

DAMPING IN COMPOSITES —

IT'S THERE, BUT IS IT UNDERSTOOD?

By A. Brent Strong and Christopher A. Rotz/Brigham Young University

What is damping

Damping occurs when vibrational energies are converted into some other energy form, usually heat. The kinds of vibration that people in the composites field are most often concerned with are either mechanical vibrations or acoustic vibrations (sound or noise). At the fundamental level, both of these vibrations are really the same and can be treated in similar fashion. It is not uncommon, of course, to have both kinds of vibrations present at the same time.

The vibrations we are speaking about are movements of the device or component itself rather than just internal vibrations of the molecules. These macro (large scale) vibrations may or may not also have internal molecular vibrations associated with them. For instance, a ringing bell would have the type of vibrations we will be discussing in this article and both mechanical vibrations and acoustic vibrations (caused by the mechanical) are present in the bell.

Another example is illustrated in Figure 1 which shows a bouncing ball. If the ball is not damped (Figure 1a), the ball will continue to bounce at the same height forever. (We know this is not realistic, but that is because all real materials have some damping.) Figure 1b illustrates the normal case where the ball material has some damping character and therefore the bouncing diminishes.

We all realize, of course, that a ringing bell and a bouncing ball will eventually stop vibrating as will the many parts made of composite materials which can often vibrate. The objectives of this paper are to examine methods that can be employed to enhance or control the damping mechanisms in composites parts, and by the use of composites, to dampen other materials. The implications in current and new markets are enormous, but perhaps, only for those who really understand damping.

The importance of damping

In some cases vibrations are desirable, such as in a violin, where the vibrations are important for creating the proper sound. In most cases, however, vibrations are bad and need to be controlled. Four situations commonly exist in which vibrations can be considered detrimental and therefore need damping. These negative vibration situations are:

- Damage – Vibrations can damage the part itself or components attached to the vibrating part. An obvious example is an airplane part that cracks because of the vibrations. Even the cracking of a part from an impact can have important implications in damping. Fatigue failure is another example of vibration-caused damage.
- Misalignment – Vibrations can cause a part to move or to change its shape in a non-controllable or problematic way. The Hubble telescope is a prime example of the need for vibration-free movement to prevent misalignment.
- Discomfort – Sometimes the vibrations are uncomfortable such as the vibrations that might be sensed from a vibrating airplane floor, the seat in a boat or the whack of a tennis racket. The market potential for these applications is huge.

- Noise – Not only might sound be uncomfortable, it can even damage hearing. Common examples are vibrating machinery and operations that are inherently noisy such as vibrating motors or turbulent air flows.

The world of composite applications is full of situations where damping is important. An additional example could be a composite housing that covers some mechanical device such as a motor. In operation, the motor will vibrate and those vibrations are passed into the composite housing. In most cases, the existence of these vibrations is detrimental because the vibrations can damage the housing such as at the fastening points or, perhaps, in general fatigue which could eventually lead to cracking of the housing along seams or ribs (stress concentration areas). The noise from the housing could also be undesired.

Another situation in which composites might be involved is the damage from earthquakes. These could cause damage from the vibrations and also misalignment of critical parts, some of which might be made of composites. A new area of composites application in connection with earthquakes is the wrapping of concrete pillars with composites because of the strength of the composite in holding the concrete pillar in place. The damping of the composite is an important advantage in this application.

Damping fundamentals

Before we can understand damping in composites, we need to understand the fundamentals of damping itself and these can best be described by examining simple systems. The examples which follow are, therefore, simplified so that the fundamentals can be understood. They should not be used for detailed design.

The amount of damping of a part depends on: 1) the materials out of which the part is made, and 2) the design of the part (geometry, mass, etc.). However, it is rare that a part would exist in total isolation. Therefore, we must also consider the entire system in which the part exists which includes the part itself and associated parts or elements and how they are interconnected. We therefore must add another consideration affecting the amount of damping, which is 3) any elements that might be added to the part, thus creating a system (which could include specific damping treatments but could also include additions whose effect on damping is more complicated).

To understand these concepts in slightly more detail, we can consider a simple system and then add complexity to see how the damping characteristics of the system change. Figure 2 shows a simple metal bar suspended from a rigid attachment on a rigid plate. If we subject the bar to a simple tensile force by pulling on the bar, the situation can be represented by the stress-strain equation,

(Equation 1)

where σ , the stress, is the force divided by the area of the bar, E is Young's modulus of the bar, and ϵ , the strain, is the displacement of the bar divided by the original bar length. In other words, the movement of the bar under a particular force is a function of Young's modulus and some geometry effects (area and original length, in this case). Rewriting Equation 1 in these terms gives

(Equation 2)

where F is the force, (A/l_0) is the geometry factor, and x is the movement.

