Thomas Young's research on fluid transients : 200 years on

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ABSTRACT

Thomas Young published in 1808 his famous paper (1) in which he derived the pressure wave speed in an incompressible liquid contained in an elastic tube. Unfortunately, Young's analysis was obscure and the wave speed was not explicitly formulated, so his achievement passed unnoticed until it was rediscovered nearly half a century later by the German brothers Weber.

This paper briefly reviews Young's life and work, and concentrates on his achievements in the area of hydraulics and waterhammer. Young's 1808 paper is “translated” into modern terminology. Young's discoveries, though difficult for modern readers to identify, appear to include most if not all of the key elements which would subsequently be combined into the pressure rise equation of Joukowsky.

Keywords
waterhammer, fluid transients, solid transients, wave speed, history, Thomas Young

NOTATION

c	sonic wave speed, m/s	p	fluid pressure, Pa
D	internal tube diameter, m	R	internal tube radius, m
E	Young's modulus, Pa	t	time, s
e	tube wall thickness, m	v	velocity, m/s
f	elastic limit, Pa	x	length, m
g	gravitational acceleration, m/s^2	δ	change, jump
h	height, pressure head, m	ε	longitudinal strain
K	fluid bulk modulus, Pa	ρ	mass density, kg/m^3
K^*	effective bulk modulus, Pa	σ	longitudinal stress, Pa
k	elasticity coefficient, m/Pa		

INTRODUCTION

By the end of the 19th century, the three key elements for the development of modern waterhammer theory were in place in the seminal works of Joukowsky and Allievi (2):

- an expression for the waterhammer disturbance wave celerity depending on both fluid and pipe wall elasticity (Eq 2 below),
- the Joukowsky formula for the waterhammer pressure rise (Eq 3 below), and
- the functional form of waterhammer solutions depending on the characteristics along which the pressure waves propagated.

The 19th century saw the gradual emergence of these key elements through the work of three principal groups of investigators:

- physiologists interested in haemodynamics (3, 4), e.g. Kries (5) and Galabin (6),
- acousticians interested in the propagation of sound (7), and
- hydrodynamicists, hydraulicians and engineers engaging with practical pipe systems and devices, including the hydraulic ram (from which the term for waterhammer in many languages arises, e.g. the French “coup de bélier” or Italian “colpo d’ariete”), of whom Ménabréa (8) is an early example.

The aim of this paper is to draw attention to the contributions of Thomas Young at the start of the 19th century.

To the modern scientific reader Young's published works can be difficult to follow. He stands at the end of an era when the style of presentation of science in England remained in the tradition exemplified by Newton's Principia, a style with a strong base in Euclidean geometry for its demonstrations and verbal (rather than algebraic) statements of physical laws and mathematical results. As will be shown, Young was one of the last proponents of this style and he became as aware as his European contemporaries of its limitations. Nevertheless, his immediate 19th century successors who built on his achievements seem to have been convinced of these, possibly because they were closer to and thus more familiar with this older style. Notwithstanding his attachment to this archaic mode of presentation, though, it will be argued that Young was a truly innovative scientist in first developing key concepts for what would become, about ninety years later, a recognisable theory of waterhammer (though he himself does not appear to have drawn them all together).

Exactly 200 years ago Thomas Young (1773-1829) published a paper entitled *"Hydraulic Investigations, subservient to an intended Croonian Lecture on the Motion of the Blood"* (1). In this paper he can be seen to have arrived at the celerity (c) of a pressure wave propagating in an incompressible liquid of mass density ρ contained in an elastic tube with Young's modulus E as

$$c = \sqrt{\frac{E}{\rho}\frac{e}{D}} \qquad (1)$$

where e/D is the ratio of wall thickness to tube diameter. This formula is valid for waterhammer in flexible hoses and for the pulse in haemodynamics. It represents “half” of the classical waterhammer wave speed derived by the Dutch mathematician Diederik Korteweg (9) seventy years later as

$$c = \sqrt{\frac{E}{\rho}\frac{e}{D}} \Bigg/ \sqrt{1 + \frac{E}{K}\frac{e}{D}} \qquad (2)$$

which takes into account the elasticity K of the liquid within the tube. Unfortunately Young's analysis is obscure to present-day readers and the actual Eq 1 was not written explicitly in his paper, so this achievement (like many others) passed unnoticed until it was rediscovered nearly half a century later by the German brothers Ernst-Heinrich and Wilhelm Weber (10, 11). It has been noted in medical historical reviews, e.g. (3, 4, 12) but overlooked in histories of waterhammer, e.g. (13, 14).

