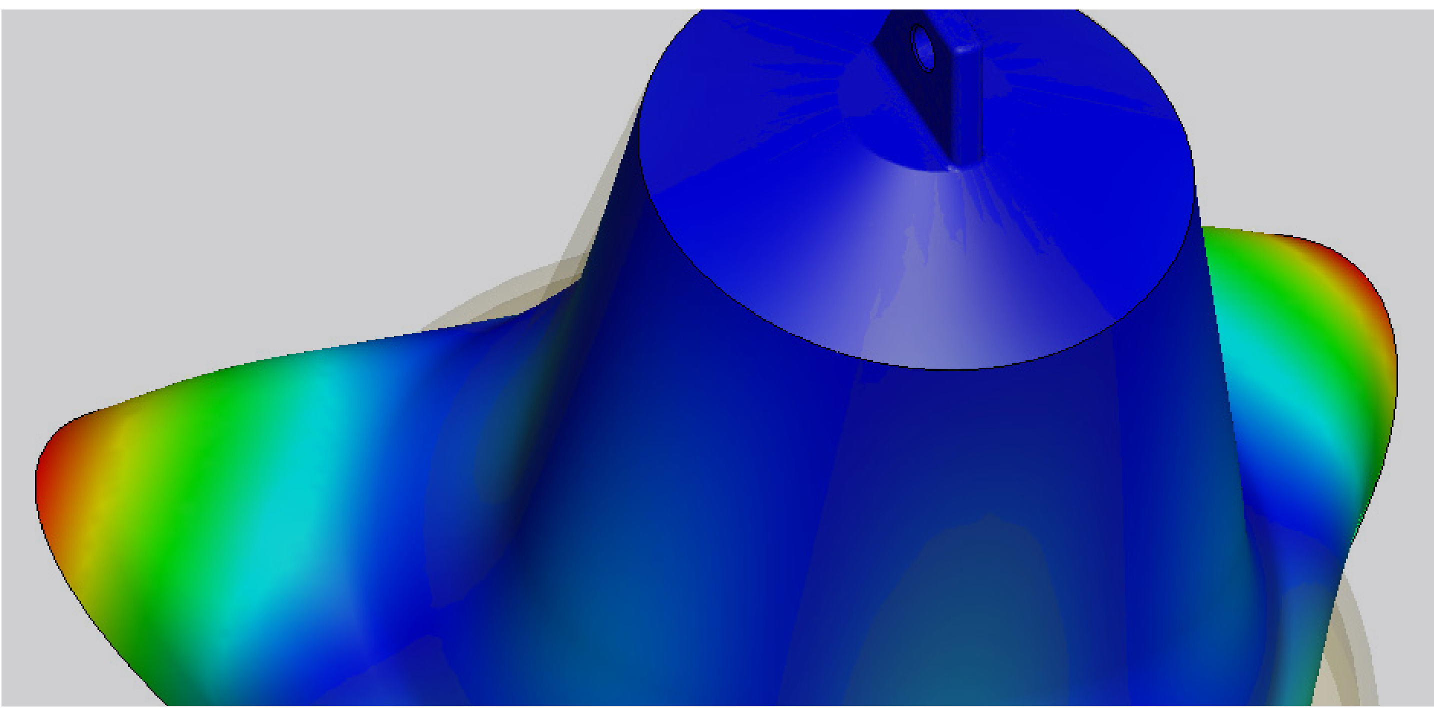
STREAMLINING DESIGN WITH REAL-WORLD VIBRATION ANALYSIS

Overview

Mechanical designers often use vibration simulation as a timesaving and cost-efficient alternative to the traditional approach of building, testing, modifying, and retesting their designs. By identifying the factors that influence the response to a dynamic load in a computer model, designers have the data needed to make the right improvements before they even cut a single piece of metal. In addition to greatly decreasing the number of actual prototypes required, vibration analysis also significantly reduces the costs involved.