This situation is analogous to the displacement of a spring (as shown in Figure 2) which can be described mathematically as

(Equation 3)

where F is the force, k is a constant that describes the spring, and x is the movement. A comparison of Equations 2 and 3 reveals that the spring constant, k , is analogous to $E (A/l_0)$.

The bar described in Figure 2 and its equivalent expressed as a simple mechanical device, the spring described in Figure 3, have no damping. They are assumed to be purely elastic, meaning, no energy is lost by any dissipation mechanism (such as damping). We could, however, add a simple mechanical device that would represent energy loss, such as would be experienced from damping. This simple mechanical device is a dashpot, as shown in Figure 4. When a dashpot is included in the system, the motion of the system is described as follows:

(Equation 4)

where c is a constant that describes the dashpot, v is the velocity of the movement and all other factors are the same as given previously. When damping is present, the relationship between Young's modulus and k no longer holds precisely. Therefore, two new quantities are introduced which, together, represent the modulus of the damped system. These quantities are called the storage modulus, E' and the loss modulus, E'' . E' represents the part of the modulus that is elastic, and E'' represents the part of the modulus that is non-elastic or dissipative. Both E' and E'' represent inherent characteristics of all real materials, although in some materials, such as metals, E'' is so small that it can be neglected and only Young's modulus is used in most

representations of the material. It has been found that k is a function of E' and a geometry factor, while c is a function of E'' and a geometry factor.

We can now look back at the beginning of this section where we said that damping was dependent upon 1) the properties of the material (represented in our equations by E' and E''), by 2) geometry (represented by the geometry factors) and by 3) any additional elements added, creating a system. We have yet to give an analogy for (3) but we can now consider both the addition of specific damping treatments and also the addition of more complicated elements.

The addition of a special damping material is analogous to simply adding a second dashpot to the system as shown in Figure 5. Of course, this new dashpot usually will have different damping characteristics from the part itself and so the damping constant for the added dashpot is likely to be quite different (indicated by c'). Nevertheless, the analogy is straightforward showing the effect of adding a specific damping treatment.

We will now consider the addition of elements which creates more complicated damping characteristics in the system. We will now add a mass to the system as shown in Figure 6. Intuitively we understand that the presence of this mass will change the motion of the system. It may not be obvious how this mass will affect damping, but by looking at the simple mathematics for the system we should be able to determine its effect.

With the added mass, the motion of the system is expressed by the following equation:

(Equation 5)

where the new term is the mass times the acceleration. The behavior of the system described by Equation 5 is complicated and depends upon the simultaneous values of k (stiffness), c (damping),

and m (mass) and, of course, the nature of the force, F . These can, however, be examined in specific cases to determine the effects of each of the factors.

We will consider the case where the force is an impact (impulsive force). Under this kind of force, a typical behavior was examined and the response curve (vibration amplitude versus time) is given in Figure 7a, the baseline case. The key parameters, damping, mass, and stiffness will be changed (by doubling them) in subsequent analyses so that their effects will be seen clearly, even though in actual practice such large changes are often not needed.

Figure 7b shows the response when the damping, c , is doubled. Note that the amplitude is reduced and the decay is more rapid. These effects are those expected intuitively from adding a damping material to the part and are like increasing the inherent c of the material or adding an additional dashpot to the system.

Figure 7c shows the effect of doubling the mass over the baseline case. Compared to the baseline (7a), the increase in mass results in lower vibration amplitude, slower oscillation, and a slower rate of decay. The lower vibration amplitude is favorable in most cases but the slower rate of decay can be detrimental. The effect of mass is, therefore, complicated and mass is usually not the first method chosen to control vibrations. However, many of the methods chosen for vibration control involve changes in mass, thus suggesting that mass be considered in each case.

The effect of doubling stiffness is illustrated in Figure 7d. A comparison of Figure 7a and 7d shows that increasing stiffness will lower the amplitude, increase the frequency of oscillation, and result in slower decay. Again, the lower amplitude is beneficial but the slower decay rate can be a problem. However, that effect is offset somewhat by the faster oscillation rate, as can be shown in a more thorough analysis that is beyond the scope of this paper. (Trust us.)

A specific, real life example is useful in understanding these behaviors. Consider a composite case subjected to impact from an object such as a flying rock whose behavior might be represented by Figure 7a. We can bond an elastomeric layer to the case and achieve a significant decrease in vibration amplitude and vibration time just as described in Figure 7b. It is not likely that you would increase the mass of the case (in any practical way) without increasing the stiffness of the case significantly. But if you did, you would see a decrease in amplitude and the other effects described above. Most often, mass and stiffness are increased together. However, you might be able to predominantly increase stiffness without significantly increasing the mass by adding low mass ribs or changing to a sandwich design. In these cases the major effect is the decrease in amplitude (good).

