Chapter 9

Transportation, Distribution, and Product Damage

In a society that depends on the continuous availability of consumer goods from around the world, transportation and distribution are a critical part of the manufacturing and packaging scenario, and the ability of a packaging system to protect products during transit and distribution is a fundamental part of package engineering. To better understand the factors that come into play with distribution, it is useful to consider the nature of the distribution system, its modes and vehicles, and the demands that distribution can place on packaged products.

The transportation of goods to market can take every form imaginable, from being carried atop a person's head to being carried into space in a launch vehicle. For the purposes of this text, we will consider the most common mass-distribution modes, although it should be remembered that the final steps in a transportation chain might be the most damaging. Food products that have been carefully refrigerated all the way to the store may be left in a passenger car's trunk in the sun for hours before being unloaded at home; appliances that have been carefully packaged and shipped may be carried by pack animal; and certainly anything traveling with children will take a beating.

Transportation and distribution systems establish themselves as a complex function of infrastructure, distance, and diversity, and often do not do so in the most energy- or time-efficient way. There may be a great difference between the distribution systems used to deliver supplies to remote areas of the Scandinavian coast, Beijing, and Omaha, although they all may use very similar vehicles. Because of the efficiencies of cargo vehicles and their infrastructure, nearly all mass distribution of merchandise is predominantly dependent on a combination of the four basic modes of transportation: truck, rail, ship, and aircraft (pipelines will not be considered). Each of these modes and their infrastructure will be described in general terms, along with some of the intermodal facilities commonly used to handle materials. The dynamic environment that each creates will be discussed subsequently in this chapter.

Energy Efficiency

With fuel supplies increasing in price and subject to both natural and man-made instabilities, the fuel efficiency of transportation, although not always accurately reflected in tariff rates and costs, becomes a large factor when deciding transportation type. Table 9.1 illustrates some of the relative efficiencies of different modes of mechanized transportation.

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Table 9.1. Fuel Consumption Comparison of Different Freight Modes

Vehicle Type	Ton-Mile Per Gallon	Kg-Km per Liter
747-400F Cargo Aircraft [1]	24.8	9,380
"Semi-Trailer" Cargo Truck [2]	155	58,640
Space Shuttle "Atlantis" [3]	187.5 + 46.88 ton-mile/lb Solid Fuel	70,930 + 92.51 tonne-km/kg Solid Fuel*
Railroad (US) [2]	413	156,230
Barge (Inland Towing) [2]	576	223,085
Oceangoing Container Ship "Emma Maersk" [4]	933	352,960

*A "tonne" (metric ton) is 1,000 kg (2,205 lb), whereas a US "ton" is 2,000 lb (907 kg).

Truck Transportation

Truck transportation is probably the most ubiquitous mode of motorized conveyance for bulk items. Although it is much less energy-efficient than rail or ship freight, it has the advantage of being able to operate over many types of undeveloped road systems and to deliver relatively small quantities of various items on a timely basis to individual locations without freight terminals. Trucks are typically constructed as some variety of a "Semi", a semi-attached articulated coupling trailer pulled by a motorized cab. In developing countries, this may be scaled back to smaller, single-chassis trucks, many of which can operate on unimproved roads and even open desert. The implementation of intermodal transport containers has provided the capacity for trucks to be the flexible beginning and final delivery component in a freight system that can also use rail and water transport.

Rail Transportation

Rail transport is the most energy-efficient means of land transportation, and makes non-stop trips across continents as a matter of routine operation. Because access to rail systems is not usually as extensive as access to roads, rail systems are often used for large shipments, unitized shipments, and for shipments of vehicles, commodities, and fuels, although due to the limited rail corridors in many regions, scheduling and conflicts with scheduled passenger service can present a problem. With the implementation of multimodal containers, rail transport has shifted from traditional freight yards to intermodal facilities where containers are offloaded from rail cars to semi-tractor transport for local delivery without direct handling of the products.

Water Transport

Oceangoing vessels are used for energy-efficient coastal and intercontinental shipment of containerized freight, bulk commodities, and fuels and vehicles. Although service is slow, as many freight vessels operate at optimal hull speeds rather than full rated speed, per-ton freight costs are very low. Access to ports and terminals may be a limiting factor for many water-based shipping operations – seaports are somewhat scarce in Ulan Bator and Laramie, Wyoming – but many distribution routes incorporate water-based shipping in at least part of their distribution plan, and nearly all trans-oceanic shipping is done by water.

Barges, which have played a role in the efficient transportation of goods throughout history and particularly at the beginning of the Industrial Revolution, are used in inland and protected waterways, although oceangoing barges may be used for coastal work and specialty products. Container barges, which are handled with standard tug-towing equipment, can be used in shallow-draft waterways, although their capacity is a good deal less than that of a dedicated container ship. These most often operate on rivers and canals, although many countries with well-developed road systems may use trucks for speed of delivery and leave barge and river transport for bulk materials and fuels.

Air Shipment

Air shipment is the fastest, most complex, most costly, and least energy-efficient means of conveyance, but it offers the advantage of very fast movement of goods. It is particularly advantageous for very perishable items such as seafood and fresh flowers and for time-critical ones such as military equipment, famine relief, and financial documents. Additionally, air shipment offers the possibility of delivery in areas inaccessible by other means such as remote, mountainous, polar, or – if one includes launch vehicles – even extraterrestrial regions.

Air shipment is not the most effective means of conveying everyday, low-value items where other means are available because of the high costs involved, but express delivery operations rely on air fleets ranging from small “feeder” propeller aircraft to very large international cargo aircraft based on the Boeing 747, Airbus 380, or even the sole Antonov AN-225. Specialized manufacturers, especially those in the aerospace industry, may also rely on specially designed aircraft to transport equipment and sub-assemblies from other operations for final assembly at their main facilities.

Mixed Transportation Modes

One of the critical problems in cargo handling and distribution occurs when goods require multimodal transportation. Moving goods from the factory to the consumer may require several changes between truck, rail, and water transport. The solution to this is the use of intermodal transport containers of various types described in the distribution packaging section. These are typically interoperable between rail, truck, and ship platforms with a minimum of handling and represent a substantial leap in efficiency and security over the traditional handling of individual cargo items.

With the rapid increase in global shipments, the limiting factors on shipments are becoming increasingly those related to transfer infrastructure, with ports, rail facilities, and roads continuously being pushed to expand their capacity. Intermodal facilities, particularly those combining rail, truck, and ship loading, are often critical bottlenecks, with the attendant congestion and pollution causing secondary problems that limit economic activity. Because of this, industries may locate sites (or relocate old ones) based on transportation availability as much as any other single factor, considering that getting raw materials in and finished goods out is critical to large-scale operation.

Distribution and Warehousing

In the food distribution industry, the extremely changeable and flexible nature of the retail food market, coupled with demands for lower costs and high response, has produced an extremely efficient and data-driven industry that has all but eliminated warehouses and backroom inventory in favor of just-in-time delivery and high-speed computer-driven ordering systems. This system uses information garnered from Point of Sale (POS) information and other data-driven systems to tailor ordering and distribution into a nearly continuous stream of goods from raw materials through manufacturing and distribution to the final consumer. In order to understand the motivation for the types of changes and infrastructure necessary to create this type of system, an understanding of the basics of inventory and supply chain management is useful.

Distribution and Inventory Economics

In very simple terms, management of inventory and ordering structures demands that a balance be struck between the costs of ordering materials, the costs of keeping inventory on hand (so-called *carrying costs*), and the lost sales associated with *not* having a particular item on hand as discussed in Chapter 8. As anyone who has done much grocery shopping will acknowledge, stores seem to prefer to err on the side of being occasionally out of stock on a particular item rather than keep excess inventory on hand. The reality is that stores must manage their supply chain very carefully because customers can take their entire purchase elsewhere if too many favorite items are out of stock, and must maintain supply of fast-selling items as well as those that may sit on the shelf for a longer period.

This process has been automated, and in some systems can incorporate information about delivery times and availability to allow orders to be sent at the correct time, such that the new inventory will be put out for sale at the same time that the last of the old inventory is being sold. These types of logistics and materials management practices stem from work done in the manufacturing industry that sought to wean manufacturing away from older make-and-warehouse practices and into just-in-time manufacturing and supply chain management that were discussed in Chapter 8.

The Information Cycle

Because the ordering and distribution system is information-driven, the information cycle, first introduced in Chapter 1, can be a useful map of how orders are generated and handled. For this, a grocery-retail model is used, but the general principles apply to any sort of manufacturing, retail, or general distribution system.

When inventory is removed, usually through sale to a customer, the item is either checked out manually (a practice that is becoming thankfully rare) or scanned out of inventory using a bar-code reader or RFID system. This information is transmitted to an inventory computer, which then subtracts that amount from the inventory on hand. When inventory on the shelf gets sufficiently low, an order is triggered to suppliers. This process is staged backward at several levels, as suppliers and then manufacturers in turn manage their own inventory and shipments. The final result of this system is that direct consumer demand drives both manufacturing and distribution on a nearly continuous basis, providing inventory "on the fly" and reducing the amount of inventory accumulating at any given point in the system to an absolute minimum. Warehouses have been replaced by *cross-docking* operations, where inventories of a single product from a manufacturer arrive by the truckload at one loading dock, are unloaded, sorted, and then redistributed into *break bulk* – mixed product truckloads – at other loading docks across the facility (thus, the term), which then leave immediately to restock retail operations. In effect, the inventory seldom stops moving from the moment it leaves the producer until it reaches the retail shelf. The exception for this continuous-flow model is for seasonal items such as fruit and vegetables, as well as holiday items that may be processed at a particular time and held for later redistribution.

Food retail businesses typically operate at a very low profit margin – often 1–2% – but have an enormous turnover of inventory. Grocery stores average 19 complete inventory turnovers in the course of a year, and often a great deal more for individual perishable items [5]. The economic implications of more efficient distribution and transportation are that large retail operations are able to reduce inventory costs by being able to sell inventory extremely quickly. Because many distributors and manufacturers offer a discount for those customers who pay for their orders before a specified period of time (for example, a "2% 10 net 30" discount reduces the final bill by 2% if it is paid within 10 days of receipt, and is due in full after 30 days), the inventory is often sold before the retail operation is required to pay for it. This provides the interesting paradox of a retail operation that sells inventory at or below its billed cost and still makes a profit because of the billing discount. This would not be possible in a slow or inefficient distribution system, and places small operations at an extreme price disadvantage. Additionally, the advent of global discount chains has changed the manufacturing-retail relationship, as manufacturers may be required to produce items such as clothing and electronics at a price point for that particular retailer and its distribution system. Beyond this, several of the largest retailers have begun to arrange for "depot" operations, where the manufacturers themselves own the inventory until it is sold, effectively transferring any inventory-carrying cost entirely away from the retailer and back to the manufacturer or wholesaler.

Data from Distribution Systems

Because data is increasingly inexpensive to gather using automatic scanning operations, information about secondary phenomena in the distribution system can be gleaned if there is a large enough statistical base to work from, and knowledgeable people and computing resources are available to extract meaningful information from the data. Information about particularly hazardous transportation routes can be taken from shipping records and return information, and delays in delivery can be correlated to both the carriers contracted for delivery as well as geographic and meteorological data (perhaps giving specific information about how much longer delivery times will be in remote winter locations).

Advanced algorithms have begun to be implemented into the manufacturing and transportation industries that manage materials sources, manufacturing locations, and delivery systems and even utility sources in order to reduce costs and risk to a minimum. These may be based on "brute force" analysis of the manufacturing system, or on advanced concepts such as genetic algorithms, neural networks, holonic systems, and swarm intelligence that have been pioneered for other fields, such as software development [6, 7].

