What is Resonance?

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In physics, resonance is the tendency of a system to oscillate with greater amplitude at some frequencies than at others. Frequencies at which the response amplitude is a relative maximum are known as the system's resonant frequencies, or resonance frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations, because the system stores vibrational energy.

Resonance occurs when a system is able to store and easily transfer energy between two or more different storage modes (such as kinetic energy and potential energy in the case of a pendulum). However, there are some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is a frequency of unforced vibrations. Some systems have multiple, distinct, resonant frequencies.

Resonance phenomena occur with all types of vibrations or waves: there is mechanical resonance, acoustic resonance, electromagnetic resonance, nuclear magnetic resonance (NMR), electron spin resonance (ESR) and resonance of quantum wave functions. Resonant systems can be used to generate vibrations of a specific frequency (e.g. musical instruments), or pick out specific frequencies from a complex vibration containing many frequencies (e.g. filters).

Resonators

A physical system can have as many resonant frequencies as it has degrees of freedom; each degree of freedom can vibrate as a harmonic oscillator. Systems with one degree of freedom, such as a mass on a spring, pendulums, balance wheels, and LC tuned circuits have one resonant frequency. Systems with two degrees of freedom, such as coupled pendulums and resonant transformers can have two resonant frequencies. As the number of coupled harmonic oscillators grows, the time it takes to transfer energy from one to the next becomes significant. The vibrations in them begin to travel through the coupled harmonic oscillators in waves, from one oscillator to the next.

Extended objects that experience resonance due to vibrations inside them are called resonators, such as organ pipes, vibrating strings, quartz crystals, microwave cavities, and laser rods. Since these can be viewed as being made of millions of coupled moving parts (such as atoms), they can have millions of resonant frequencies. The vibrations inside them travel as waves, at an approximately constant velocity, bouncing back and forth between the sides of the resonator. If the distance between the sides is d, the length of a round trip is $2d$. In order to cause resonance, the phase of a sinusoidal wave after a round trip has to be equal to the initial phase, so the waves will reinforce. So the condition for resonance in a resonator is that the round trip distance, $2d$, be equal to an integer number of wavelengths $\lambda$of the wave:

$$2d = N\lambda, \qquad N \in \{1, 2, 3, \dots\}$$

If the velocity of a wave is v, the frequency is $f = v/\lambda$so the resonant frequencies are:

$$f = \frac{Nv}{2d} \qquad\qquad N \in \{1, 2, 3, \ldots\}$$

So the resonant frequencies of resonators, called normal modes, are equally spaced multiples of a lowest frequency called the fundamental frequency. The multiples are often called overtones. There may be several such series of resonant frequencies, corresponding to different modes of vibration.

Q factor

The quality factor or Q factor is a dimensionless parameter that describes how under-damped an oscillator or resonator is,[8] or equivalently, characterizes a resonator's bandwidth relative to its center frequency.[9] Higher Q indicates a lower rate of energy loss relative to the stored energy of the oscillator, i.e. the oscillations die out more slowly. A pendulum suspended from a high-quality bearing, oscillating in air, has a high Q, while a pendulum immersed in oil has a low Q. In order to sustain a system in resonance in constant amplitude by providing power externally, the energy that has to be provided within each cycle is less than the energy stored in the system (i.e. the sum of the potential and kinetic) by a factor of. Oscillators with high quality factors have low damping which tends to make them ring longer.

Sinusoidally driven resonators having higher Q factors resonate with greater amplitudes (at the resonant frequency) but have a smaller range of frequencies around the frequency at which they resonate. The range of frequencies at which the oscillator resonates is called the bandwidth. Thus, a high Q tuned circuit in a radio receiver would be more difficult to tune, but would have greater selectivity, it would do a better job of filtering out signals from other stations that lie nearby on the spectrum. High Q oscillators operate over a smaller range of frequencies and are more stable. (See oscillator phase noise.)

The quality factor of oscillators vary substantially from system to system. Systems for which damping is important (such as dampers keeping a door from slamming shut) have Q = ½. Clocks, lasers, and other systems that need either strong resonance or high frequency stability need high quality factors. Tuning forks have quality factors around Q = 1000. The quality factor of atomic clocks and some high-Q lasers can reach as high as 1011[10] and higher.