In this respect it is typical that Young had also implicitly derived (but for elastic solids rather than fluids) an equivalent of the Joukowsky equation

$$p = \rho c v \qquad (3)$$

that relates pressure (p) to velocity (v) in sound and vibration, in his encyclopaedic book *"A Course of Lectures on Natural Philosophy and the Mechanical Arts"* (15-17). In addition, he was also an early commentator on the hydraulic ram.

This paper concentrates on Young's achievements in the field of hydraulics and waterhammer. Young's implicit discovery of the Joukowsky equation for solids is discussed. Young's 1808 paper (1) is difficult to read and therefore, following the example of Boulanger (3), his derivation of Eq 1 is "translated" into modern terminology. Finally, the work of Young's immediate successors, who first expressed his Eq 1 in its modern form, is briefly summarised.

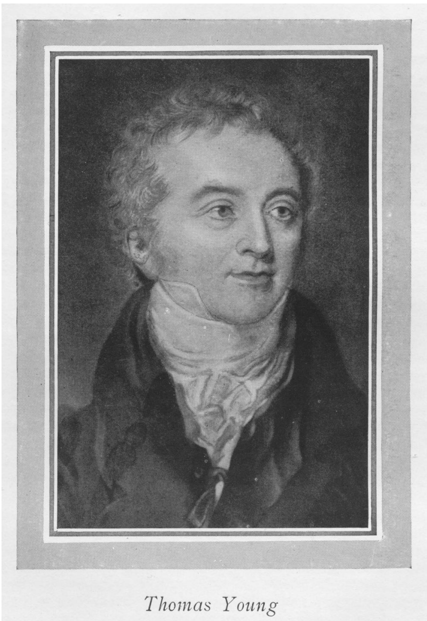
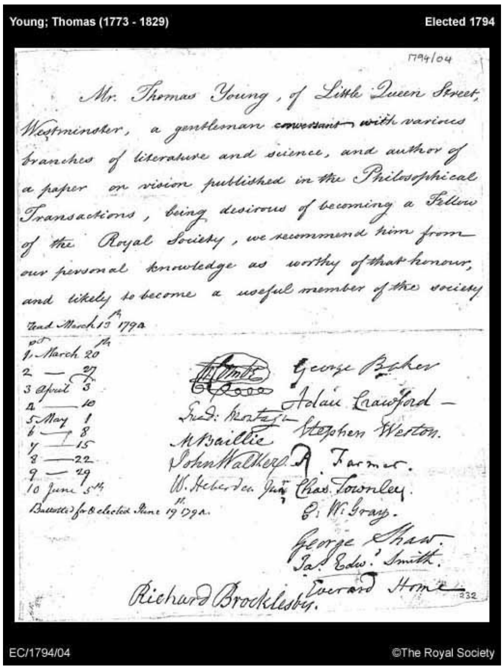


Figure 1 Thomas Young in the 1820s.

YOUNG'S LIFE AND WORK

Thomas Young (Figs. 1 and 2) was an intriguing person and scientist. He has inspired many people to write biographical papers in all sorts and sizes (see App. A), mostly of hagiographic nature and none of them highlighting Young's under-appreciated contribution to the theory of fluid transients. Some of the most revealing comments about his style were written by himself (characteristically in third person) in his own "Autobiographical Fragment", rediscovered and published by Hilts (18), e.g. "...and for about two years he was the colleague of Sir Humphrey Davy as a lecturer, though his language was never either very popular or very fluent, his compressed and laconic style and manner being more adapted for the study of a man of science than for the amusement of a lady of fashion." In view of what follows below, his own comment on one of his papers also deserves notice: "The mathematical reasoning, for want of mathematical symbols, was not understood; from a dislike of the affectation of algebraic calculation which he had observed in the French, the author was led into something like an affection of simplicity, which was equally objectionable." (18).


Young; Thomas (1773 - 1829) Elected 1794

1794/04

Mr. Thomas Young, of Little Queen Street, Westminster, a gentleman conversant with various branches of literature and science, and author of a paper on vision published in the Philosophical Transactions, being desirous of becoming a Fellow of the Royal Society, we recommend him from our personal knowledge as worthy of that honour, and likely to become a useful member of the society

EC/1794/04 ©The Royal Society

Figure 2 "Mr Thomas Young, of Little Queen Street, Westminster, a gentleman conversant with various branches of literature and science, and author of a paper on vision published in the Philosophical Transactions." So reads the citation on Young's Royal Society certificate for election.