Integration of distribution and sales information and correlation with credit card information, customer "Rewards Cards," product registration cards, and user surveys allow retail operations to pinpoint information about particular customers' buying habits, locations, and timing. When coupled with optimal cost data, delivery information, and alternatives and advertising promotions, a comprehensive and fairly adaptable system of retail management has emerged that allows fast and responsive distribution of goods. Deeper data mining into customers' habits for both commercial and governmental ends have been a subject of debate and litigation as data storage and computational costs have dropped to the point where whole populations may be scanned for particular attributes or behaviors [8].

The Role of Packaging in Logistics and Inventory Management

The old image of distribution packaging has always been stacks of boxes and barrels sitting in a dusty warehouse, when in fact most inventories do not remain in one place any longer than is absolutely necessary once they leave the manufacturer. In this scenario, packaging becomes, in the most literal sense, the spokesman for the product in automated inventory and distribution systems. The package now carries machine-readable data that serves as both inventory control and distribution routing information, principally through bar coding, although there is great pressure to make the transition to RFID information systems that do not require access to the individual product in a bulk shipment. The shipping container or bulk package may also contain shipping or routing information in addition to standard information about contents and production data.

Logistics systems may use this information to properly route and handle products that require special consideration such as flammable and perishable goods. It is also possible to attach devices that will measure and record temperature fluctuations, shock and vibration, and other environmental inputs to assist in the effective and safe distribution of goods.

Data Tagging and Data Acquisition Methods

Bar code formats are simple, standardized optical patterns that may be stripes, checkered patterns, or even roundels that allow an optical scanner to interpret the pattern to decode the tags' data. These are usually incorporated into the label design on consumer packages and may be imprinted on distribution container tags, although at larger scales of distribution, they may be applied via inkjet printer or adhesive tag to the outside of the shipping container. The specifics of bar code and RFID data systems are more fully described in Chapter 4, but this chapter will be more concerned with the larger-scale applications of the data contained in the bar codes and their effect on distribution systems and manufacturing flow. Similarly, passive RFID tags are machine-readable components that are energized by the electromagnetic field of a reader device and return digital data via a radio link. Unlike optical systems, the data capacity of RFID systems is not constrained by size and optical resolution, although cost barriers are the current limitation. RFID systems for specialized use, typically self-powered "active" RFID systems, can support enormous quantities of data and may be linked to powered onboard systems for temperature, shock and vibration, or other data.

Data is collected from most optical code systems via a monochromatic laser scanner, similar to those used in supermarkets. Railroad cars historically used a large, multicolored coding system for traffic management, although this was only marginally successful due to dirt and maintenance problems, and has been replaced with RF-based AEI (Automatic Equipment Identification) systems. RFID data is transferred from the package or device via a reader that incorporates a transmitting antenna to power the RFID device and a receiver to receive and translate the returned signal. Restrictions on allowable power for readers, combined with the tendency of many packaged goods to damp out radio signals buried in the interior of a shipment of lossy materials, have proven to be a frustrating limitation for many RFID systems and, when combined with relatively high tag costs, have slowed the large-scale implementation of RFID inventorying and distribution systems for small consumer items, although larger-scale assembly operations such as automobile plants use them to assist in adaptive assembly automation and painting-line sequencing.

Hybrid systems that reference tag data to larger files stored in devices or online databases for customer use are often used as a means for overcoming data storage limits, and have opened the possibility of other applications such as "intelligent" home appliances, although these may create accessibility or security issues for more remote or sensitive applications.

Limitations on Data

Although the previously described linked systems have no realistic limit to the amount of data linked to a particular package, discrete systems will have several limitations. Bar code systems have limitations on the surface area available for data encoding. Although some very data-dense printing methods and coding schemes have been developed, practical limits on printing accuracy and scanner resolution limit data tags to several kilobytes of on-board information. Similarly, memory capacity of current RFID tags used on consumer goods and luggage is less than 1 kb of data, although larger active units for military and equipment use may have extensive data storage capacity.

Distribution Packaging

Distribution packaging is distinct from consumer packaging in that in most instances, distribution packaging is used for the large-scale shipment of materials or components to be used in the manufacture of other products. These are typically shipped in multiple quantities and are seldom labeled for use by the consumer. Some notable exceptions to this are the bulk distribution of materials such as gasoline, landscaping materials, or even water in remote areas. "Large-scale" may be a relative term as well, considering the distribution packaging for high-value items such as pharmaceuticals or electronics, which are physically small and go against the notion of a huge bulk shipping container filled with product. Most often, the distribution of goods such as food ingredients and machine parts from suppliers to manufacturers involves the most economically advantageous quantity to be shipped, whether it is a tanker truck full of molten chocolate or a single case of high-value pharmaceutical ingredients. This, in turn, depends on the production needs of the customer.

Distribution packaging for food items depends on the food material itself, the order quantity, and its intended use. Food items for use in small restaurants or delicatessens are packaged in substantially different systems than bulk ingredients intended for use in large food-manufacturing operations. Bulk transport of food ingredients in the most economically efficient manner may involve large tanker vehicles or intermediate bulk containers. If these are to be used, the distribution system must be able to load, transport, receive, and use the product properly. Sanitation, temperature control, and specialized loading and unloading systems may be required to make the best use of large-scale shipping, but the savings in manpower and handling efficiency can be enormous. The dairy industry is the most pervasive example of this, with temperature- and time-controlled shipment and clean transfer and handling facilities from the dairy to the consumer.

Containerized Transport

In 1956 the container ship *Ideal-X*, a reinforced military surplus oil tanker, sailed from Newark, New Jersey to Houston, Texas, with ordinary semi-truck trailers chained to the deck. In Houston, the loaded trailers were re-attached to truck cabs and driven to their final destinations without any other handling. This elimination of the manual labor of cargo loading and unloading reduced the cargo loading cost from US$5.83 per ton to less than US$0.16 a ton, and began the revolution away from cargo nets and toward shipping container standardization 9. The result of this is the current use of Intermodal Shipping Containers, which, although no longer made of surplus truck trailers, can be swapped from rail to air to truck transport with simple mechanized handling equipment. Intermodal shipping containers are large steel containers that can be loaded and sealed, then shipped by oceangoing vessel, truck, or train (and, in rare cases, by air) without opening the container and handling the contents. Intermodal shipping containers are typically specified in *twenty-foot equivalent units* (TEU), derived from the original US military shipping container that was ten feet long. TEU are used to express the relative number of variously sized containers being conveyed, based on the equivalent length of a 20-feet-long container. A 40-feet-long container, therefore, is equivalent to two TEU, and large-scale shipping operations are usually measured in numbers of TEU that are shipped, with world container ports expected to handle in excess of a half-billion total TEU in 2009. This has resulted in lower shipping costs as well as a substantial reduction in theft and damage during the shipping operation, and has caused the redesign of the world's cargo shipping fleet into container ships, including huge "post-Panamax" carriers that can carry 11,000 TEU in shipping containers lashed to the decks and stowed in the hold areas but are too wide or long (greater than 294 meters in length, 32 meters in width, and 12 meters in tropical freshwater [TFW] draft) to transit the Panama Canal's older locks, and thus designated to travel the distance around the Cape Horn. A third, wider set of locks is scheduled to go into service in 2014, creating a "new Panamax" size limit of 366 meters LOA, 49 meters in beam, and 15.2 meters in tropical freshwater (TFW) draft to partially alleviate the problem [10, 11]. When back on land, one or several containers may be loaded onto flatbed rail cars, and over-the-road trucks with specialized trailers can carry cargo containers directly from the port to the final customer without ever having to directly handle the cargo. Thus, the increasingly integrated container shipping system allows intercontinental shipping using trucks, rail, and oceangoing vessel to efficiently move products from nearby location to customers everywhere.

Unitized Air Shipment

Aircraft shipping often uses smaller cargo containers called *Unit Load Devices* (ULD) that can be either an air-freight pallet or a container configured to the specific aircraft's fuselage design and freight deck. They are necessarily lightweight in design and do not offer the same degree of protection to the cargo as an intermodal container because they are always carried inside the aircraft, but carry individual freight manifests and tracking information [12]. These offer the same speed of loading and unloading that make the intermodal containers advantageous and further accelerate the pace of rapid air-freight operations. ULDs are loaded into the aircraft fuselage and rolled back along the cargo deck for air transport. They are usually not intended for intermodal use but can be shipped by truck flatbed into sorting facilities and are most often used by express parcel services.

Fluid Tanks

Fluid tanks other than the common tank-trailer are available for large-scale, secure shipment of fluid materials ranging from chemicals to wine. Two methods predominate for this type of distribution shipping: tank containers and flexi-tanks. The former is a discrete tank that is unitized to fit within a space frame that fits intermodal standards, and can be handled by the same equipment. These can be constructed to handle sterile and aseptically processed, hazardous, or pressurized materials, and can be constructed to safely handle a variety of fluid densities. Flexitanks are standard intermodal shipping containers that have been fitted with a flexible liner bag allowing the full volume to be filled with liquid. This method has the advantage of a lower initial construction cost, but great care must be taken, particularly with high-density liquids, that the hydrostatic pressure of the fluid does not distort the sidewalls of the container and that fluid surge does not allow the container to become unstable.

Intermediate Bulk Containers (IBC)

These are large containers that can be used to store and ship ingredients, and can be constructed in many variations to suit the product and the nature of the distribution system. Most often these are sized to the approximate footprint of a standard shipping pallet, although larger ones for specialized loads such as live fish fingerlings may be the width of the transport vehicle. These containers nearly always require mechanical handling assistance, most often a fork lift, overhead hoist, or similar device. Rare exceptions exist that have been built for aircraft assemblies and may be fitted with casters to allow manual movement.

Rigid-wall IBC systems may be constructed of plywood, welded steel wire, molded plastic or corrugated paper, or Coroplast™, and can be lined to provide a sealed environment to any degree necessary. The latter is important because it allows the container to be used for bulk liquid or semi-liquid ingredient shipping from production facilities in one location to another, including trans-oceanic shipment without contamination. Less stringent conditions permit the shipment of nearly any type of material such as grains, flours, and plastic resins. IBC systems may be designed as returnable, semi-returnable, or one-trip containers, depending on the nature of the product, the distribution system, and the requirements of the customer. Returnable systems may be emptied, with the liners – if present – removed and folded flat for return shipment. Semi-returnable systems may have a recyclable sidewall made of corrugated and a returnable bottom pallet. One-trip containers are made to be recycled or disposed of after a single trip, and may be more lightly designed. Any of these containers can be ordered with specialty fitments to allow product unloading, pumpout, drainage, or other functions as necessary.

Flexible Intermediate Bulk Containers

Flexible Intermediate Bulk Containers are, as their name implies, made of flexible materials, and are designed to be handled from above using sling straps that are an integral part of the container design. These containers are intended for use with dry granular materials ranging from fine pharmaceutical powders to crushed stone and, although they are available in any size necessary, are often sized to be half the width of the shipping vehicle, so that they sit two-across in the truck bed. These can be fabricated of a range of fabrics, liners, and coatings – although polypropylene (PP) with various coatings for static electricity dissipation, UV protection, or food contact predominates – and may have a polyethylene or polypropylene liner. FIBC systems may be designed with filling and emptying spouts in the top and bottom of the bag, as well as a variety of lifting sling arrangements to suit the type of handling systems and bag capacity [13].

Institutional Packaging

Institutional packaging is food packaging that is intended to be used in retail operations, restaurants, commissaries, and cafeterias, and is intended to be manually handled. It is often intended for use in quantities approaching those of consumer packaging, although the unit size and labeling may be optimized for efficient use in the retailer's application rather than retail customer appeal, because it is a package that is not often seen. Restaurants, bakeries, creameries, and other food service operations that cannot use truckload quantities of a particular ingredient will typically use institutional quantities to gain more efficiency in storage and product pricing, and these are often delivered in the distribution packaging that is subsequently described.

An ancillary category that is often neglected in the institutional packaging milieu is the home delivery meal segment. These are subscription or order services that deliver consumer products direct to the home (as opposed to a grocery delivery service that simply delivers regular retail items). These may be produced in non-standard sizes, are often frozen, and may be labeled quite differently than retail containers because they will be designed to encourage repeat purchases rather than identifying them as unique among a host of competitive products on a retail shelf.