Introduction to dynamic simulation

Dynamic simulation can help mechanical designers create better products. When designing a product, you often need to address operational questions, such as:

- How much error will be introduced in a tool by shaking in a fixture on a milling machine?
- Can player fatigue be lessened by reducing the vibration felt through a new tennis racket or golf club?
- Will components loosen due to the vibration of road noise when transporting electronics?
- How thick should the motor mounts of an automotive engine be without over-designing them in weight or cost?
- Is it possible to predict whether the spindle speed of oil well-drilling machinery will keep the system in a safe operating region without vibrating apart?
- Do systems or structures need to conform to MIL spec, Telcordia GR-63, or Uniform Building Code (UBC) vibration or seismic requirements?

In the past, you may have answered these types of questions with hand calculations and a few build/test/redesign cycles. But now, you can take the guesswork out of the initial design phase by using dynamic simulation.

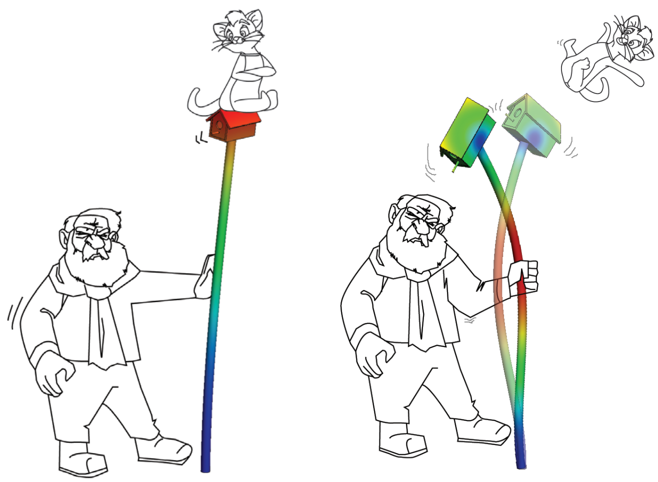
Any time a component or an assembly is subjected to a changing or dynamic load, it may react or vibrate in a way that ranges from merely annoying to critically dangerous. Consider these three real-world examples: Although the vibration in a poorly designed cordless drill may not lead consumers to return the product, they might tell their friends not to purchase it. During a test-drive, uncomfortable road-induced vibrations could turn off a prospective buyer and result in the loss of a sale. And, the stress of vibrations on the mechanical housing or solder joints of sensitive electronics during transport has the potential to be quite destructive.

The main goal of vibration analysis is to determine if inputs that change with time create an unacceptable response, in terms of actual part failure or user perception. With this detailed knowledge, you can improve your design before you even build a prototype or an actual structure. In the following pages, several approaches for examining vibrations are discussed, as well as their impact on the success of your design.

The main goal of vibration analysis is to determine if inputs that change with time create an unacceptable response, in terms of actual part failure or user perception.

Describing three types of vibrations

Consider an example that illustrates the basic concepts in vibration and the techniques used to simulate it. You would like to discourage the neighbor's cat from perching on your pole-mounted bird feeder for a free lunch. If you give the pole just a little push, the velocity and displacement of the feeder will be linearly proportional to the input speed and magnitude of the push (Figure 1a). If you start shaking the pole with the same magnitude of input but with greater speed, however, you will eventually cause the pole to "whip" at the top and thus achieve your cat-removal goal (Figure 1b).



(a) (b)

Figure 1: Pole shaken slowly (a) compared with the whipping motion caused by faster input (b)

This whipping effect indicates that your shaking speed has excited resonance in the bird feeder system: the output (a) is now disproportionately high compared to the input (b), much to the chagrin of the cat.

Vibration analysis enables you to understand just when shaking will cause minor or catastrophic responses elsewhere in your product.

This back-and-forth motion represents a simple view of what happens during vibration. Time-varying input that excites resonance in a system can result in a dramatic, even catastrophic, response. Yet, a similar input at a different speed that does not excite resonance may not show any cause for concern. These concepts apply to all systems of any complexity. As a result, vibration analysis enables you to understand just when shaking will cause minor or catastrophic responses elsewhere in your product.