Of his own work, he similarly wrote (18): "His pursuits, diversified as they were, had all originated in the first instance from the study of physic (i.e. medicine): the eye and the ear led him to the consideration of sound and of light...". The range of his achievements is too extensive to cover in a single paper. A short and incomplete list of his achievements includes, inter alia:

- Young advocated Huygens' wave theory of light as opposed to Newton's particle model; he discovered the principle of (light) wave interference and he invented the double-slit experiment. He made vast progress in the field of optics, an area later fully developed by Fresnel.
- Young discovered that the three primary colours are not a property of light but of the structure of the human eye. His theory of colours was rediscovered fifty years later by Helmholtz and further developed by Maxwell. He discovered the phenomenon of astigmatism.
- Young estimated the size of molecules and blood corpuscles, fifty years before anyone else.
- Young and Laplace independently derived the fundamental equation of surface tension, and Young calculated the contact angle between an adhesive liquid and a solid, an idea elaborated sixty years later by Dupré. He studied the tensile strength of liquids.

- Other investigations by Young include: sound waves and harmonics, tides, visualization techniques (shadows of water waves; wave superposition, foreshadowing Fourier analysis).
- Young led the basis for the deciphering of Egyptian hieroglyphics, a task later accomplished by Champollion.

He was the first to use the term (kinetic) "energy" in the modern sense and he introduced the term "Indo-European" for a large family of related languages. Named after him are: Young's modulus (of elasticity), Young's fringes (of interference patterns), Young's rule (for the dose of medicine), Young's temperament (for keyboard tuning), and Young's mode (of wave propagation). Helmholtz (himself a figure in the development of waterhammer theory) wrote (19): "Young was one of the most acute men who ever lived, but had the misfortune to be too far in advance of his contemporaries. They looked on him with astonishment, but could not follow his bold speculations, and thus a mass of his important thoughts remained buried and forgotten in the Transactions of the Royal Society until a later generation by slow degrees arrives at the rediscovery of his discoveries, and came to appreciate the force of his arguments and the accuracy of his conclusions."

YOUNG'S WORK ON SOLID AND FLUID TRANSIENTS

The theory of impact

In the years 1801-1803 Young interrupted his medical career at the newly founded Royal Institution in London, where he held the chair of Natural Philosophy in 1802-1803. For his lectures he prepared in very short time a syllabus (20) consisting of an amazing five hundred articles on the subjects: 1. Mechanics, 2. Hydrodynamics, 3. Physics, and 4. Mathematical demonstration. These "Lectures" were published in 1807 (15), and reprinted in 1845 (16) and 2002 (17). It is remarkable that Young never received the promised remuneration of 1000 pounds owing to the bankruptcy of the publishers.

Young (15, pp. 143-145) found that the strain ε produced by the impact of elastic solid bodies equals v/c. With Hooke's law stating that $\varepsilon = -\sigma/E$, where σ is stress and E is Young's modulus of elasticity, this gives $\sigma = -Ev/c$. Assuming that $c = \sqrt{(E/\rho)}$, one obtains for the solids equivalent of the Joukowsky Eq 3:

$$\sigma = -\rho c v \tag{4}$$

where (in contrast to pressure) the stress is defined as negative when the material is compressed. Young (1) was the first to find the pressure wave speed for incompressible liquids contained in elastic tubes, and the authors think, and Beal (21, p. 31) states, that Young was also aware of the speed of sound in solid bars,

$$c = \sqrt{\frac{E}{\rho}} \tag{5}$$

As ever, Young's work is difficult to read, but Timoshenko (22, pp. 93-94) gives a neat summary of the above expressed in modern terminology. It is noted that the strain ε in liquids contained in pipes equals p/K^*, where K^* is the effective bulk modulus representing fluid compressibility and pipe wall elasticity. According to Saint Venant (23), Babinet independently arrived at Eq 5 in 1829 (the year of Young's death).

It is typical for Young (24, 25, 15, 1) that he had found all the ingredients to arrive at the "Joukowsky equation" for solids *and* fluids, but that his achievements were not picked up by his contemporaries. For example, Young (26, p. 23) mentions that "the magnitude of the pulse ... is proportional to the velocity of the transmission ... ". Young also showed that his E modulus applied both to compression and to extension of rods, and also extended its application to liquids (21, p. 31).

