Going into resonance

The notion of 'resonance' is among the most familiar ideas in science. Two pendulum clocks in resonance synchronize themselves, sound waves of the right frequency drive strong vibrations in a drum, and photons tuned to atomic transitions put atoms into excited states. Particle physicists often detect new particles through the appearance of resonances in scattering data. And we all, of course, rely on resonance in our use of wireless communications.

In 1965, in his famous *Lectures on Physics*, Richard Feynman suggested that the resonance concept had become so influential that every new volume of the *Physical Review* would feature at least one resonance curve — the characteristic absorption peak in the spectral region around the natural internal frequency of some probed oscillatory system. And yet, the modern familiarity of the concept obscures an unusual history of extremely slow recognition, full appreciation taking some 300 years. As Jörn Bleck-Neuhaus of the University of Bremen notes in a recent historical review (preprint at https://arxiv.org/abs/1811.08353; 2018), few scientific ideas of comparable importance have come to be appreciated so slowly.

In the mid-seventeenth century, Galileo noted that one man pulling in the right way on a heavy pendulum could drive it into such large motion that it could then readily lift six men into the air. No doubt others had seen similar effects before; Galileo recorded it. He could offer no mathematical treatment, however, and came to some very incorrect conclusions about what happens when a periodic force drives a naturally oscillatory system. In particular, he concluded that the resulting motion could never be made to deviate from natural inherent frequency of the oscillating system. This view, apparently, suited his belief that the tides could not be driven by the forcing of the Moon, but must have some other origin.

Despite founding classical and celestial mechanics, Isaac Newton never engaged directly with the issue of the driven motion of a non-astronomical harmonic mechanical system. The first modern understanding of the matter — and correction of Galileo's error — awaited the development of calculus in the eighteenth century, when Leonard Euler solved the problem using a differential equation much like we would write down today. He concluded that, in the off-resonance condition, the motion of a driven oscillatory system lacking friction or damping would exhibit two components at different frequencies — the forced frequency and the natural frequency of the driven system. He also considered the case of resonant match of the two frequencies, concluding that the amplitude of the oscillation would increase linearly in time, and potentially without bound.

One might expect this breakthrough in mechanics to have propelled the resonance phenomenon into the centre of physics and engineering, and yet it didn't. Perhaps, as Bleck-Neuhaus notes, that's because Euler himself only considered the problem as a mathematical curiosity lacking any practical import. Euler's results were then ignored for well over a century, until derived again independently in the nineteenth century by Thomas Young. Oddly, however, Young only considered the problem in connection with the analysis of tides, and so his work was also subsequently ignored, and failed to have any impact on mechanics in general, either in physics or engineering.

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Indeed, all along, until the very late nineteenth century, scientists were reluctant to use the term 'resonance' in connection with anything except acoustic phenomena, where it originated. Use of the word in other fields — especially in mechanics and the analysis of vibrations in machines — always included some disclaimer that the link was "only by analogy", despite the formal equivalence of the fundamental dynamical equations.

Use of the concept only spread with the recognition of resonance-like effects in general acoustic systems by Rayleigh and Helmholtz in the 1860s, followed by experiments of William Thomson demonstrating the natural resonant behaviour of LC circuits. In 1885, the German physicist Anton Overbeck entitled a paper 'On a phenomenon with electrical oscillations which is similar to resonance'. As it turns out, Overbeck was the first scientist ever to record the famous resonance curve, showing the voltage excited at different frequencies, and the peak due to resonant interaction.

Not soon, Heinrich Hertz linked such resonance phenomena to the generation of propagating electromagnetic waves, and Guglielmo Marconi soon exploited them to realize wireless communications. But all of this, it turns out, took place before engineers really began appreciating the role of resonance in more tangible mechanical systems. The gradual acceptance of resonance as a mechanical phenomenon only took place as dramatic failures in bridges and machines made engineers painfully aware of the inadequacy of the static analysis of forces, and the need to consider the surprising effects of interactions at similar frequencies.

Working mostly from original sources in Germany, Bleck-Neuhaus readily admits that his history of the resonance concept is weighted towards German scientists. That was interesting for me. My knowledge of Arnold Sommerfeld — learned as a physics student in the United States, mostly from his appearance in textbooks of quantum mechanics — centres on his relativistic improvements to the Bohr model of the atom, which played an important role in the early or 'old' quantum theory. Perhaps this was his most important contribution. But it's fascinating to learn that in 1902, as a young professor at a key technology institute in Aachen, Sommerfeld played an important role in pushing engineers to recognize the practical importance of mechanical resonance — then largely unknown.

Sommerfeld did so, in part, through a dramatic experiment. In the experiment, he arranged for a wobbly table to support a heavy machine. Increasing the power supplied could make the machine run faster, but only to a point. As increasing power pushed the machine faster and faster, approaching the resonance frequency of the table, onlookers could see that the extra energy only made the table vibrate more violently. Sommerfeld, as Bleck-Neuhaus notes, "did not fail to say that this would mean an increase of the fuel bill without getting anything but the risk of damaging the machine and the building." The phenomenon became known as the 'Sommerfeld effect.' Only later did Sommerfeld move to the University of Munich and found his hugely influential school of theoretical physics.

One of the more surprising things in science is how obvious certain principles can seem, once understood, when they were anything but obvious before. This history of resonance is another good example — the idea is obvious now to any engineering undergraduate, but it challenged the best minds in science for over three centuries. ❒

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Published online: 1 March 2019
https://doi.org/10.1038/s41567-019-0458-z