Vibration can be described in three ways, primarily by the nature or form of the driving input:

1. In the physical or time domain, you can expect to see the actual changing movement in real time. A simulation in the time domain is often called a transient analysis. In the bird feeder example above, you can count the frequency of pushes per minute, as well as measure the amplitude of the push, and then provide these inputs to a simulation. As the input speed increases in the simulation, you would see the same gain in tip-speed and displacement as you would see and measure in your yard. Another output could be the time or number of oscillations it would take for the pole to come to rest due to natural damping once the shaking stopped.

In the transient method of describing a dynamic event, any parameter (such as speed, magnitude, direction, or number of inputs) can change just as it might in a real-time event. The computer simulation of such events must report these outputs at specific time intervals as opposed to displaying a continuous response—the digital versus analog dilemma. As the duration increases, the solution to these problems consumes more time and resources. You must specify sufficiently small time-steps to capture all changes as well as the responses to those changes. A common guideline for determining the number of required time-steps is five per every peak or valley in a response. As illustrated in Figure 2 below, this number can quickly grow for a transient analysis of an event.

In the transient method of describing a dynamic event, any parameter (such as speed, magnitude, direction, or number of inputs) can change just as it might in a real-time event.

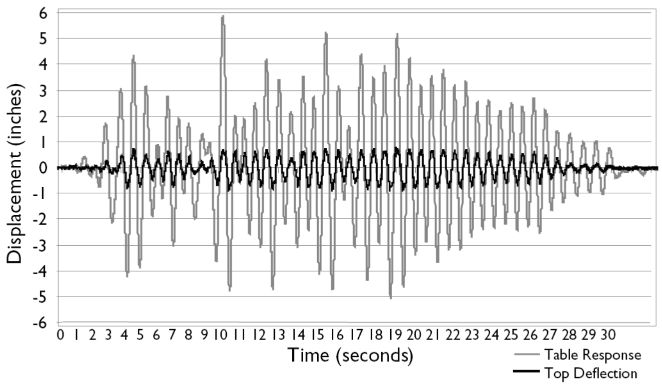


Figure 2: Transient input for a shaker-table test

2. With a frequency domain approach, we can only speak in terms of output magnitude versus input at a given frequency. You must assume that all inputs are cyclic, or sinusoidal, in nature and have a constant amplitude at that frequency. This simplified output is most efficient when the input varies only in speed, not in amplitude, orientation, or number of inputs. This method is commonly used to vary, or sweep, the input frequency across the operating range and identify the maximum possible response, as one might do on a shaker table (Figure 3).

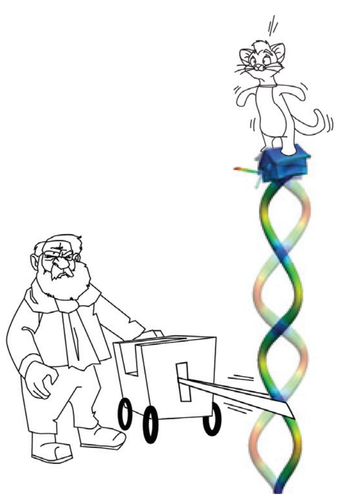


Figure 3: Automated shaker device with variable frequency applied to bird feeder, cat-removal problem

The input can be a simple peak force, displacement, or acceleration at a single frequency, or a complex function or table that describes how the magnitude of the input changes with frequency.

3. The third way of describing vibration involves the domain of statistics and probabilities. Common usage often misleadingly labels this approach as random vibrations. Situations that require a random vibration study are ones where the speed or frequency of the input and the amplitude are not repeatable but have a predictable average loading. Consequently, you need to compile a mathematically representative input over a given time period to provide a probable amount of input energy at a given frequency.

   We can represent these various estimated energies at all frequencies of concern in a power spectral density (PSD) curve or table. Using a comparative approach is the best way to use the output of these problems, as you can see the increase or decrease in the stress or displacement a system experiences for a given change in these inputs. While clearly a more approximate approach than the other two methods, the PSD curve or table is the only way to describe a system's response to the variable inputs found in earthquakes or road noise (Figure 4).

We can represent these various estimated energies at all frequencies of concern in a power spectral density (PSD) curve or table.