The waterhammer wave speed

In 1808 Young delivered the prestigious and still existing Croonian Lecture of the Royal Society. In preparation for this lecture he wrote Ref (1), which is the key paper for his work on the propagation of pressure waves in tubes. It included a new formula for the steady flow of fluids in pipes, the resistance to flow caused by bends, and the propagation of a disturbance through an elastic tube. The Croonian Lecture itself was on the functions of hearts and arteries (26). The prevailing view of the time was that contraction of the walls of arteries was an important cause of the circulation of blood in the human body, but Young's paper conclusively disproved this idea. Young's paper (1) is of fundamental importance to the history of waterhammer, because he derived for the first time the now standard Eq 1 for wave velocity for an incompressible fluid in an elastic tube.

Young's argument proceeded as follows. "The same reasoning, that is employed for determining the velocity of an impulse, transmitted through an elastic *solid* or *fluid* body, is also applicable to the case of an incompressible fluid contained in an elastic pipe" (this clearly suggests that Young had obtained the speed of sound in a solid bar). The problem is then to determine the apparent modulus of elasticity conferred on the incompressible fluid by the elasticity of pipe walls, or, in Young's terminology, to discover "the height of the modulus" to be substituted into Newton's basic formula (24, 25)

$$c = \sqrt{gh} \qquad (6)$$

for the speed of sound, this formula giving a velocity half as great as that of a body falling freely from a height $2h$ [$2h = g\,t^2/2$ gives $t = \sqrt{(4h/g)}$, and therefore $gt = 2\sqrt{(gh)}$]. Note that Young first introduced his modulus with the dimension of height rather than the modern dimension of stress (22, p. 92; 27, p. 82; 28, p. 155) which is due to Navier (29), a custom that is continued by contemporary hydraulicians who use head to denote pressure in liquids. Note that $h = p/(\rho g)$ in Eq (6) gives the sonic speed in gas, $\sqrt{(p/\rho)}$.

Continuing the argument, if the pipe is such that the increase in tension force varies as the increase in circumference or diameter from the natural state (i.e., the pipe is elastic and obeys Hooke's law) up to the limit (at which the pressure in the fluid must balance the tension in the pipe by Newton's first law) where an infinite increase in diameter occurs (i.e., plastic deformation at elastic limit), then the height of a column of liquid equivalent to the pressure causing failure is designated "the modular column of the pipe". This is an application of the maximum stress theory that was favoured by English writers over the maximum strain theory, which was favoured on the Continent (22, p. 89). The relationship is readily demonstrated since, from the stress/strain curve up to the elastic limit $f=\sigma\varepsilon/2=\sigma^2/(2E)$ (for $\sigma=E\varepsilon$) or, replacing the stresses with their equivalent "heights", $2h=(2h)^2\rho g/(2E)$, i.e., $h=E/(\rho g)$.

For the equivalent elasticity conferred on the incompressible fluid Young used the continuity principle. If a short length of pipe of diameter D and length x is compressed in length by a pressure pulsation to $(x-\delta x)$, then if the fluid is incompressible the diameter D must increase to preserve continuity so that $(2\delta D/D-\delta x/x)$ = 0. But the increase in hoop strain $(\delta D/D)$ = (σ/E) for a pipe in tension, and the hoop stress for an increase in pressure δp is given by $D\delta p/(2e)$, thus

$$\sigma=\frac{D}{2e}\delta p \tag{7}$$

so that $D/(Ee)$ = $\delta p/(\delta x/x)$. Eq 7 is probably the oldest formula for fluid-structure interaction, and analogous to Young's equation for surface tension (30). The right-hand side of this last relationship defines precisely an apparent compressibility for the liquid, which is therefore given conveniently by the expression on the left-hand side. Young terminated his argument at this point, but it is a trivial matter to make the substitution into Eq. 6 to give the classic result of Eq 1 above explicitly.

Young was undoubtedly in a position to obtain the celerity of the waterhammer wave given by Eq 2, if he so desired. The continuity method he used can be extended to take account of compressible fluids (indeed it was the method used by Korteweg (9), Kries (5) and Joukowsky (2), seventy to ninety years later). Nevertheless he did not, though he did go on to consider the reflection and collision of waves, to state that the particle velocity must be less than the wave velocity and to examine the effect of a contraction in a pipe. As indicated in the previous section, he was also in the position to formulate Joukowsky's Eq 3.