Bag-in-Box Packaging

In addition to the usual shipping container and large steel can, many ingredients such as cleaning agents, fruit juice, milk, soft-drink syrups, and toppings for hamburger and pizza operations may use a bag-in-box system, allowing pumped application to speed operations. Bag-in-box packaging is most often a corrugated container fitted with a flexible plastic bag and usually a dispensing or emptying fitment. They are typically lined with a high-barrier liner bag to preserve the contents and because of the flexibility of the container are not well-suited to carbonated beverages. These have almost completely replaced the heavy stainless steel syrup containers that were used in carbonated beverage dispensing and are often part of fast food and self-serve restaurant operations. These are seldom seen at the consumer level with the exception of some cleaning agents, juices, and large wine containers (which suffer from a persistent perception of poor quality). Ankerbräu breweries in Nordlingen, Germany, have produced a 25-liter bag-in-box beer distribution system with a claimed 8-month shelf life, but this relies on re-carbonation of the uncarbonated beer at the time of dispensing [14].

Shipping Sacks

The "burlap bag" has always been synonymous with the shipping of loose materials ranging from citrus fruit to grain, but in the last several decades has largely been replaced with mesh, paper, paper-composite, and plastic shipping sacks for bulk materials ranging from dog food to cement. For applications requiring extreme strength and puncture resistance, bags may be made of woven polyethylene or polypropylene, either alone or in conjunction with other layers for lining and labeling. These are traditionally filled and then sewn shut, although heat-sealing, tapes and adhesives have begun to replace these methods to speed production and aid in consumer utilization. Additionally, handles, spouts, zip seals, or other features may be added as required. Sizes are typically limited by the density of the product, with 40kg bags of cement being near the limit of practical use, and less dense items such as dog food available in 20 kg bags.

Jugs, Drums, and Pails

Jugs, drums, and pails are a common method of supplying small quantities of bulk ingredients such as pastry filling or soy sauce to operations such as bakeries and restaurants. Food ingredients may be hot-filled and then shipped for use in the food service operation, and aseptic liners may be added if necessary. Jugs, which often are blow-molded containers made to lay flat on a shelf with a dispenser feature hanging over the edge, can be used to contain and dispense everything from sauces to detergents.

Pallets

Pallets are flat platforms that provide spacing for mechanical material-handling devices to move intermediate loads of goods while assisting in the stability of the load. Most often, pallets are moved by manual pallet jacks or motorized fork trucks that move across the relatively smooth floor surfaces encountered in modern material handling. It is also possible to use pallets with sling lifts, and roller or belt conveyor systems, although these types of uses are less common. Pallets may be made in a variety of sizes and any number of materials, but wood predominates, particularly for reusable pallets, with plastic and paper pallets gaining ground, particularly for one-way trips and specialized loads that may require custom features on the pallet deck.

Pallet Types

Wooden pallets predominate in the market, as previously mentioned, with nearly a half-billion being produced in the United States every year. Beyond this, wooden pallets may vary a great deal in strength, stiffness, wood type, type of load to be carried, and fasteners used in construction. The two most common types of wooden pallets are stringer and block pallets, which will have either a notched, solid side stringer (with a four-way lift capability) or use simple wood blocks as spacers [15]. They may have solid plywood decking and be constructed of new, recycled, or a combination of materials. Simple softwood pallets may be used once and recycled, with more expensive types of pallets generally requiring a deposit and are intended for reuse, often within a "pallet pool" that handles the returns and re-supply on a for-fee basis.

Because of the FAO International Plant Protection Convention's International Standard for Phytosanitary Measures (ISPM 15), pallets (and other shipping fixtures such as *dunnage, crating, packing blocks, drums, cases, load boards, pallet collars, and skids*) intended for international shipping must be made of materials that are incapable of spreading invasive species. Wooden pallets, because of their capacity to carry agricultural pests such as the Formosa termite must be heat treated to a core temperature of at least 56°C for 30 minutes, or treated with a chemical fumigant such as Methyl Bromide to achieve this standard, and must display appropriate markings indicating compliance. Fabricated wood products such as plywood, paper, and laminates are typically not considered a harbored insect problem, nor are shavings or sawdust because of their thin cross-section [16]. As one might expect, plastic and metal pallets and materials are exempt until such time as plastic- and metal-eating insects appear.

Plastic pallets represent less than 5% of the total pallet market, and are typically constructed of HDPE, PP, or PVC. These may have a high recycled material content and can be produced in any number of fabrication methods, with the most common being structural foam molding. These are more expensive than wooden pallets but are generally considered cleaner and more durable, with the ability to include complex design features for specialized applications such as shipping automotive sub-assemblies. Industry efforts are underway to produce simple plastic pallet from recycled resin, and recycled plastic "lumber" is being examined in traditional pallet construction methods.

Paper-based pallets, made of molded pulp or corrugated and honeycombed paper, are a smaller portion of the market than plastic pallets. Although generally weaker than other types of pallets, they are well suited to light loads that are subject to high weight-based shipping charges such as air freight. Paper pallets are also easily recycled but are susceptible to both humidity and moisture effects and are typically not durable enough for multiple-trip use.

Metal pallets are typically used in specialty distribution systems that require high strength and the ability to resist a great deal of transit abuse. Because of their high cost and weight, they are typically part of a "captive" pallet system, where pallets are returned within the organization rather than being pooled as wooden pallet loads might be. Although heavy and expensive, they are capable of securing heavy, dangerous, and expensive cargos such as automobile engines and ammunition, and eliminate the risk of disastrous fires that may occur with stockpiles of the other types of pallets.

Slip Sheets

Slip sheets are simple, heavy-duty sheets that allow material-handling equipment to slide thin metal plates (fitted to a standard fork truck) under a unitized load of containers without use of a pallet, saving weight, space, and money. These may be used in conjunction with a *push-pull* device that slides the load on and off the tines more efficiently. These systems are best suited for packaged items such as lightweight consumer goods that are in stabilized loads that do not need any sort of support from the pallet. They are typically less than approximately 12 mm in thickness, are usually made of plastic laminated paper or heavy plastic to reduce friction, and will have lips on the edges of the load where handling access is required.

Shipping Fixtures

Shipping fixtures are a category of shipping device that is distinct from the mass-produced containers, pallets, and boxes that have been previously discussed. These are typically used for very fragile and high-value items that require specific support and protection, such as automobile dashboards and aerospace components that will justify their high price. Most of these are designed and built for a single purpose and may include any number of onboard devices including climate and pressure control, as well as active vibration-damping systems. Simpler variations are used to transport large diesel and jet engines for installation and rebuilding, large building installations such as air conditioning evaporators, and fully assembled boats and aircraft sub-assemblies. In nearly all cases, the shipping fixture is intended for reuse, either after return to the manufacturer or as a service stand for the original component.

Wood Crates and Boxes

Once the iconic container for distribution and long-range shipping, wooden crates and boxes have become cost-prohibitive for most items and somewhat unnecessary for long-distance shipping protection with the advent of the intermodal shipping container. Although still used in consumer applications where a wooden case will add marketing appeal, such as with alcoholic beverages, cosmetics, and occasionally fresh fruit, wooden crates and boxes are currently seldom used in food packaging except as bulk haulers in growing operations. The ISPM-15 restrictions on untreated wood being used for international shipment further limit their use. In most cases, wooden boxes have plywood or chipboard panels (eliminating the infestation concern), and crates are made of lumber slats. These are more often used for large machinery shipments and specialty applications that may not be able to travel in standard distribution methods than for low-value consumer goods.

Integration of Distribution Packaging and Manufacturing

In some cases, products may utilize the packaging as part of the manufacturing system itself. The previously mentioned bulk containers replace bulk tanks and bins in many manufacturing operations, and laptop computers can be assembled using their shipping tray as an assembly jig. The food industry has many such examples, because many canned goods rely on the heat of thermal processing as a cooking step to achieve their final consistency or quality, and frozen meals are also assembled in their final service trays. It is unlikely that computer manufacturers' ability to produce a custom product order for the consumer directly from an online request will trickle into the consumer foods arena, because computers are typically in a fixed-form factor and have relatively few options whereas there are many deli service counters and their equivalents available to consumers. Still, integrated Web orders for retail groceries have been seen as a potentially profitable service extension for grocery stores.

Response of Packages to Shipping and Handling

Once products are produced, packaged and shipped, the packaging becomes a large part of protection against damage during shipping. To understand how to prevent damage, it helps to have some basic concepts of how packaged goods behave.

Static Compression Damage

Compression from stacking loads, particularly those intermittently applied over long periods of time in high-humidity conditions, can damage package-product system, which means that the high safety factor described Chapter 4 will come into play. Although it is possible to rely on design data to estimate strength, it is important that a good estimate of the actual stacking strength of containers is known. This can be achieved by compression-testing the final containers, in both loaded and unloaded configurations, to determine how much of the load can be absorbed by the primary or secondary containers, and what the most likely mode of failure will be. Additionally, although there are a number of good compression-testing devices and protocols, careful observation will show that the real-world failures often involve asymmetric load application or palletization that compromises stacking strength by allowing the box edges to hang over the pallet's supporting surface. Products such as fresh fruit, seafood, and meat, which can support little stacking load and produce high levels of humidity, present a substantial challenge in maintaining package stacking strength. Care must be also taken that any shipping or storage damage is not inflicted during the package filling and closing process, and that good design practices are followed, usually involving coated corrugated board or plastic materials to resist moisture [17].

Dynamic Considerations in Packaging

Because packaged goods must get from the producer to market in usable and salable shape, it is important that the producers and transportation providers work together to provide a safe and economical means of transporting the goods. In the United States, a large volume of freight moves via truck transport even though it is less energy-efficient than rail, owing to the relatively difficult and inflexible nature of the nation's rail system, particularly for small loads of goods, but goods can be moved by truck, rail, air, and water, and each of these modes has its own considerations with regard to the dynamic environment.

To ensure that the goods reach the marketplace intact, it may be necessary to engage in some means of testing the package-product system. In order to conduct useful and accurate transportation, it is important to understand the basic concepts behind the shock and vibration environment's impact on packages and how they can be simulated.

In the world of packaging, getting goods to market requires that they be placed in some (usually) mechanical conveyance, each of which will have its own peculiar considerations with regard to dynamic environment and required packaging protection. Although many products are robust enough to survive the distribution system, and others are overpackaged in an expensive attempt at protection, damage to goods in shipping is a huge economic burden and potential safety hazard to shippers, manufacturers, and consumers. To understand how to get products to market in intact and saleable condition, the packaging engineer must have a good understanding of the environment that the product will endure, and must have a grasp of the basic physics of how mechanical devices respond to the shocks and vibrations to which they will be exposed.

Natural Frequency

Nearly all solid objects have a set of frequencies at which they will either amplify or attenuate vibration that they are subjected to. The specific response of the item will be a function of its structural design, materials, and any external constraints that may exist. The resonant frequencies in these may be very low, with a value of less than 1 Hz for large building structures in lateral seismic movement and some kinds of vehicle suspensions, or extremely high as with turbine parts, but the process is essentially the same. For elastic materials, described in more detail in Chapter 2, energy is stored and released in sympathetic cycles, driven by the inertia of the mass acting under some external force.

Fluid systems also oscillate cyclically, sloshing and surging, and exhibit natural frequencies and resonance modes of their own. For this reason, large tank carriers are built with internal baffles or tank separators to prevent or reduce the potential for the fluid movement that can cause the vehicle to capsize or lose control. This occurs because fluid flow tends to dissipate energy rather than store it like elastic solids. Modeling and prediction of this is complex, usually requiring advance computer simulation, and will not be considered in this text.

Viscoelastic systems have very interesting intermediate resonance properties and are often used as vibration dampers both in shipping and engineering applications such as engine mounts and vehicle isolation pads. The mechanics of this will be discussed in this chapter in general terms but are still the subject of a great deal of research.