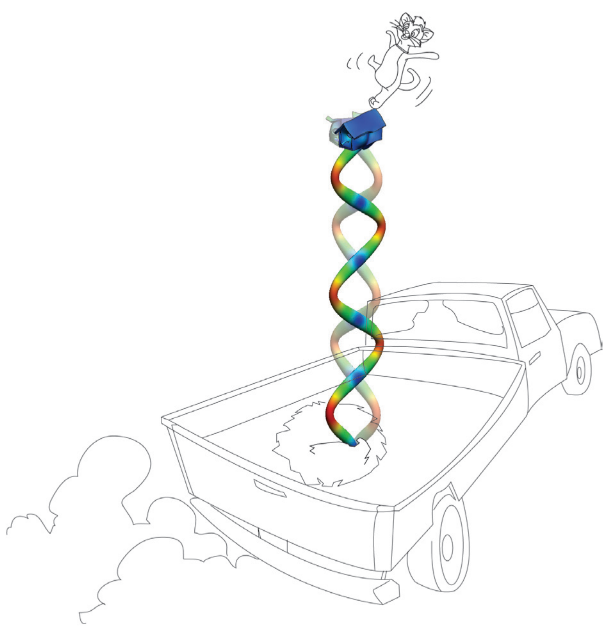


Figure 4: Automated shaker device with variable frequency applied to bird feeder, cat-removal problem

Defining the fundamentals of vibration simulation

Static versus dynamic analysis

Static studies assume that loads are constant or applied very slowly until they reach their full values, thereafter remaining constant with time. Because of this assumption, all inertial effects must be considered negligible, including the velocity and acceleration of the excited system. Static studies therefore produce stresses and displacements that are constant.

For many practical cases, however, loads either are not applied slowly or they change with time or frequency. Inertia and damping become relevant, and meaningful simulation demands the use of a dynamic study. An often misused practice is the application of a static force to simulate the deflection that a structure might experience in a seismic or impact event. These events involve accelerations or decelerations that act on all the mass in the system everywhere, not just at a point or at the center of gravity of each component. Additionally, in the case of seismic or shaker-table loading, if the applied loading is reversed as a system is responding from the initial application, induced accelerations in components can be very difficult to predict without a dynamic simulation. Consequently, a static simplification can be very misleading. Because there is no consistency as to whether it will be conservative or nonconservative, a static simplification is inappropriate for most cases.

The building blocks of all dynamic solutions are the natural frequencies or modes of the system.

General modal analysis

The building blocks of all dynamic solutions are the natural frequencies or modes of the system. All bodies display resonant or natural frequencies independent of any loading. This phenomenon is seen as the free vibration of a system after a bump or a rapidly removed displacing force. The lower natural frequencies, defined in hertz (cycles per second), are the deformed shapes, or mode shapes, that require the least amount of energy to achieve. For the long and slim cantilever, which is similar to a yardstick (Figure 5), clearly much less energy is required to deflect the part in (a), the lowest natural frequency than in (b), a higher natural frequency.

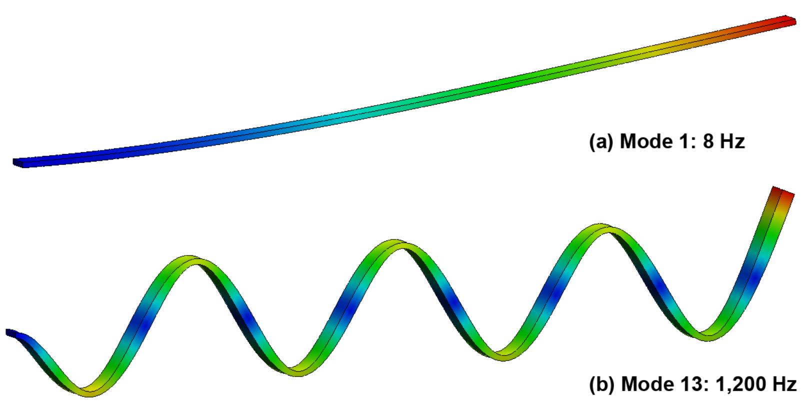


Figure 5: Two natural frequencies of a thin beam

As a result, designers are usually interested only in the first few modes since those are where most of the action happens. When higher frequencies are resonated, the response amplification is typically smaller than at lower frequencies. However, for long-term vibration where small stresses might cause fatigue failure, the response at higher frequencies may still be significant and so should be examined.