Let's now consider the situation where the composite case is a shroud that encloses a continuously vibrating engine. Here, vibrations are not induced by an impact but, rather, by a continuous oscillation of the engine. The effects are found to be dependent upon the frequency of the engine vibration as well as the factors for damping, mass and stiffness. Adding damping (c) improves upon the baseline case but has only minor benefits at very low frequencies. Adding stiffness (k) will improve performance at low to intermediate frequencies, but may become detrimental at very high frequencies. Adding mass (m) is a benefit only at very high frequencies and is otherwise detrimental. The frequency ranges which determine the "low" and "high" ranges depend upon each particular situation.

Controlling damping

Damping can be controlled by two major methods – **passive control and active control**. Passive control can involve several strategies for damping, all of which involve some mechanical

characteristic of the system, either inherent or added, to control vibrations. Once the characteristic becomes part of the system, no further action is taken; hence, the system is passive.

All of the treatments which have been implied in the previous examples, such as adding damping materials, weight or stiffness are passive. Passive control also includes the use of discrete devices, such as shock absorbers, and the addition of materials that have high inherent energy loss.

Materials with highly mobile molecules, such as elastomers, have long been known as highly damped materials. Therefore, damping control can be achieved by making the part out of an elastomer. A part could also be damped by adding elastomers to the normal material that the part is made of. In both of these cases, the internal molecular nature of the part furnishes the desired damping. Changing the shape of a vibrating system by joining system components together with elastomeric adhesives would also increase damping. Damping could also be achieved by mounting the vibrating part on an elastomer, such as would be done by using a damping pad for a motor. You might also wrap the part in an elastomer. These solutions reflect the general methods of damping that were discussed previously in the discussion of damping fundamentals.

Active damping is a much more recent development in damping engineering. This strategy involves the addition of elements to the part that sense the amount of vibration and trigger some remedial action to dampen the movement. The most common system of this type can be achieved by embedding sensors in a part to detect vibrations and piezo-electric devices which extend and retract in response to the sensor signals in such a way as to counteract the vibrations. This system requires that electric power be supplied to the actuators.

Active systems of the type described above have been used in aircraft. These systems drastically reduce the vibrations associated with flight, especially at times such as breaking the sound barrier. They are able to control these vibrations without the penalty of reducing the stiffness of the aircraft parts or changing their shape.

Some advanced active systems also use the signals from piezo-electric devices to drive actuator motors which can make minor adjustments to the shape (geometry) of the airplane components. For instance, the wing shape can be changed during high turbulence to optimize flight control.

Another method of active control is through the use of embedded fiber optics. These fibers can sense gross vibrations much like electronic sensors. The fiber optics can be monitored for changes in cross-sectional area of the fiber which will cause a change in the light transmission and, therefore, indicate that vibrations are occurring. These changes might even be able to pinpoint the actual location of the vibration, thus giving tighter control than is usually possible with electronic sensors.

Damping in composites

As a general rule, composites have better damping properties than structural metals. Typically, the range of composite damping begins where the best damped structural metals stop. The damping in composites is controlled by the matrix properties, the fiber properties, the interaction between the fibers and the matrix, laminar stacking sequence, and embedded or attached viscoelastic layers.

Matrix properties. The matrix properties which relate to damping are E' and E'' , as has already been discussed. In general, matrix materials with high amounts of internal molecular

motion, such as elastomers and most thermoplastics, have higher E'' than do highly crosslinked thermosets. Therefore, use of thermoplastic composites, such as those that can be made by injection molding, will improve damping (assuming no effect from the fibers). Of course, other considerations, such as overall strength and stiffness, may preclude the use of these thermoplastic composites in some applications.

Fiber properties. The fiber properties which relate to damping are also E' and E'' . Generally, the amount of E'' in these fibers is quite small and so their internal energy loss is not usually considered to contribute directly to damping, at least in comparison to the matrix. In aramids, however, the amount of E'' can be significant and should be considered.

Interactions between fibers and matrix. The damping arising from the interactions between fibers and matrix can be very large and are quite complicated because so many different aspects of composites affect the interactions. For instance, the damping arising from the interactions can be affected by fiber length, fiber orientation, and interface effects.

Within almost any reasonable fiber length range, the **effect of length** on damping is small. What little effect there is, seems to suggest that shorter fibers give slightly better damping, probably because there are more ends and, therefore, more interactions with the matrix. Fillers can be thought of as very short fibers. Therefore, the possibility exists that fillers can improve damping. However, perfectly spherical fillers show no damping improvement. Therefore, for fillers to cause significant damping, they must be non-spherical but not very long, perhaps like short whiskers.