The hydraulic ram

Young was acquainted with the hydraulic ram, a pumping device based on the waterhammer principle. In his "Lectures" (15, Vol. 1, pp. 337-338) he writes:

"The momentum of a stream of water, flowing through a long pipe, has also been employed for raising a small quantity of water to a considerable height.

The passage of the pipe being stopped by a valve, which is raised by the stream, as soon as its motion becomes sufficiently rapid, the whole column of fluid must necessarily concentrate its action almost instantaneously on the valve; and in this manner it loses, as we have before observed, the characteristic property of hydraulic pressure, and *acts as if it were a single solid*; so that, supposing the pipe to be perfectly elastic and inextensible, the impulse must overcome any pressure, however great, that might be opposed to it, and if the valve open into a pipe leading to an air vessel, a certain quantity of the water will be forced in, so as to condense the air, more or less rapidly, to the degree that may be required, for raising a portion of the water in it, to any given height. Mr. Whitehurst (31) appears to have been the first that employed this method: it was afterwards improved by Mr. Boulton (32); and the same machine has lately attracted much attention in France under the denomination of the hydraulic ram of Mr. Montgolfier (33). (Fig. 3.)" (references added by the present authors.) This is Joseph Michel Montgolfier (1740-1810), one of the brothers who built the first manned balloon (in 1783).

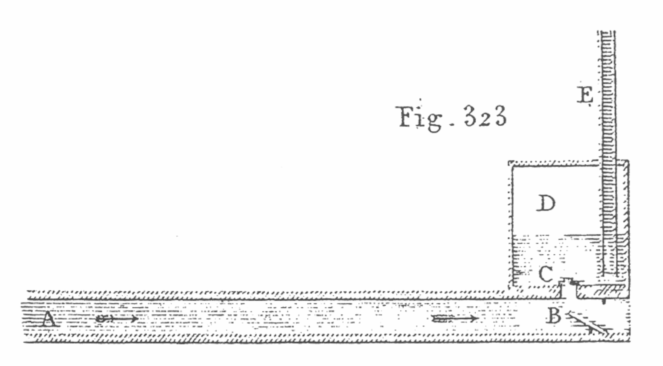


Figure 3 The hydraulic ram of Montgolfier (15, Vol. 2, Fig. 323). When the water in the pipe AB has acquired a sufficient velocity, it raises the valve B, which stops its passage, so that a part of it is forced through the valve C, into the air vessel D, whence it rises through the pipe E.

YOUNG'S WORK ON PIPE FRICTION

Prior to addressing transient flow, Young studied steady flow in pipes (34-36; 15, p. 166). Also, the first part of paper (1) concerns steady pressure losses in pipes. "From own and others' experimental data" Young concluded that "the friction could not be represented by any single power of the velocity, although it frequently approached to the proportion of that power, of which the exponent is 1.8; but that it appeared to consist of two parts, the one varying simply as the velocity, the other as its square. The proportion of these parts to each other must however be considered as different, in pipes of different diameters, the first being less perceptible in very large pipes, or in rivers, but becoming greater than the second in very minute tubes, while the second also becomes greater, for each given portion of the internal surface of the pipe, as the diameter is diminished." With hindsight, Young found here the laminar (linear), fully turbulent (square), and intermediate turbulent (Blasius 1.75) flow regimes. Laird (37) writes on this: "In the 1808 paper (1) Young gives an analysis of the (steady) pressure-flow relations in tubes and was well ahead of his time in describing scaling laws of such a flow. The relative importance of the square law vs the linear "Poiseuille like" term are discussed as a function of dimensions, velocity, viscosity, etc. In fact, the essence of scaling with Reynolds' number is clearly enunciated roughly forty years before Osborne Reynolds (38) carried out his crucial experiments." A historical account of the subject is given in Refs (39) and (40).

AFTER YOUNG

In 1850, Ernst-Heinrich Weber published a paper (10) on experiments with blood flow in which he stated that his brother Wilhelm Weber had prepared a theory for the wave celerity which was found to be the same as the till then forgotten result for Eq 1 of Thomas Young. Wilhelm finally published this (11) in 1866. Going further than Young, he combined the two first-order linear relations for the elasticity of the pipe walls and the acceleration of the fluid column to give a wave equation including the wave celerity in the form

$$c = \sqrt{\frac{R}{2k\rho}} \qquad (8)$$

where his elastic modulus was defined as k = dR/dp, which in modern notation is $k = R^2/(Ee)$ for circular pipes with $R = D/2$, hence giving Eq 1.