Bell motion makes a fascinating study of modes. You can visualize a wobbling effect in a ringing bell whose edge is physically rippling in an exaggerated motion as different tones resound. The sounds vary and last for different lengths of time, depending on geometry, precision in casting, and material. The overall sound is a compilation of the tones simultaneously generated by each different pattern of movement (mode) of the bell as seen in Figure 6 below.

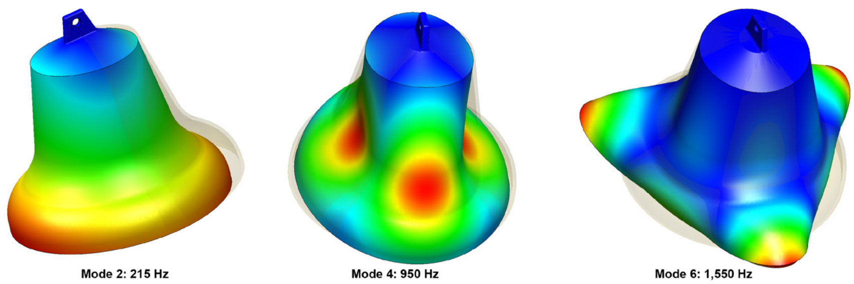


Figure 6: Mode shapes of a ringing bell. Actual tone is the superposition of the tones resulting from each movement.

A critical factor in determining whether or not a dynamic solution is required is the frequency or pulse duration of the input.

A critical factor in determining whether or not a dynamic solution is required is the frequency or pulse duration of the input. Generally, if the frequency of an input is similar to or larger than the lowest natural frequency of the component or system, designers should conduct a dynamic study. In cases where the dynamic input is a pulse, the simulation should compare the duration of the pulse with the period of the natural frequencies, whose mode shape might be excited by that pulse.

The period of a frequency is the inverse of that frequency; for example, the period of a 10 hertz waveform is 1/10, or 0.1 seconds. If the duration of the pulse is similar to the period of an applicable natural frequency, consider performing a dynamic analysis.

Time-based analysis

Time history (transient) analysis is often used to see the magnitude of stresses or deflections given a short duration pulse (Figure 7). If this excites a resonant frequency, the resulting stress or deflection may be greater than that for a static load of equal magnitude. The actual time duration is also critical, however. If the same load is applied and released far more quickly, it may come and go before the system has had time to react; in that case, no problem will arise. In a similar way, if the load is applied at a much slower rate, the response will also approach that of a static situation; and again, the response may be unremarkable. Transient analysis will illuminate all three situations.

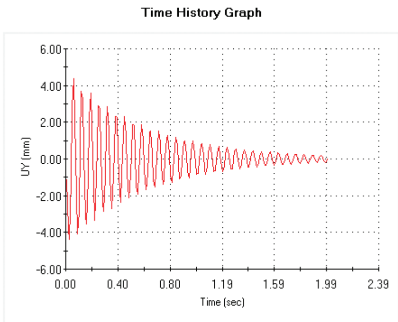


Figure 7: Sample plot of displacement versus time at a single point on a structure, with the initial displacement due to a transient load

Harmonic, or frequency response, analysis

Harmonic analysis is important for analyzing a structure when the applied force at one or more natural frequencies continues over time (Figure 8).

Random vibration inputs are derived from an event that lasts a finite amount of time, but where the details of the event are not time-dependent.

