FOURIER

Is this French mathematician the true father of modern engineering? By Eugene F. Adiutori

Concepts that engineers use every day—as fundamental as the homogeneity of equations and the heat transfer coefficient—were pioneered by a French thinker who died in 1830. His name was Joseph Fourier. He is better known for his career in mathematics, but his contributions to engineering science are so important that a case can be made for calling him the father of modern engineering.

Joseph Fourier

Fourier's contributions to engineering science, many of which were presented in his 1822 book, *The Analytical Theory of Heat*, include the original view of dimensional homogeneity. The heat transfer science it presented has been handed down to us virtually unchanged, and has served as a model for other branches of engineering.

The book also presented his concept of "flux" (that is, a flow of something per unit area and time), his view of homogeneity, and his original methods for solving engineering problems, all of which are used today in many branches of engineering and science.

In short, this treatise by Fourier presented the groundwork, as well as some of the finish work, for modern engineering. Fourier conceived the view that scientifically rigorous equations must be dimensionally identical—that is, each term in an equation must have the same dimension. For example, if the left side of an equation is pounds per cubic foot, the dimension of the right side must also be pounds per cubic foot. If the left side is measured in pounds per cubic foot and the right side feet per second, the equation is irrational.

Fourier's view of homogeneity is now considered almost self-evident, but in the early 19th century, it was revolutionary. It required the multiplication and division of dimensions—mathematical operations that had been deemed irrational for more than 2,000 years.

Fourier was born in Auxerre, France, in 1768. He trained for the priesthood, but spent much of his life teaching mathematics at French universities, principally the École Polytechnique. He was active in the French Revolution, and was twice imprisoned for his political activism. He acted as Napoleon's scientific adviser and sometime administrator in the Egyptian campaign, from 1798 to 1801. From 1804 to 1807, he was prefect of Grenoble, a post that he reluctantly accepted because the appointment was made by Napoleon. He was elected to the Académie des Sciences in 1817, and served as its secretary.

Before Fourier's time, Newton and his successors generally expressed laws in the form of proportional expressions. For example, Hooke's law says that stress is proportional to strain. Newton's second law holds that the change of motion is proportional to the impressed force.

But Fourier was not satisfied with proportional expressions. He wanted to arrive at laws in the form of equations that could be used quantitatively to describe and predict natural behavior, specifically of heat transfer. To do it, Fourier had to create a new kind of parameter.

During his years at Grenoble, he conducted heat transfer experiments. In the manner of his predecessors, he could have considered his work finished when he observed that convective heat flux is proportional to temperature difference and that conductive heat flux is proportional to temperature gradient. Neither expression will yield a homogeneous equation.

The proportional expression for convective heat transfer is $q_{conv} = a\,\Delta T$, where a is a pure number generally referred to as the constant of proportionality. Fourier would not accept that as a law because q and ΔT have different dimensions: The left side is energy flow per unit time and area, and the right side is temperature.

He solved the dilemma by stating that a is a parameter

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with the same dimension as $q/\Delta T$, which makes the equation homogeneous. Rather than retain a generic name and symbol for the new parameter, he called it "heat transfer coefficient" and gave it the symbol h. The end result is Fourier's law of convective heat transfer, $q_{conv} = h\ \Delta T$. (American heat transfer texts call this equation "Newton's law of cooling," but it should be attributed to Fourier.)

By a similar process, Fourier arrived at the law of conductive heat transfer, $q_{cond} = k\ dT/dx$, where the constant of proportionality has been assigned the name "thermal conductivity," the symbol k, and the same dimension as $q/(dT/dx)$.

Fourier's view of homogeneity makes it necessary to create parameters such as resistances and coefficients because without them, engineering phenomena cannot be described by homogeneous equations. Engineering phenomena are cause-and-effect processes: electromotive force causes electric current; temperature difference causes heat flux; stress causes strain.

Because cause and effect generally have different dimensions, a third parameter is necessary to obtain a homogeneous equation.

Ohm's law underwent a transformation from its original form to make it homogeneous. Georg Ohm published his treatise, *The Galvanic Circuit Investigated Mathematically*, in 1827. He originally expressed his famous law as: "The force of the current in a galvanic circuit is directly as the sum of all the tensions, and inversely as the entire reduced length of the circuit." Reduced length is the equivalent length of a copper wire of a standard diameter.

As an equation, it was $I = E/L$, which does not conform to Fourier's view of homogeneity. To render it homogeneous, a parameter was later assigned the dimension "ohm" (a synonym for volts per ampere), and it is now called "electrical resistance." The homogeneous form of the equation is $E = IR$.

Hooke's law, that "stress is proportional to strain," also was transformed into a homogeneous equation in the manner pioneered by Fourier. It was stated that the proportionality constant between stress and strain was a parameter. The parameter was assigned the same dimension as stress, since that would make the equation homogeneous. This parameter is now called "material modulus." The homogeneous equation based on Hooke's law is called "Young's law."

Fourier's contemporaries forestalled the general publication of his work for 15 years while they claimed to find fault with it. For example, they strongly objected to his concept of flux, a concept that now seems so simple and straightforward as to border on the obvious.

They ultimately accepted his revolutionary view of homogeneity, solely because he was able to solve many practical and theoretical problems that had never been solved. He attributed his success to the homogeneity in his equations. ■

Editor's Note: A fuller discussion of Fourier, on which this article is based, is available at www.memagazine.org.