For very simple systems made of purely elastic materials (without viscous or viscoelastic elements), the mechanical response of systems can be predicted by elementary equations, but for complex, real-world systems, it is often impractical and usually uneconomical to attempt to model the vibration response of the item in question. In this case, it may be necessary to attempt to simulate the transportation environment using vibration simulation equipment (Figure 9.1) and observe the response of the system to determine the best type of packaging for the product, to conduct real-world trials, or both.

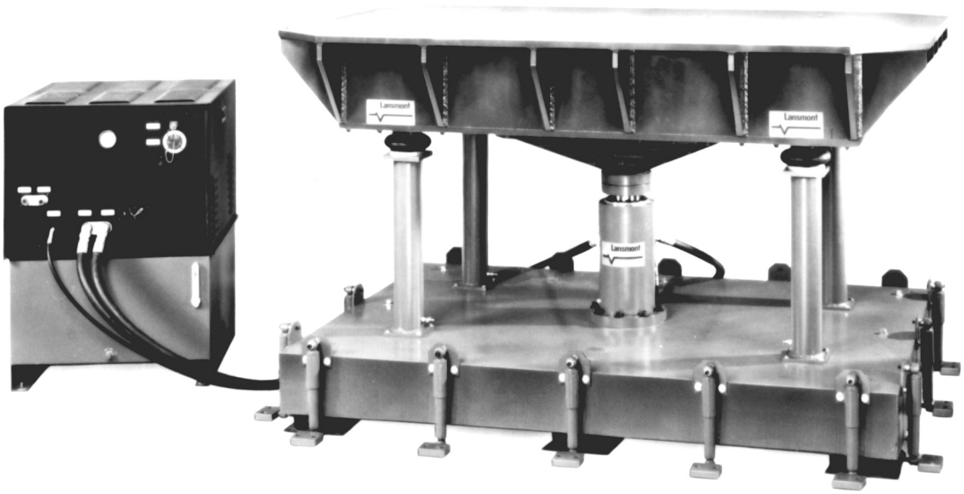


Figure 9.1. Vibration Table
Source: Courtesy of Lansmont Corporation

Resonance

Resonance is the matching of the natural frequency of a periodic system and a corresponding energy input. This results in the reinforcement and amplification of the energy within the structure. Intentional resonance is found and used in many applications ranging from circuit design to aerodynamics and atomic spectrometry. In mechanical systems, unchecked resonance can result in catastrophic failures as more and more energy builds in the system until the structure disintegrates (Figure 9.2).

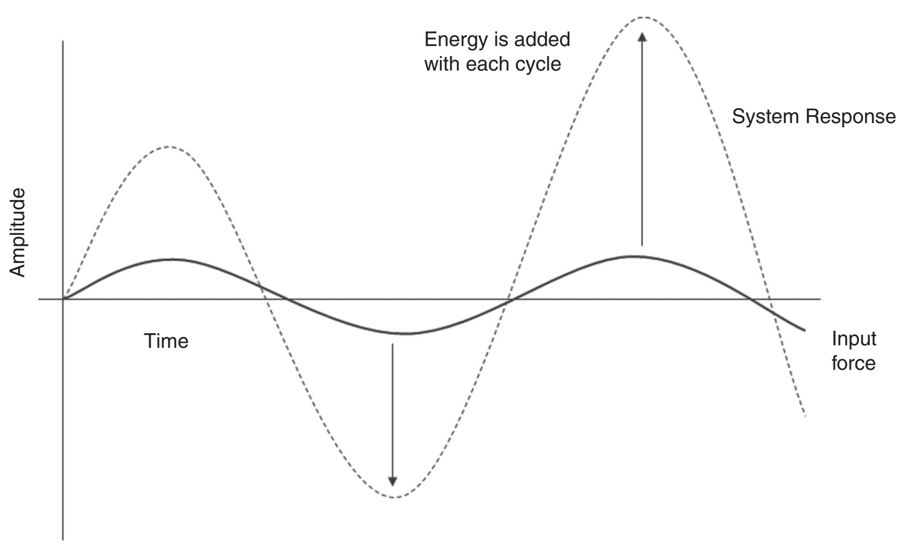


Figure 9.2. Resonance in Vibrating Systems

Because solid materials have both mass and some degree of elasticity, and fluid systems have similar resonance phenomena as previously described, nearly any structure can be said to have some potential for resonance. Reducing or eliminating resonance in structures may require a great deal of engineering effort and is often achieved by engineering a structure that interrupts the forcing energy, incorporates mutually cancelling resonance phenomena, or uses damping phenomena to dissipate energy from the system and prevent catastrophic levels of motion.

Response of Simple Spring-Mass Systems

The equation that describes the motion of a simple spring-mass system is:

$$m\ddot{x} = -kx \tag{9.1}$$

m: mass, kg
k: spring constant, N/m
x: displacement, m
$\ddot{x}$: acceleration, $\mathrm{m/s^2}$

A large value for the spring constant (k) implies a "stiff" spring that requires a great deal of force for a given amount of deflection. A "soft" spring, by contrast, has a low k value and requires less force to deflect. Note that this is simply an energy balance trading kinetic energy of motion for potential energy stored in the spring:

$$\begin{aligned} m\ddot{x} &= -kx \\ m\ddot{x} &= \vec{F}_{\text{mass}} \\ &= m\vec{A} = \text{mass} \cdot \text{acceleration}, \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \\ -kx &= \vec{F}_{\text{spring}} \\ &= \text{displacement} \cdot \text{spring constant}, \frac{\text{m} \cdot \text{N}}{\text{m}} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \\ &\therefore \\ \vec{F}_{\text{mass}} &= \vec{F}_{\text{spring}} \end{aligned} \tag{9.2}$$

This may be solved as a second-order homogeneous differential equation:

$$x(t) = \frac{\dot{x}(0)}{\sqrt{\frac{k}{m}}} \sin\left(\sqrt{\frac{k}{m}} \cdot t\right) + x(0)\cos\left(\sqrt{\frac{k}{m}} \cdot t\right) \tag{9.3}$$

$x(t)$: position at any time t, m
$x(0)$: initial displacement, m
$\dot{x}(0)$: initial velocity, m/s
t: time, s

and is surprisingly useful for describing many types of packages and other systems. The system's natural frequency (f_n) given by the equation is actually the primary resonant frequency – the frequency at which the system will oscillate when displaced and released. The easiest way to envision this is to imagine a spring with a weight hanging at its end. If the weight is pulled gently, the weight will bob up and down on the spring at the spring-mass system's natural (primary resonant) frequency:

$$f_{\mathrm{n}} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{9.4}$$

f_{n}: the undamped natural frequency, Hz

It is also possible to calculate the natural frequency from the static displacement – the degree to which the cushioning is compressed at rest, although this may be hard to measure with stiff materials under light loading.

$$f_{\mathrm{n}} = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}} \tag{9.5}$$

g: acceleration of gravity, typically $\sim 9.82\,\mathrm{m/s^2}$

Δ: static deflection of system at rest, m

These frequencies are often stated in Hertz (Hz), although with large spring-mass systems, the frequency may be fractional, as the structures can take several seconds to go through a complete cycle. In some cases, a *natural period* (Π_n) may be described:

$$\Pi_{\mathrm{n}} = \frac{1}{f_{\mathrm{n}}} = \frac{2\pi}{\sqrt{\frac{g}{\Delta}}} \tag{9.6}$$

which is the inverse of the frequency – the time required for the structure to go through a complete cycle – and is usually described in seconds per cycle. This is most useful in the present application when considering the relationship of natural period of a structure to the duration of a shock pulse.

Changing the ratio of the spring's stiffness (k, the ratio of displacement to force) to mass (m) will inversely affect the natural frequency, as shown in Table 9.2.

Harmonics

Harmonics exist as resonance points that are an integer multiple of the natural (fundamental) frequency. Thus, if a system has a fundamental resonant frequency of 15 Hz, it is quite likely that there will be progressively less active resonance points at 30 Hz, 45 Hz, 60 Hz, and so on. Practically speaking, the response at each of the resonance points will decrease significantly as the difference between the forcing frequency and the natural frequency increases. With the

Table 9.2. Frequency Response Relative to Mass and Spring Stiffness

(Mass)/(Spring Constant)	Natural Frequency Change
Increase *Larger mass or softer spring*	Decrease
Decrease *Smaller mass or stiffer spring*	Increase

exception of musical instruments and other very elastic structures with little damping, this decrease will usually render higher-multiple harmonics insignificant.

Damped Systems

Damping adds another term to the equation and represents a force that opposes the instantaneous motion of the vibration. The net effect of this is to remove energy from the system in some manner, usually by conversion to heat either by mechanical braking, current opposition as with induction damping, or hydraulic fluid or air flow with rate-dependent, viscous damping, as shown in the examples below. Without damping, a theoretical spring-mass system will oscillate indefinitely because there is no allowance for the removal of energy from the system.

In practice, this does not occur in nature because energy is lost from all vibrating systems, even though it may be a subtle effect such as the heating of a metal spring as it oscillates or the loss of energy as air-resistance from movement of the system components. The most common explicit device for oscillation damping that is seen in everyday use is the shock absorbers installed in automobile suspensions. These contain a combination of fluid and a one-way valving system that allows the wheel to move upward quickly as it hits a bump, but then forces fluid to travel through small orifices as the wheel re-extends, slowing its return. The net effect of this is to "decouple" or detune the system and ensure that the wheel does not resonate endlessly against the elasticity and rotational energy of the spinning tire after a single bump:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{9.7}$$

c: damping constant, $\dfrac{\mathrm{N \cdot s}}{\mathrm{m}}$

Again, this can be seen as an energy balance:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{9.8}$$

$$\begin{aligned}
m\ddot{x} &= \vec{F}_{\text{mass}} \\
&= m\vec{A} = \text{mass} \cdot \text{acceleration} = \frac{\mathrm{kg \cdot m}}{\mathrm{s}^2} = N \\
c\dot{x} &= \vec{F}_{\text{damping}} \\
&= \text{velocity} \cdot \text{viscous damping force, } \frac{\mathrm{N \cdot s}}{\mathrm{m}} \cdot \frac{\mathrm{m}}{\mathrm{s}} = N \\
-kx &= \vec{F}_{\text{spring}} \\
&= \text{displacement} \cdot \text{spring constant, } \frac{\mathrm{m \cdot N}}{\mathrm{m}} = N \\
&\therefore
\end{aligned}$$

$$\vec{F}_{\text{mass}} + \vec{F}_{\text{damping}} + \vec{F}_{\text{spring}} = 0$$

Damping may be considered to range from over-damped, where the structure does not completely oscillate properly when perturbed, to under-damped when it goes through many

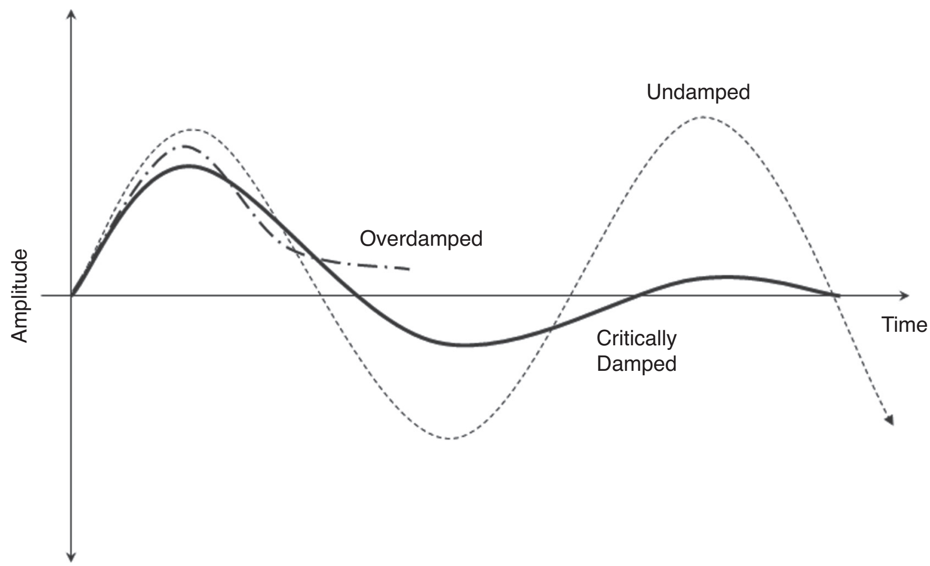


Figure 9.3. Damping in Vibrating Systems

oscillation cycles before settling to a resting state. The damping ratio can be described as:

$$\zeta = \frac{c}{2\sqrt{km}} \tag{9.9}$$

ζ: damping ratio, dimensionless

In general, the higher the value for the damping ratio (ζ), the fewer cycles it will undergo before coming to equilibrium. The damped natural frequency(f_d) of the simple spring-mass system is related to the natural frequency (f_n) by:

$$f_d = f_n\sqrt{1-\zeta^2} \tag{9.10}$$

There are typically three conditions of damping that are considered when evaluating or designing vibrating systems, as shown in Figure 9.3.