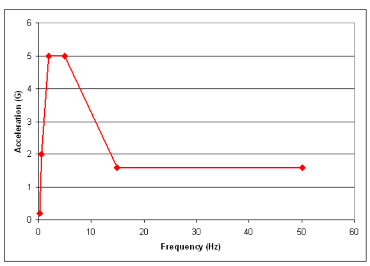


Figure 8: Acceleration versus frequency spectrum for electronics testing

The classic example of a continuous energy-pumping disaster is the collapse of the Tacoma Narrows suspension bridge across Puget Sound, Washington, four months after its opening in 1940. As a cost-saving measure, the original design had been changed to decrease the amount of bridge-deck stiffening by more than a factor of four. Early one morning, winds of 35 to 46 miles per hour started a rippling motion of the bridge with an up-down displacement of three to five feet. Within hours, the wind's effect shifted so that a twisting mode was excited. This grew stronger until chunks of the concrete roadbed broke up. Finally, an entire section snapped free, and large parts dropped into the river. Fortunately, no one was injured as officials had closed the bridge by 10 AM.

Random vibration analysis

Random vibration inputs are derived from an event that lasts a finite amount of time, but where the details of the event are not time-dependent (Figure 9). The longer the evaluated period of time, the better the statistical sampling in the frequency domain. The resulting data supplied to the dynamic analysis is essentially a summary of the total energy at all the frequencies excited by the input event. Variations in road-surface geometry or the random forces of an earthquake are examples of such inputs.

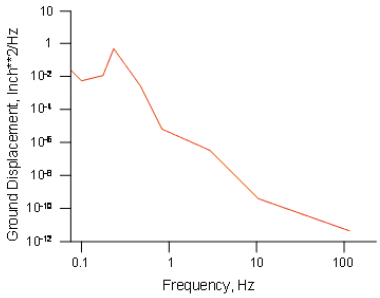


Figure 9: PSD representation of ground displacement near building a demolition site

Approaches for performing dynamic analyses

Mechanical engineers must determine which, if any, of the three possible linear dynamic software simulations—time history (transient) analysis, harmonic analysis, or random vibration analysis—are appropriate for their engineering challenge. As stated previously, the best indicator of the study requirements is the form of input data that you have. For all three, the recommended software sequence is: create an appropriate CAD model, set up and perform a frequency analysis to identify the applicable resonant frequencies, and then set up and run the selected dynamic analysis.

Create an appropriate CAD model

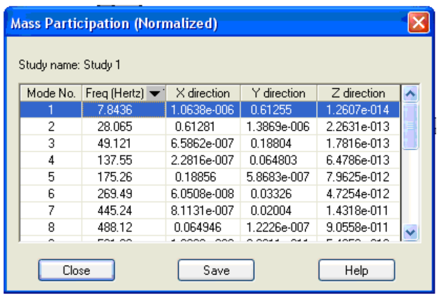
Dynamic simulations are typically time-consuming and memory intensive. For those two reasons alone, creating a simplified and efficient CAD model usually pays off. The guidelines for model type choice—beam/line models, shell/surface models, or solid models—are even more important to consider for these studies. For stress results, CAD detail is critical; while for displacement or acceleration data, a simpler CAD model may suffice. When creating your geometry, also keep in mind the relative level of approximation for the different studies. Since a transient analysis uses “real” input with little filtering or simplification, the large resource requirements of a detailed solid model may pay off. On the other hand, since harmonic analyses use simplified datasets, and random vibration studies further simplify the original time-based inputs, the value of highly detailed CAD descriptions begins to decrease rapidly.

Dynamic simulations are typically time-consuming and memory intensive. For those two reasons alone, creating a simplified and efficient CAD model usually pays off.

Perform the frequency analysis

A dynamic analysis is typically based on the natural frequencies in a system. Before proceeding with a more detailed study of the time-varying response, you must identify these frequencies (i.e., determine the modal response). In most software simulation tools, you can find this response before doing the dynamic analysis, or you can have it done automatically as the first step in one of three possible dynamic-analysis sequences.

The output of the frequency study (Figure 10) includes modal shapes, modal frequencies, and mass participation factors. This last output is an indication of how significantly you might expect each calculated mode to participate in a dynamic response.