There are many alternate quantities used by physicists and engineers to describe how damped an oscillator is that are closely related to its quality factor. Important examples include: the damping ratio, relative bandwidth, linewidth and bandwidth measured in octaves.

Types of resonance

Mechanical and acoustic resonance

Mechanical resonance is the tendency of a mechanical system to absorb more energy when the frequency of its oscillations matches the system's natural frequency of vibration than it does at other frequencies. It may cause violent swaying motions and even catastrophic failure in improperly constructed structures including bridges, buildings, trains, and aircraft. When designing objects, Engineers must ensure the mechanical resonance frequencies of the component parts do not match driving vibrational frequencies of motors or other oscillating parts, a phenomenon known as resonance disaster.

Avoiding resonance disasters is a major concern in every building, tower and bridge construction project. As a countermeasure, shock mounts can be installed to absorb resonant frequencies and thus dissipate the absorbed energy. The Taipei 101 building relies on a 660-tonne pendulum (730-short-ton) — a tuned mass damper — to cancel resonance. Furthermore, the structure is designed to resonate at a frequency which does not typically occur. Buildings in seismic zones are often constructed to take into account the oscillating frequencies of expected ground motion. In addition, engineers designing objects having engines must ensure that the mechanical resonant frequencies of the component parts do not match driving vibrational frequencies of the motors or other strongly oscillating parts.

Many clocks keep time by mechanical resonance in a balance wheel, pendulum, or quartz crystal

Acoustic resonance is a branch of mechanical resonance that is concerned with the mechanical vibrations across the frequency range of human hearing, in other words sound. For humans, hearing is normally limited to frequencies between about 20 Hz and 20,000 Hz (20 kHz),[12]

Acoustic resonance is an important consideration for instrument builders, as most acoustic instruments use resonators, such as the strings and body of a violin, the length of tube in a flute, and the shape of, and tension on, a drum membrane.

Like mechanical resonance, acoustic resonance can result in catastrophic failure of the object at resonance. The classic example of this is breaking a wine glass with sound at the precise resonant frequency of the glass, although this is difficult in practice.

Electrical resonance

Electrical resonance occurs in an electric circuit at a particular resonant frequency when the impedance of the circuit is at a minimum in a series circuit or at maximum in a parallel circuit (or when the transfer function is at a maximum).

Orbital resonance

Main article: Orbital resonance

In celestial mechanics, an orbital resonance occurs when two orbiting bodies exert a regular, periodic gravitational influence on each other, usually due to their orbital periods being related by a ratio of two small integers. Orbital resonances greatly enhance the mutual gravitational influence of the bodies. In most cases, this results in an unstable interaction, in which the bodies exchange momentum and shift orbits until the resonance no longer exists. Under some circumstances, a resonant system can be stable and self-correcting, so that the bodies remain in resonance. Examples are the 1:2:4 resonance of Jupiter's moons Ganymede, Europa, and Io, and the 2:3 resonance between Pluto and Neptune. Unstable resonances with Saturn's inner moons give rise to gaps in the rings of Saturn. The special case of 1:1 resonance (between bodies with similar orbital radii) causes large Solar System bodies to clear the neighborhood around their orbits by ejecting nearly everything else around them; this effect is used in the current definition of a planet.

Failure of the original Tacoma Narrows Bridge

Main article: Tacoma Narrows Bridge (1940)

The dramatically visible, rhythmic twisting that resulted in the 1940 collapse of "Galloping Gertie," the original Tacoma Narrows Bridge, has sometimes been characterized in physics textbooks as a classical example of resonance. However, this description is misleading. The catastrophic vibrations that destroyed the bridge were not due to simple mechanical resonance, but to a more complicated interaction between the bridge and the winds passing through it — a phenomenon known as aeroelastic flutter. Robert H. Scanlan, father of bridge aerodynamics, has written an article about this misunderstanding.

Resonance causing a vibration on the International Space Station

The rocket engines for the International Space Station are controlled by autopilot. Ordinarily the uploaded parameters for controlling the engine control system for the Zvezda module will cause the rocket engines to boost the International Space Station to a higher orbit. The rocket engines are hinge-mounted, and ordinarily the operation is not noticed by the crew. But on January 14, 2009, the uploaded parameters caused the autopilot to swing the rocket engines in larger and larger oscillations, at a frequency of 0.5 Hz. These oscillations were captured on video, and lasted for 142 seconds.