Under-damped Systems

(ζ too low, with $\zeta = 0$ representing an undamped system)

Under-damped systems typically oscillate excessively before coming to an equilibrium state. The practical implications of this are that the system will not remove energy quickly enough, and may oscillate excessively. This, in turn, can cause divergent oscillation that can cause damage or an uncontrollable device.

Over-damped Systems

(ζ too high)

Over-damped systems will not oscillate at all, but will attempt to come directly to equilibrium, and because of the high degree of damping, may not achieve this. In physical systems, this typically means that the system will not allow phase damping or energy removal.

Critical Damping

($\zeta = 1.0$, or as required)

Critically damped systems will oscillate a minimal number of times before coming to an equilibrium state. Although a mathematically perfect damping ratio is approximately $\zeta = 1.0$, the actual physical system will dictate the damping coefficient required, with vehicle suspensions in the range of $\zeta = 0.2 - 0.4$. In packaging applications, damping may be provided by many types of fixtures and materials, commonly made of dunnage, foam, or plastic film. These will be discussed in detail later, but the energy in these structures is typically given up as heat evolved from the deflection of polymer or other padding and dunnage structures, air displacement, or – if done improperly – deflection or destruction of the product.

Phase Lag

Phase lag is a phenomenon, most often tied to viscous or viscoelastic structures, where the response of a system is delayed in time relative to the forcing frequency (Figure 9.4).

Because destructive resonance and amplification depend on the system responding in phase with the forcing frequency, phase lag may be used as a means of "detuning" the system so

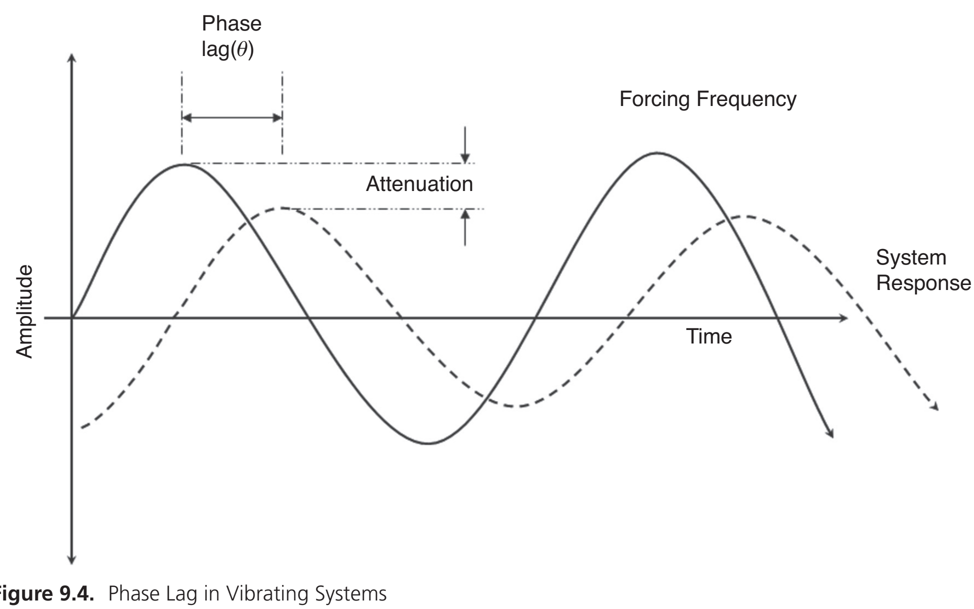


Figure 9.4. Phase Lag in Vibrating Systems

that the system responds in opposition to the forcing energy, and oscillations and vibrations are reduced or eliminated.

Forced Vibration

Forced vibration is vibration that is driven by an external cyclic input that continues beyond the initial disturbance of the spring-mass system, and is much more indicative of real-world situations. The energy of forced-vibration systems generally comes from either environmental sources such as wind turbulence or wheels rolling over bumps in the road, or from engines or actuators in a structure. In nearly every application of vibration analysis, the object is to avoid resonance in the structure under study either by altering the structure or by defining those conditions under which they occur such that they may be avoided.

Simple Spring-Mass Response to Forced Vibration

A simple spring-mass system will respond to forced vibration in one of several ways, some of them important to the design of useful packaging. The general response of a simple spring-mass system to a harmonic force can be given by the equation:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t$$

$$\omega = 2\pi f_f, \ {}^{\text{rad}}\!/_{\text{s}} \tag{9.11}$$

F_0: harmonic force component, N
$\sin \omega t$: harmonic periodic component
$\sin \omega t = \sin 2\pi f_f t$
f_f: forcing frequency, Hz

Without considering the variable values, this can again be seen as a generalized energy balance:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin 2\pi f_f t \tag{9.12}$$

$$\begin{aligned}
m\ddot{x} &= \vec{F}_{\text{mass}} \\
&= m\vec{A} = \text{mass} \cdot \text{acceleration} = \text{kg} \cdot \frac{\text{m}}{\text{s}^2} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \\
c\dot{x} &= \vec{F}_{\text{damping}} \\
&= \text{damping force} \cdot \text{velocity}, \frac{\text{N} \cdot \text{s}}{\text{m}} \cdot \frac{\text{m}}{\text{s}} = N \\
-kx &= \vec{F}_{\text{spring}} \\
&= \text{spring constant} \cdot \text{displacement}, \frac{\text{m} \cdot \text{N}}{\text{m}} = N \\
\vec{F}_0 \sin 2\pi f_f t &= \vec{F}_{\text{applied}}, \ \text{cyclic applied force}, \ N
\end{aligned}$$

$$\therefore$$

$$\vec{F}_{\text{mass}} + \vec{F}_{\text{damping}} + \vec{F}_{\text{spring}} = \vec{F}_{\text{applied}}$$

The sign convention for force in most systems provides that the damping force opposes the direction of motion, because fluid friction opposes the direction of flow and removes energy

Table 9.3. Ratio of Forcing Freqencies to Natural Frequencies and Their Responses

f_{f} v. f_{n}	Amplification (A)	Phase Relationship	Type of Motion
$f_f \ll f_n$	$A = 1$	In phase	Synchronous Motion
$f_f <= f_n$	$A > 1$	In phase	Amplification
$f_f \cong f_n$	$A \approx \infty$	Indeterminate	Resonance point, amplification determined by available damping
$f_f >= f_n$	$A \gg 1$	Out of phase	Amplification and/or repetitive shock mode
$f_f \gg f_n$	$A \cong 0$	Out of phase	Attenuation

from the system. The implication of this is that an undamped, forced system has the capacity to build energy indefinitely in resonance.

Amplification Factor

The amplification factor during resonance can be seen as a function of the ratio of forcing and natural frequencies and the damping available to the system in Table 9.3. This is also graphically illustrated in Figure 9.5.

In Phase

The force that is exciting the motion and the object being excited are moving in the same direction at the same time.

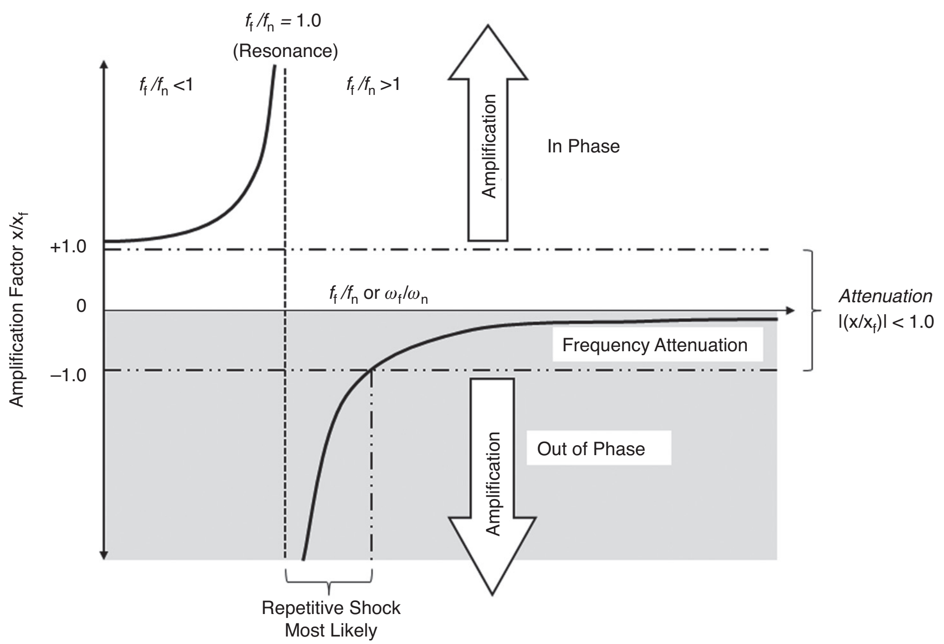


Figure 9.5. Resonance and Amplification in Vibrating Systems

Out of Phase

The force that is exciting the motion and the object being excited are moving in different directions at the same time, usually related by a phase angle φ.

Indeterminate

Although a mathematical solution for phase angle may be constructed for this point, practical experience has shown that the phase and amplitude relationship will be a mathematically chaotic system that is sensitive to both initial conditions and frequency hysteresis (whether the frequency is increasing or decreasing).

Synchronous

The object moves at approximately the same amplitude as the forcing motion.

Amplification

The object is moving at a larger amplitude than the forcing motion due to the energy being stored in the system by its elastic components being synchronous with the forcing frequency and reinforcing it.

Resonance

Object moves at an enormous amplitude, restrained only by the damping force c, if any, because all of the elastic energy storage is being fed back into the system in phase. In theory, an undamped system will continue to increase its range of movement until it disintegrates.

Repetitive Shock

Repetitive shock is the point at which the force that is exciting the motion of the object and the object being excited may be moving in opposite directions at all times. In practical applications, this is typically the top box of a stack, or a container on a floor. During shipping, the amplification is out of phase, providing enough acceleration for the container to "lift off," and subsequently the opposing motion causes the containers to repeatedly slam together, usually with a specific rate of repetition that may cause further problems with shock amplification.

In packaging dynamic situations, this results in extreme levels of damage and may exhibit facets of both shock amplification and vibration resonance damage. Because of amplification and repetitive shock, as well as lateral shifting of the load, most palletloads of material are restrained by a plastic overwrap, either stretch wrap or a heat-shrink film, or straps of plastic fiber or steel banding.

Attenuation

In the attenuation region, energy is being returned to the system out of phase with the forcing energy, giving the system the ability to reduce amplitude or even remain almost stationary while the forcing motion continues to act on it. This is usually the design goal of dynamic cushioning and damping systems, as well as suspension systems and other damping device designs.