Subsequent to the brothers Weber, there were a number of studies in this field, including a comprehensive series of experiments in flexible tubes by Marey (41, 42). Marey, though, lacked the necessary mathematics to develop a theory, so this was done for him by Resal, editor of the Journal de Mathématiques Pures et Appliquées. Resal (43, 44) rederived independently the result of Young and Wilhelm Weber and seems to have been the first to write it explicitly in its familiar modern form of Eq 1. Contemporaneously Moens (45) had modified the Weber Eq 8 with a factor whose mean value was close to 1 (4) and finally in 1878 Korteweg (9) derived the complete result including fluid elasticity (Eq 2).

CONCLUSION

On the basis of the following statements:

- about waterhammer (pulse) pressure rise (26, p. 23):
  the magnitude of the pulse ... is proportional to the velocity of the transmission ...
- about liquid flow suddenly stopped by valve closure (15, p. 338):
  ... and acts as if it were a single solid ...
- about impact of solids (15, pp. 143-145):
  the strain produced by the impact of elastic bodies equals the ratio of the convective velocity to the acoustic speed
- about the acoustic speed in solids (21, p. 31):
  he calculated the velocity of the compression wave that travels through a material following an impact
- about the analogy between solids and liquids (21, p. 31):
  Young showed that his modulus applied both to compression and to extension of rods and also extended its application to liquids

and in addition to his well known pressure wave speed Eq 1, Young arguably arrived at the concepts embodied in the Joukowsky Eq 3, which is the fundamental equation for waterhammer.

ACKNOWLEDGEMENT

Much of the material presented is based on the papers (18), (20) and (21) and on the biographies listed in the Appendix. Figures 1 and 2 are reproduced with kind permission of the Royal Society (London, UK).

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APPENDIX B: YOUNG'S LIFE

Thomas Young has inspired many people to write biographical papers in all sorts and sizes (20-21, 37, 46-79), mostly of hagiographic nature (80). The major biography is Peacock's "Life of Thomas Young" (75), which is based on a large collection of letters and on Hudson Gurney's "Memoir of Thomas Young" (79). Gurney is Young's long-time friend and his "Memoir" is an extension of Young's own biographical sketch, which was published by Hilts in 1978 (18) shortly after its rediscovery around 1976. Other biographies are those of Oldham (72), Wood (70), Kline (58) and Robinson (49).

Young was born as the eldest son in a Quaker family on 13 June 1773 in Milverton (Somerset, UK). At the age of two he could read fluently and before the age of four he had read the bible twice. At the age of fourteen he was fluent in the classic languages and requested to be the "director general" of the Latin and Greek "of the whole party" (18, p. 251). Although he had several teachers and tutors in his early education, he may be regarded largely as self taught. From 1792 to 1803 he studied medicine in London, Edinburgh, Göttingen (Germany) and Cambridge. By coincidence, in Göttingen he lived in the building where in 1833 Wilhelm Weber (with Gauss) invented an electromagnetic telegraph. He was a physician – and not a physicist – his whole life, running a private practice from 1799 to 1814. In 1794, at the age of 21 and officially still a student, he was elected Fellow of the Royal Society, rewarding his paper on vision (read before the society in 1793). He was Professor of Natural Philosophy in the Royal Institution from 1801 to 1803. However, his friends were of opinion that his longer continuance, in the situation of a public teacher, would be unfavourable to his success in medicine, and after having lectured for two winters, he gave up the professorship. In the intervening summer of 1802 he had the pleasure of hearing Napoleon speak at the National Institute in Paris. In the same year, he became Foreign Secretary of the Royal Society, holding this position for the rest of his life. In 1804 he married Eliza Maxwell, which whom he had a happy marriage without children. In 1807 he was an unsuccessful candidate for the post of Physician to Middlesex Hospital, but in 1810, after a very arduous contest, he succeeded to become Physician at St. George's in London and remained this until his death. He was Adviser to the Admiralty on shipbuilding, Secretary of the Board of Longitude, and Superintendent of the vital "Nautical Almanac" from 1818 on, besides physician to and inspector of calculations for the Palladian Insurance Company from 1824 on. He was elected Foreign Member of the French Academy of Science in 1827, succeeding Volta. The French scientists Arago and Gay-Lussac were amongst his friends as well as Humboldt in Germany. Thomas Young died in London on 10 May 1829.