Mass Participation (Normalized)

Study name: Study 1

Mode No.	Freq (Hertz)	X direction	Y direction	Z direction
1	7.8436	1.0638e-006	0.61255	1.2607e-014
2	28.065	0.61281	1.3869e-006	2.2631e-013
3	49.121	6.5862e-007	0.18804	1.7816e-013
4	137.55	2.2816e-007	0.064803	6.4786e-013
5	175.26	0.18856	5.8683e-007	7.9625e-012
6	269.49	6.0508e-008	0.03326	4.7254e-012
7	445.24	8.1131e-007	0.02004	1.4318e-011
8	488.12	0.064946	1.2226e-007	9.0558e-011

Figure 10: Typical modal frequency list with mass participation factors

Review the frequency results

For the first dynamic simulation of a system, you should always solve for the modal response and review it before deciding whether or not dynamic analysis is required; if it is needed, you must then decide which dynamic analysis to use.

If no resonant frequencies are in the range of interest or operation, you probably do not need to follow up with a dynamic analysis. Even if frequencies are in the range of operational inputs, you should ensure that they represent shapes which the applied loads would actually excite. For example, a lateral load may stimulate a resonant frequency, but the mode shape at that frequency may be longitudinal. In this case, the dynamic aspect of the load will have very little effect on the results.

If the operational frequencies are likely to excite several natural frequencies and mode shapes, your first step should be to modify the design by pushing the calculated natural frequencies above the operational frequencies. This task is called modal avoidance. Common techniques include weight reduction or redistribution, addition of stiffening features, or even material changes.

If you cannot modify the design such that the entire operating speed range is below the first natural frequency, it is often acceptable to push the lower modes even lower. Excitation at lower speeds corresponds to lower energies, so the resulting vibration will be minimized. Many designers have seen the effects of this when a piece of machinery "shudders" as it is coming up to speed, only to have all the noticeable vibrations dissipate at working speeds. If you are unable to adjust your design so that natural frequencies can be acceptably avoided, you probably should perform a dynamic analysis.

If the operational frequencies are likely to excite several natural frequencies and mode shapes, your first step should be to modify the design by pushing the calculated natural frequencies above the operational frequencies.

Set up the dynamic analysis

Since the modal solution is the building block for subsequent dynamic study, you will need to make sure that enough modes have been identified to characterize the system. At a minimum, you should calculate enough modes to include a natural frequency of at least twice your maximum operating frequency. For example, if your input frequency ranges from zero to 50 hertz, your natural frequency list should include enough modes to include 100 hertz.

In addition to this guideline, you should also review mass participation factors for the specified direction of input. The mass participation factors included should add up to at least 0.8 (or 80 percent). This may require you to include more modes than twice your maximum input speed, or it may suggest that you include fewer modes. Do not reduce the number of included modes beyond twice the maximum input frequency, however. To do so may cause the solution to ignore responses at that frequency, which could combine with lower frequency results to push output beyond an acceptable range.

The necessary inputs for dynamic analysis include load magnitude, direction, point or area of interest, damping, and frequency range or time span. With the output values, you have the ability to compare such parameters as stress, acceleration, and displacement with the known limits for your system. This allows you to determine if failure is likely or if cost reduction is possible.

The necessary inputs for dynamic analysis include load magnitude, direction, point or area of interest, damping, and frequency range or time span.

For a transient analysis, you should apply the loads and restraints exactly as you would in a static analysis, with the exception that the loads should be defined to vary with time.

When using a harmonic analysis, you must vibrate the system with the applied load. You can define a table or function for your loads that increases or decreases their amplitude as the frequency varies. Alternatively, you may vibrate your system at one of the restraints, which is called base excitation. Mathematically, this is analogous to a shaker-table test.

Although setting up a random response analysis is similar to preparing a harmonic analysis, the inputs to the load or base excitation are in terms of PSD versus simple force, displacement, velocity, or acceleration. The output of the random vibration analysis provides the RMS (root mean square) and PSD values of the response (displacements, velocities, accelerations, and stresses). This data actually represents the probable maximum of the expected response at a given frequency. Since the input is a statistical sampling, the output cannot be any more precise. However, this is the most efficient way to get reliable design data in random events.