More simply put, the response of an undamped system as the frequency increases will go through an interval of in-phase resonance of increasing amplitude, a resonance point where the response of the system achieves a theoretically infinite value, and an out-of-phase period where the response of the system is at first in the most danger of repetitive shock and then is attenuated to nearly zero. A damped system will show similar responses, depending on the type of damping mechanism used, but with reduced response.

These relationships are shown in more mathematical detail in Figures 9.6 and 9.7 as well.

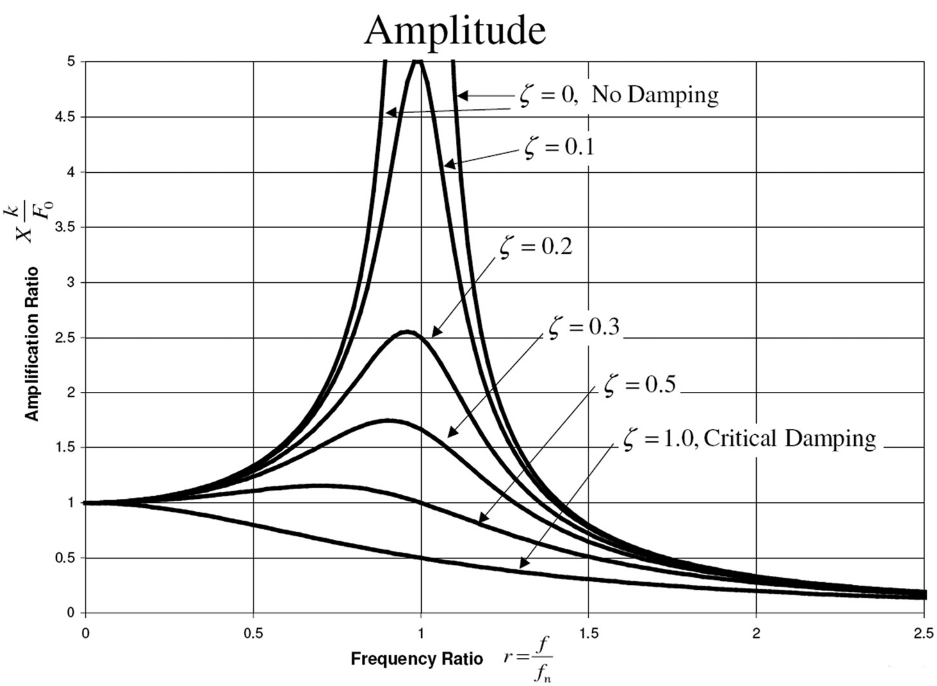


Figure 9.6. Amplificaton Ratio and Damping

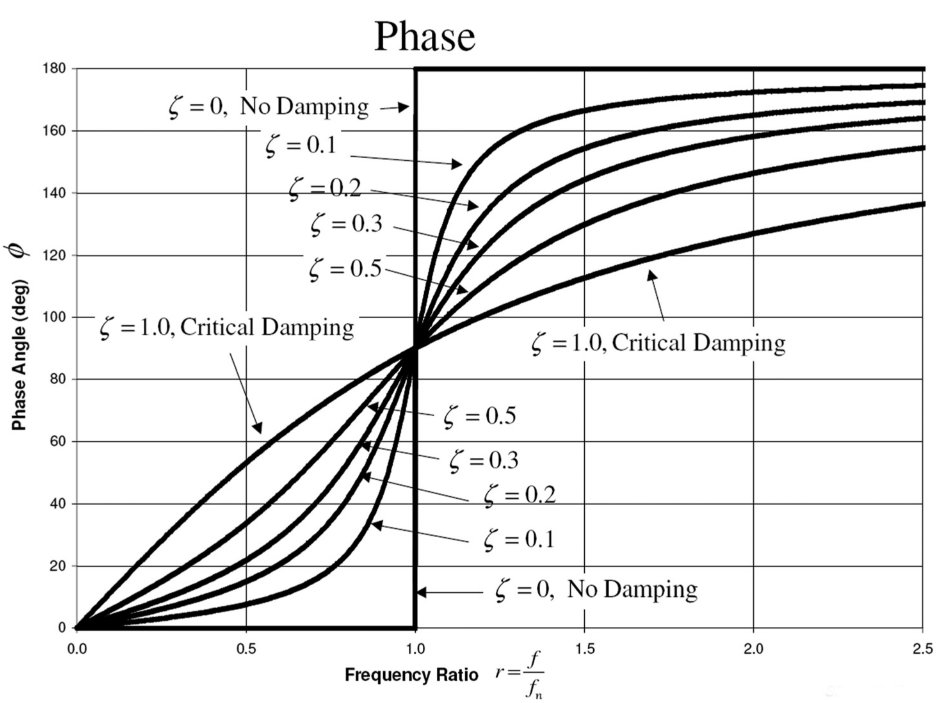


Figure 9.7. Phase Shift and Damping in Vibrating Systems

Clearly, it is advantageous to consider these design factors when designing a package for distribution. The product should not be exposed to undamped or unattenuated environmental inputs that closely match the product's resonant frequency. The result of this would be to have a huge amplification of the products' response with attendant product damage. There are some exceptions to this, where the mechanical action of the resonance might be beneficial, such as with the mixing of reconstituted juice products that are initially made as water and unmixed juice concentrate and then shipped by truck. The motion of the truck during shipping mixes the product thoroughly and results in a shelf-ready product.

Shock, Resonance, and Shock Amplification

Shock is generally taken to mean a single, non-repeating mechanical input, and in packaging applications it usually is unintentionally inflicted during material handling operations and transportation as the package impacts along its vertical axis either as an intentional handling step or by accident. Humping damage is a result of the collision of railcars as they are rolled up a "hump" (a low hill in a rail-switching yard) and then coast downhill to slam couplers together during train assembly, creating a unique, lateral shock hazard that packaging engineers must be aware of if their product is shipped by rail. Typically, similar design methods are used, but are applied to the horizontal axes of the package.

The previously discussed vibration and its related properties also affect how systems behave when they are subjected to a shock from being dropped or bumped during shipping and handling. Because shock inputs do not have a distinct frequency, more often shock analysis is concerned with the amplitude and duration of the shock, with the latter having some correspondence to a half-cycle of vibration.

Shock resonance phenomena may be hard to grasp, but they have a corresponding influence on structures, which can result in anomalous damage levels. The simplest way to visualize this effect is to consider that a shock impulse will comprise several overlapping frequencies, each of which may excite a resonant frequency in the product. If the duration of the shock applied to an object is very much shorter than its natural period, the effects will be minimal, which is one reason that designers will try to provide "soft" springs or cushions to reduce shock damage (Figure 9.8).

On the other hand, if the period of the shock and the natural period of an object are similar, this may result in resonance-induced effects such as breakage that can occur with very little apparent mechanical input. If the shock pulse is considered as a *half-cycle input*, the concept of resonance appears again. If the natural period (as described in Equation 9.6) of the product package system is close to the shock input duration, amplification may occur, damaging a well-padded product more than its unpadded equivalent (Figure 9.9). This paradoxical effect has cropped up in many products, from filament-style light bulbs to audio equipment.

The Soft Cushion Paradox

The soft cushion paradox is the result of the instinctive over-padding of delicate structures that result in more damage being caused rather than less. Sometimes, the cushioning systems induce more damage than having no protection at all. From the previous discussion of spring-mass systems, a "soft" (low k value) spring will have a relatively low natural frequency. If the product to be protected has a similar low frequency, and if the input, whether from shock or vibration, is similarly low (such as the vertical vibration from a truck bed), then amplification may occur

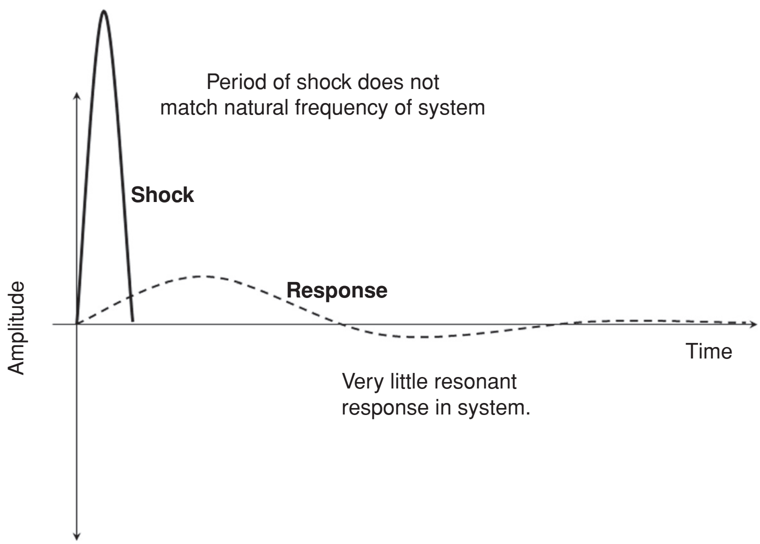


Figure 9.8. Shock Attenuation Phenomena

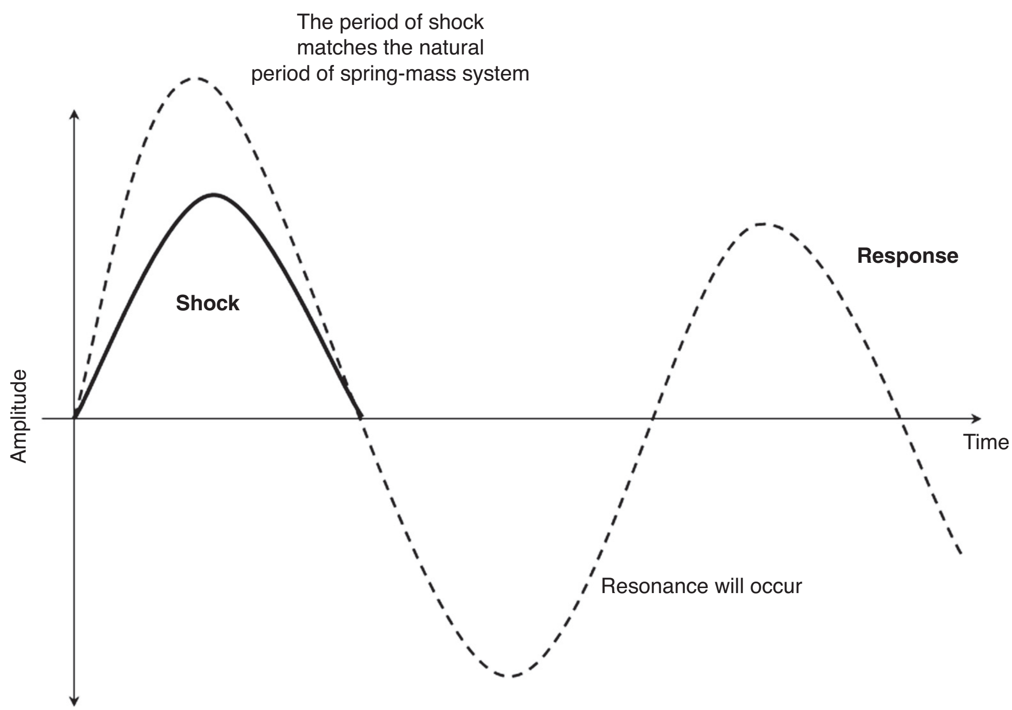


Figure 9.9. Shock Resonance

throughout the system, resulting in damage to the product. The usual solution to this problem is to change the natural frequencies of the packaging system and perhaps the product as well, sometimes in counterintuitive ways.

For example, if a product's critical element has a resonant frequency of 7 Hz, and the package is padded sufficiently against shock to bring its natural frequency in the 7 Hz range, then two things may happen. A shock input may be "tuned" into the correct frequency range by the package cushioning system, causing great damage. More certain is vibration damage from the padding intended to prevent shock, since the 7 Hz input is common in most modes of wheeled vehicle, and will be amplified through the package padding and cause the cascaded amplification to make resonance problems in the product worse.