Damping is increased when the **orientation of the fibers** is off-axis by 5 to 30°, with fiberglass being generally in the higher end of that angular range. Generally the stiffer the fiber,

the smaller the angle for maximum damping. Going all the way to 90° results in a composite where the damping is principally controlled by the matrix and the fiber has only a small contribution. Random fiber orientation will, in general, result in higher damping than would occur with aligned fibers. Note that the fiber orientation effects for aramid fibers have been reported to be far less dependent on fiber orientation than for carbon or glass fibers.

The **fiber-matrix interface or interphase region** is an area where energy can be converted into heat and thus, a region of potentially high damping. Factors which would tend to increase the energy loss in this area are: poor fiber-matrix adhesion, low modulus of the interphase itself, high molecular motion within the interphase, and a high total volume associated with the interface or interphase. Unfortunately, although these would all give higher damping, they would also result in decreased stiffness and, perhaps, lower strength and other normally desirable properties. Because of the effort to improve interfacial bonding, the damping effects of the interface are usually small. However, some circumstances could arise, such as the absorption of water at the interface or intentional poor bonding as in composite armor, that would cause the interface effects to be quite large.

Interlaminar stacking sequence effects. If, in the stacking sequence, we put the plies with the most damping (that is, those which are off-axis) in areas where they would experience the most strain, damping is optimized. For instance, in bending, the outer parts of the composite would have the most strain and would be the places where the off-axis layers should be placed to maximize damping. Sadly, that type of placement will also decrease the overall stiffness of the laminate. We must, therefore, deal with tradeoffs.

When a laminate is impacted on its surface, the sequence of stacking can affect the amount of energy that is transmitted from one fiber layer to another. The maximum amount of energy transmission occurs when the layers are aligned, and the minimum energy transmission occurs when the layers are orthogonal (90° from each other). When the energy is not transmitted, it is either converted to heat in the region between the fiber layers (thus causing damping) or it is rerouted into a sideways transmission (thus causing delamination). Therefore, the fiber sequences that improve damping are the same as those that make delamination worse. The optimum overall condition might be achieved, therefore, by using a sequence in which the angles between the layers are more than 0° but less than 90° .

Embedded or attached viscoelastic layers. A common method of constructing damped composite structures which are effective in damping bending forces, is to add layers of viscoelastic (damped) material to composite materials, thus creating a hybrid structure. Three methods of making these attachments are illustrated in Figure 8. If the viscoelastic material is simply attached to the outer surface of the composite, the damped layer is called a free viscoelastic layer. If the viscoelastic layer is on the surface but a constraining layer (typically a thin layer of aluminum) is also added, the layer is called a constrained layer. If the viscoelastic layer is embedded within the composite, the viscoelastic layer is called a co-cured or embedded damping layer. In all of these cases, the damping occurs because the viscoelastic layer absorbs (and converts into heat) some of the energy that is transmitted into it by vibrations in the composite. Viscoelastic materials of all these types can be purchased commercially as tapes, sheets and prepregs. The constrained and embedded methods are more effective than the free

viscoelastic layer because of the shear forces which arise from the constraints and the tendency of the system to convert these shear forces into heat.

The embedded method gives the greatest amount of design flexibility because the viscoelastic layer can be placed wherever it will be most effective. The drawback is, of course, that the embedded layer must be incorporated into the laminate when it is cured whereas with the other methods, the damping layer can be added after the part is made. The effect of the embedded system is illustrated in Figure 9 which shows the results of vibration tests on two stiffened panels – one baseline panel and one with an embedded viscoelastic layer. The displacements of the embedded sample are much less than the baseline across the entire frequency range, thus attesting to the damping value of this method.

A new technology derived from the embedded layer concept gives the promise of being able to increase damping tremendously without the usual decrease in stiffness. In this method, a viscoelastic layer is embedded between composite layers having unique fiber orientations. The fibers are oriented into a zig-zag or a wavy pattern such that the fibers in one layer are zigging when the fibers on the other side of the viscoelastic layer are zagging as shown in Figure 10. Under these conditions, when vibrations occur in the composite, the vibrations tend to straighten the wavy arrangement. However, because the layers on composite layers on either side of the viscoelastic layer are oppositely oriented, this straightening of the fibers causes tremendous shear within the viscoelastic layer. Damping from this type of structure has been shown to be over 10 times greater than without the wavy configuration. This system is called stress-coupled damping which has now become commercially available. Another advantage of the stress-coupled damping

method is that unlike free, constrained, and embedded layer damping, the stress-coupled damping method is effective in motions other than flexure.

Summary

Because composites are inherently better damping devices than metals, the opportunities for use of composites in damping are very large. As composites are used more and more just because of their damping capabilities, the need to meet competition by optimizing the damping will increase. Many variables within composites can be changed to optimize the ability of the composite material to dampen. These are being explored and even new concepts invented as damping becomes ever more important and the role of composites in damping is more widely promoted.