Damping

A dynamic analysis is usually meaningless without a modal damping factor. Damping (ζ) represents the amount of energy lost in the system due to the vibratory movement. Without damping, an excited system would vibrate forever. Many sources of damping contribute to the damping factor, including material effects, friction, noise, and environmental effects such as fluid interaction. This factor is typically in the range of 0.01 for lightly damped systems (single steel parts) to 0.15 for highly damped systems. When there is no other data on damping, two percent (0.02) is a commonly chosen default. Having a valid damping factor is crucial to guiding realistic design choices.

Figure 11 shows the typical gain (Acceleration, A) in a system at various frequencies where the X value of 1 represents excitation of a system at the first natural frequency (ω = excitation frequency; ω_n = natural frequency). You can see that at a damping factor (ζ) of 0, the dynamic amplification (gain) can, theoretically, be infinite. As damping increases, the gain diminishes rapidly. Based on the results, this can greatly influence the decision you make. Simple testing can aid in determining the applicable damping.

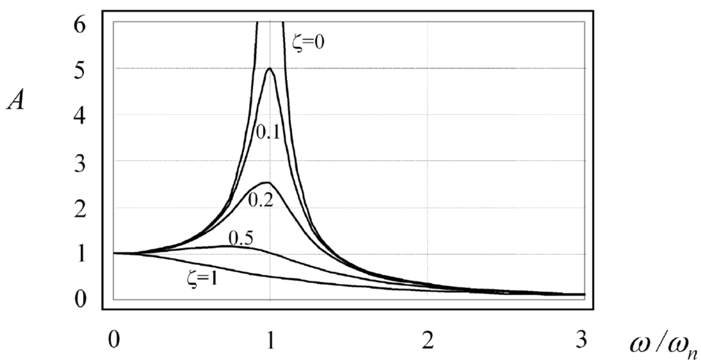


Figure 11: System gain when a system resonates with various damping factors

Many sources of damping contribute to the damping factor, including material effects, friction, noise, and environmental effects such as fluid interaction.

Nonlinear dynamics

Another aspect of dynamic analysis to consider is that all the simulation techniques discussed thus far are linear studies, in that all the rules for a linear analysis apply. You must perform a nonlinear dynamic study if the material itself displays nonlinear properties, there is nonlinear contact between components, or the system undergoes large displacements requiring a nonlinear solution. Most nonlinear dynamic solutions operate in the physical or time domain, as the basic mathematical approach of modal frequencies does not work well with nonlinear behavior.

Conclusion

Since most products have moving parts and are handled or moved by an external force, even simply during transportation, dynamic simulation is a natural extension of any predictive simulation program. Having early data on product response to vibration or collision allows companies to make correspondingly early design-change decisions. This insight not only reduces the need for developmental prototypes, but also ensures that the prototype and test plan are as effective as possible.

For example, one telecommunications cabinet manufacturer invested four to six weeks in building, shipping, and testing a single prototype for seismic vibrations in three axes, only to learn that some welds failed on the first test. They then had to discard all subsequent test results. While cost was important, the lost project time was even more critical. In response, they began performing virtual shaker-table testing using harmonic-response analysis and were able to determine the likely areas of failure. This data enabled the designers to identify efficient and cost-effective fixes to reduce the chances of these failures. They also planned the order of prototype testing such that the test most likely to cause failure came last. As a result, the revised destructive-testing program offered the maximum benefit with little or no wasted time, money, or effort.

You will find the techniques described in this paper in mainstream design simulation tools. Some versions are even integrated in popular CAD systems, such as SolidWorks® 3D CAD software from Dassault Systèmes SolidWorks Corp. Since dynamic simulation can help you design better products, you might consider exploring this technology in more depth for your own applications. Listed below are three definitive works on vibration analysis.

References:

Elements of Vibration Analysis; Leonard Meirovitch; McGraw-Hill, Inc., 1986.
Mechanical Vibrations (fourth edition); Singiresu S. Rao; Pearson Education, Inc., 2005.
A Finite Element Dynamic Primer; D. Hitchings (ed.); NAFEMS 1992.

Dassault Systèmes
SolidWorks Corp.
300 Baker Avenue
Concord, MA 01742 USA
Phone: 1 800 693 9000
Outside the US: +1 978 371 5011
Email: info@solidworks.com
www.solidworks.com