Packaging Design for the Dynamic Environment

Often, the lowest systemic cost for this kind of protection involves changes in the design of the product, as well as the design of a thoroughly protective package, which is another strong argument for concurrent development of the product and its packaging system. In too many cases, the product is simply handed to the packaging engineer in its finished form, much too late to make substantial and necessary changes for the product to survive distribution. This results in both the delay of product introduction and expensive over-packaging, which reduces the overall profitability of the product line.

Critical Element Analysis

Critical element analysis is a general concept for product quality and testing analysis, and can be used to prevent damage or quality loss. In this section, it will be used in the traditional form of physically fragile components that may cause catastrophic failure of the structure, but the underlying concept can be used in other product quality issues such as shelf-life control and product quality deterioration. Use of critical element analysis can remove a lot of the confusion that ensues from trying to determine the failure mode for a structure – or whether failure has actually occurred at all. The basic steps of critical element analysis are:

1. *Determine the "critical element"*: The critical element is the element that is critical to the function or integrity of the product. This usually involves some preliminary testing or a prior knowledge of the system involved. In an electronics assembly, it may be a component on the end of long wires (one of the reasons for the ruggedness of newer surface-mount electronics), or it may be much more obscure, such as the components that provide the proper product viscosity and texture.
2. *Determine what constitutes failure in the critical element*: This could be mechanical failure, such as an assembly that will not operate, or in a food product it might be product breakage, the separation of ingredients, leaking packages, or a much more subtle reduction in shelf life. Getting an agreement on what constitutes failure, particularly when it involves subtle factors such as flavor or texture rather than something that can be objectively analyzed and quantified, can be one of the more difficult exercises in completing this process.
3. *Determine which hazards cause critical element failure*: In the previous section on product quality, the factors were inputs such as heat, light, oxygen, or other detrimental factors. In distribution processes, the physical hazards are almost always dynamic in nature: shock, vibration, and handling damage.

4. *Reduce or eliminate those hazards*: This may involve creating a better package, but it also may involve changing shipping modes, changing the design of the unit load, modifying the product, or some other subtle change to provide the most effective systemic improvement.

The Dynamic Environment of Distribution

Each distribution mode has its own separate characteristic mechanical frequencies, and within each of those modes, there is tremendous variation between types of vehicles, and between individual vehicles in any particular type. This does not mean, however, that the range of significant forcing frequencies in the dynamic environment is completely random. The basic design of each type of vehicle, along with standardization among components (wheel diameter, propeller shaft designs, and so on), ensures that there is a range of predictable frequencies available to cause damage to a product. For shock damage, there are some broad assumptions that may prove to be useful in designing protection for products as well. Finally, it is important to remember that shock, vibration, and compression may happen at any point in the manufacturing, distribution, and use cycle.

Many efforts at remediating distribution damage are wasted because the product is damaged before it ever leaves the factory, or because it is damaged during normal use by the consumer. Before embarking on any attempt to reduce distribution damage, it is vitally important to ensure that the product is leaving the manufacturing facility in good shape, and that the product design itself is both sufficient to withstand distribution and is satisfactory for customer use after proper packaging is supplied.

Vibration and Repetitive Shock

Vibration in transportation equipment is due almost entirely to rotating components in the vehicle, or in regular features that are a part of the surface that the vehicle travels on. Some examples of the former are wheel and driveshaft rotation, engine vibration, and propeller-shaft imbalance. The latter, surface-related vibration and repeated low-amplitude shocks may be a result of joints or welds in the rails, or expansion joints in the roadway surface. Air turbulence may be included in this type of input, as might runway vibration on takeoff and landing, but these are over a less protracted period that a days-long truck or rail trip. Water transportation suffers less from these latter types of inputs than do the other modes of transport, because water surface features result in very low-frequency movement of the ship, but propeller vibration and structural resonance still exist.

For a typical limited-access highway, road joints that are spaced at approximately 25 meter (82 feet) intervals (although this can vary widely), and for a five-axle truck travelling at 120 km/h (75 mph), each set of wheels will hit a road joint approximately every 0.76 seconds [18]. Given that most semi-trailers have one double set of wheels at the back of the trailer and another just under tractor coupling, this makes for a double set of repetitive shocks that are impacting the load in the truck. Over a long trip, from California to Chicago, for instance, the distance is approximately 3,300 km (2,050 miles), which means that each set of tires on the vehicle will transmit more than 100,000 moderate-amplitude shocks into the loaded trailer. Combining this with vibration from the rotating wheels, suspension, driveshaft and motor will provide a huge and continuous source of shock, vibration, and mechanical energy to damage the products.

Package Design and Testing

Packaging structures and materials, particularly for food packaging applications, must be produced cheaply and provide for a great deal of protection of the product. Industries that produce high-value goods, such as the aerospace industry and the electronics equipment industry, have a very high cost associated with damage occurring during shipping, whereas with the food industry, the product design response to complaints about damage in shipping may actually be counterproductive in the long run.

Food damage during shipping often goes unreported, with small, indicative quantities of broken product containers being discarded by store personnel and being unreported unless occurring in large quantities, and products that become undesirable to the consumer may be discarded by the consumer and will only show up in a slow erosion of consumer sales that may be masked by marketing blitzes, price reductions, and other wide swings in the marketing-driven food industry.

With high-value items such as those mentioned earlier, it is often desirable to design the product to be rugged enough to survive the shipping environment without the need for excessive packaging. If a food product is treated in this manner, it may become so unpalatable that consumers will no longer purchase it, even though it survives shipping perfectly. This has happened in several sectors of the food industry, and the resulting loss of customer sales has proven that "ruggedizing" food is often not a good idea. There have been other instances, however, where the solution to shipping problems, often with dairy or sauce type products, is to modify the product slightly, often by adding a binding or gelling agent or emulsifier to prevent stratification or evolution of excess liquid during shipping. These changes, if properly done, do not affect consumer preferences and will keep the product in an appealing state even after long shipping exposure.

Because packaging in the food industry is most often seen as a cost item to be minimized, rather than an integral part of a complex food safety and delivery system, the designing of food packages to withstand the distribution environment is often overlooked completely or treated in a perfunctory, "palletload-level" manner. Because consumers have been conditioned to accept a certain number of broken products, particularly in brittle goods such as cereal flakes, baked goods, and pasta, there is little benefit for extensive design work to prevent shock and vibration damage. With other products, however, a simple redesign of a tray molding or bottle configuration may prevent substantial losses due to product breakage or liquid motion. The general progression of package designs to protect a product against damage is as follows:

1. Determine Product Fragility
2. Determine Environmental Conditions
3. Calculate Cushion Requirements
4. Build and Evaluate a Prototype
5. Consider Vibration Effects
6. Monitor Performance in The Field

Determine Product Fragility – Damage Boundary Curves

The Damage Boundary Curve (DBC) of a structure represents the limits of shock duration and amplitude that an item can withstand without damage. The usual test procedure is to use a shock tester (Figure 9.10) that can be programmed to control both the amplitude and duration of the

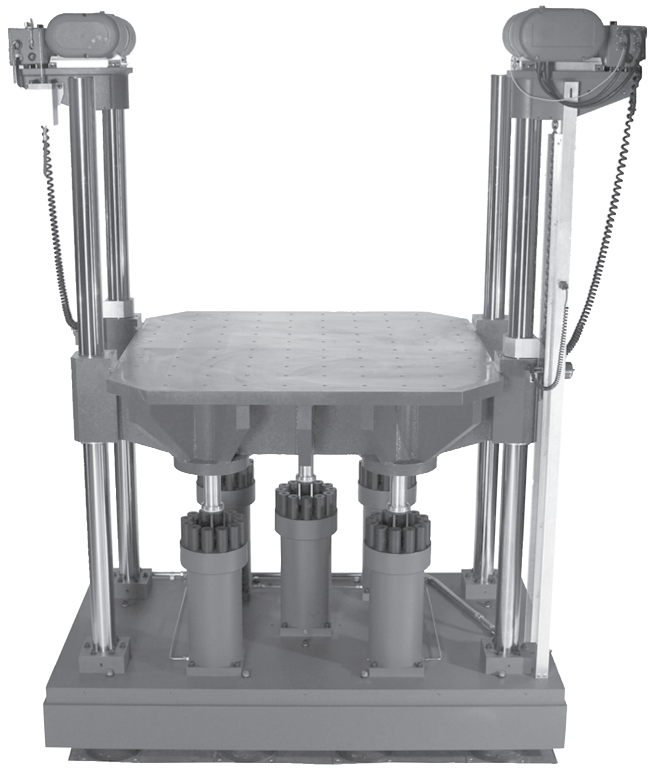


Figure 9.10. Lansmont Shock Machine
Source: Courtesy of Lansmont Corporation

shock pulse imposed on the product. The typical test procedure will involve constructing two variables of increasing severity, first holding the pulse duration at an approximately constant level while increasing the peak amplitude of the shock pulse, then varying the pulse duration while holding the amplitude constant. Both of these tests are performed using "new" products for each separate trial.

The data provided by this test method will allow the construction of an approximate DBC that will describe the levels of shock intensity and duration that the product can withstand, as shown in Figure 9.11. The test protocol usually does not take into account several factors that can affect the final accuracy of the curve provided: repeated shock and period-dependent shock amplification.

Effects of Repeated Shock and Shock Amplification

Repetitive shock – the repeated application of shock pulses to the same item – may have cumulative effects that modify the existing damage boundary curve. The considerations of repeat shocks provide a third parameter to be considered when describing the fragility level of a test sample. Further complicating the issue is the concept of shock amplification, as previously described. If the test sample has a resonant periodicity that matches the velocity change impulse

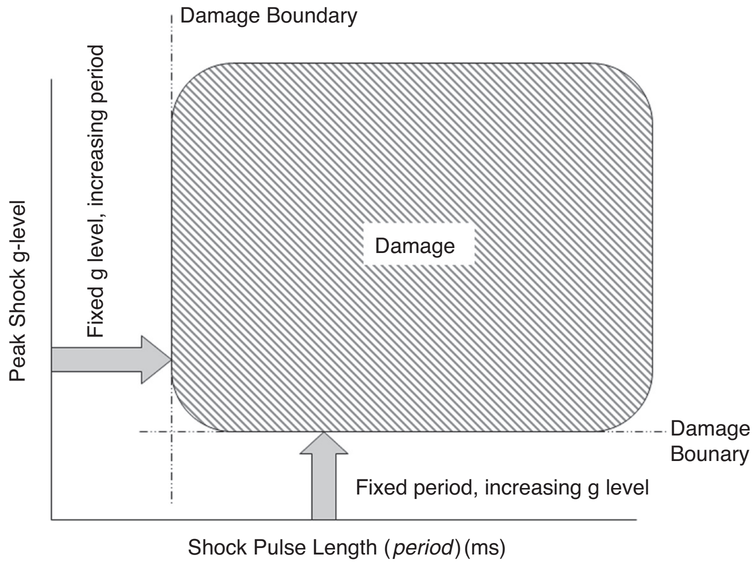


Figure 9.11. Damage Boundary Curve

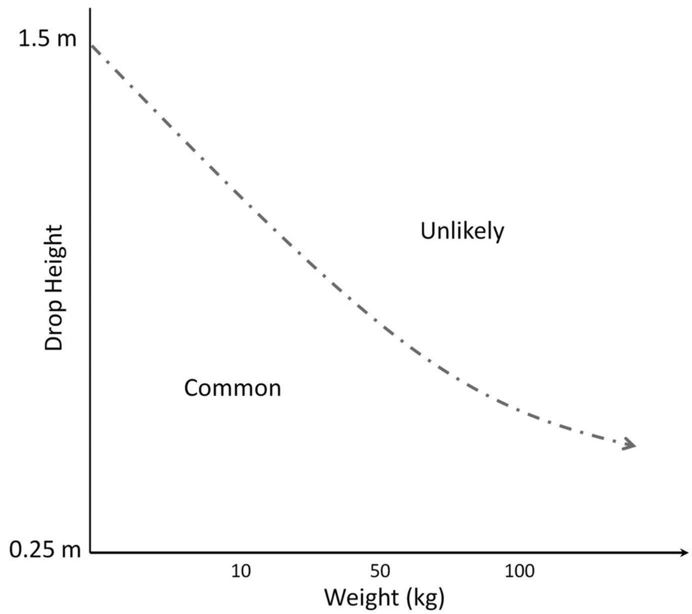
duration, the shock amplification may distort the "velocity change" axis significantly. Also, it may be possible that a very high rate of peak acceleration may be survivable at particular ranges of velocity change values that provide attenuation rather than transmission or amplification – in effect, creating "safe zones" behind the damage boundary curve. Research on this last issue is lacking and may or may not have practical significance.

Determine Environmental Conditions

To develop a working system to protect the product against distribution damage, it is necessary to understand the kinds of hazards to which the product will be exposed. Whereas it may be enough to estimate the likely drop height and use an estimate for design purposes, as shown in Figure 9.12, it may also be necessary to go in the field and measure actual handling conditions and the kinds of damage that they are inflicting on the product.

Shock and Vibration Indicators and Recorders

Electronic recorders that use accelerometers based on a small mass on a piezoelectric quartz crystal to produce an electric voltage when acceleration results in deflection of the crystal structure are often the most accurate. These systems have shown a huge price drop as accelerometers, often incorporated into a monolithic circuit component, have begun to be incorporated in everyday electronics, and particularly video game controllers and toys. Piezoelectric accelerometers typically are tested or designed to have a very high resonant frequency, minimizing the resonance effects of most common transportation frequencies. It is important to understand that these high frequencies *do* occur in aerospace environments (and very rarely in other types of transportation modes such as steam-turbine-driven ships) as a result of turbine and propeller operation, and thus there may be some high-frequency amplification that occurs.



Means of Movement:	Hand Carry	Cart or Pallet Jack	Fork Lift

Figure 9.12. Drop Height versus Weight and Transport Method

On-Package Recorders

There are any number of shock and vibration recorders and indicator devices available on the market. Some of these are simple tubes that stick on the outside of a container and supposedly rupture at a particular shock level; others contain a spring-mass system that draws a trace on a slowly moving piece of paper; and still others are electronic systems that contain piezoelectric accelerometer systems that record data in digital format. Although not common, it is possible to instrument packages, or intermodal shipping containers with systems that will record both position (using GPS based navigational fixes) and the dynamic environment, which may help engineers pinpoint particular locations where damage occurs.

The effects of some of these devices may be more psychological than physical. An expensive piece of equipment with a highly visible abuse indicator on it will likely receive more careful handling than one without.

Resonance-Induced Errors

Because shock and vibration recorders have natural frequencies in the same manner that package and product systems do, it does not take a great leap of imagination to see how resonance might occur in such a device. What is less intuitive is the sort of erroneous damage indications that may occur when the indicator or recorder has a very different natural frequency than the product-package system does. A common type of damage indicator is a self-adhesive label containing a tube and a dye capsule with a frangible barrier. The barrier ruptures at an approximate shock amplitude value, indicating that the container has been dropped or otherwise abused. Because the natural frequency of the indicator itself is very high, due to its few rigid components, the indicator may not indicate a shock of long duration and low amplitude. If the product has a low resonant frequency and is subjected to a drop with the same approximate period, or is subjected to long-term low-frequency vibrations, the indicator will not show that any damage should have occurred, yet the product may be ruined.

Similarly, resonance can produce false-positive readings. In the case of a spring-loaded mass that draws a trace on a moving piece of paper, the resonant frequency of the spring-mass systems driving the recorder stylus is usually low enough that they will resonate at lower frequencies, amplifying the amount of vibration or shock transmitted through the stylus's structure and producing large pen deflections when the actual mechanical input may have been rather small. Worse, if the resonant frequency of the product is very high, there is likely to be little resonance damage, but the indicator will show large shock and vibration inputs, leading to the conclusion that damage may have occurred.

Calculate Cushion Requirements

Cushion design has traditionally been concerned with various types of resilient materials, but the principles can be used to design packaging structures of many types and materials. Initially, fragile items were packaged in straw, wood shavings, or other natural materials. These were supplemented with materials such as rubberized boar's hair matting and elastic bungee cords. These materials, though very elastic and capable of absorbing shocks, highlighted the problems with resonance in package structures that has been alluded to previously.

Newer package cushioning materials have been made of viscoelastic materials that, if properly designed, can be tuned to damp out both shock and vibration to within tolerable limits. Although the majority of these materials are of foamed polyolefins, there have been several clever developments that use items suspended between sheets of plastic film under tension in an open frame of corrugated board. This allows the film to be used as an inexpensive viscoelastic damper, and the material may be recycled once the films have been separated from the corrugated.

Calculating the proper cushioning criteria for foam materials is, in its simplest form, a matter of determining the maximum level of acceleration that the product should be subjected to, then choosing and sizing a cushioning material to provide that level of shock reduction at a particular drop height. Manufacturer's data is usually supplied to make this a relatively easy process, but it is also important to test the prototypes and to monitor the performance of the design in the field to take into account any previously unforeseen damage sources.

When choosing a cushioning material, manufacturer's data will typically be supplied that provides a "cushion curve," showing the transmitted G force relative to the static loading on the cushion surface (Figure 9.13). The design process usually favors the selection of high static loadings in the acceptable range of values in order to use as little material as possible, and to reduce the exterior shipping container and reduce materials costs, but it may become a trade-off between large areas of thin cushioning and small, thick pads, although these will require a larger shipping carton and take up more volume.

Additionally, the effects of end-on shocks or being dropped upside down should be considered. With large, monolithic objects such as electronic assemblies, the design has evolved to a more or less standard end-cap, usually made of Expanded Polystyrene (EPS) foam and designed to protect in all three axes. This presumes that there is little flexural deformation in the chassis of the assembly, which does not apply to many types of consumer items and food products.

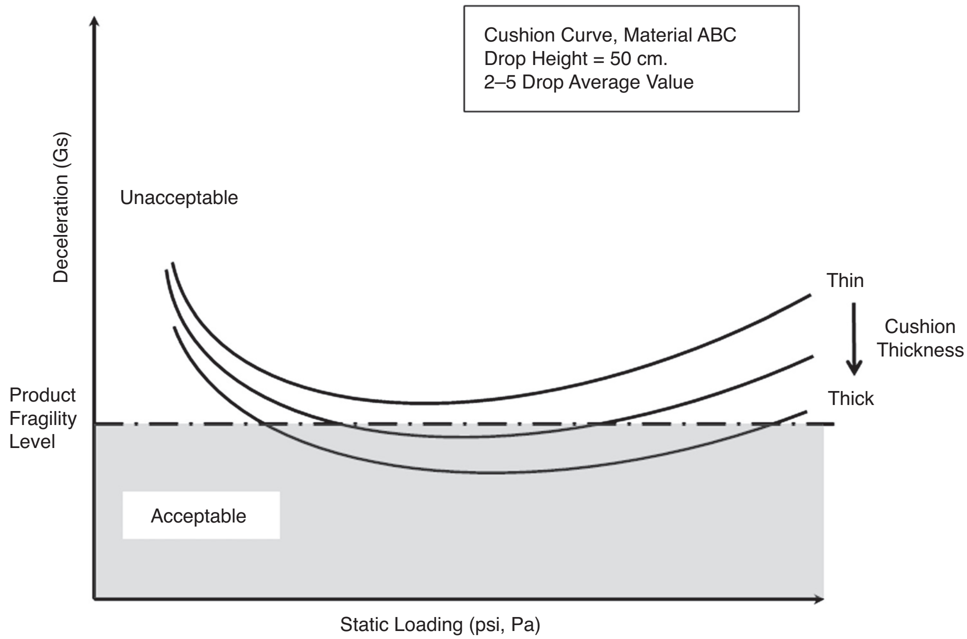


Figure 9.13. Generic Cushion Curve

Additional Cushion Design Factors

Once the cushion design has been developed, it must be examined for other design constraints, the most common of which is buckling, where the cushioning material deforms in non-axial manner such that its linear cushioning capability is severely compromised. This often makes another argument for more surface area and thinner cushioning materials because they are less likely to buckle, but it must be checked, usually against buckling criteria relating thickness and static loading. Some other factors that must be considered are temperature, creep, and variability in materials.

Temperatures will directly affect the viscoelastic properties of padding materials, with the result that a cushion that performs well in the laboratory may be too stiff in cold weather and too soft when transported in hot climates, drastically changing its performance. When stored for long periods of time in hot weather, creep, as described in Chapter 2, can permanently deform the cushion structure and compromise its effectiveness. Finally, with the increasing use of recycled materials, the variability in the materials properties should be considered, because studies have shown that incorporating recycled materials will provide a padding structure that may be softer than the original [19].

Design, Build, and Evaluate Prototype

Although the packaging of fragile, expensive items such as instrumentation assemblies and aircraft components may justify the expense of complex foam pads or support frames, the extreme price pressures on food items makes the likelihood of anything beyond minimal padding for most food items unlikely. This is not to say that cushion design principles cannot be included in the design of food packaging, but it must be done using existing materials and structures. Further, it may be difficult to justify the expense of dynamic testing to ensure the survivability of the product-package system until after a problem comes to light.

Design of food packaging to minimize dynamic input may include the use of well-designed trays or boxes, the reduction of mobility of the item in the container so that it does not have enough freedom of movement to be damaged, or the redesign of the product itself. This last step, though often an inexpensive solution to the problem, can have unintended consequences in that the product may gradually become so mechanically durable as to be unpalatable, and sales of the (undamaged) product could suffer.

Design of Protective Packaging for Shipping Food Products

The design of packages that can prevent mechanical damage to food products must include several design features:

1. They must be strong enough to resist compression damage, although the shipping container often bears the majority of the load during stacking and shipping.
2. They must restrain the product so that it does not have enough freedom of movement to be damaged during shipment. A product that is sufficiently well restrained will usually have a higher frequency than the one that has some freedom of movement inside the package. One opportunity that is seldom used for providing restriction of movement of products is to design an interlocking stacking pattern such that each package provides partial restraint of the product underneath. This allows the product to be easily taken from the container by the consumer, but when in a packed shipping container, will help prevent damage from excessive movement. One of the simple examples of this is the nesting trays that are used to display produce in supermarkets.
3. There should be some allowance made for the prevention of shock damage. Although it is often not economically attractive to do in-depth analyses of the shock response of package-product systems, careful observation of the dynamic environment and of the types of product damage that occur may yield opportunities for improvements.

Consider Frequency and Resonance Effects

As previously mentioned, the shock impact of dropping an item does not have the continuing periodic inputs that vibration in moving vehicles and conveyors provide, but resonance effects can and do occur. The other, often destructive frequency effect is the soft-cushion paradox, previously described. Sufficient padding to counteract shock inputs may lower the natural frequency of the product-package system to the point where it will resonate and be damaged in shipping. Although it may not be feasible to do vibration testing on the finished design, the design data of static loading, static deflection, and product mass can be used to roughly estimate the primary natural frequency, using Equation 9.5.

Monitor the Performance of the Packaging System

Once the design is put into production, it should be monitored for actual damage during distribution. Obviously, if the final design is inadequate and damage is excessive, it should be corrected. On the other hand, the complete absence of any kind of damage may be an indicator of over-packaging. This will depend on the type of product, the cost of damage, and the hazards, costs, and impacts associated with damaged product. At this point, the opportunity to reduce materials use and cost may present itself by redesigning the package so that an acceptably small, non-zero loss rate is achieved. Damage should also be examined for co-factors such as particular handling locations or carrier routes, anomalous abuse, and excessive environmental conditions such as direct exposure to rain because these will alter the apparent source of observed damage and the apparent ineffectiveness of the package design.

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