Coulomb's Data on Harpsichord Wire

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Introduction

Charles-Augustin Coulomb published data on the size, strength, and stiffness of harpsichord wire available in Paris in the late 18th century which has not been cited in the literature on musical instruments despite this century's revival of baroque music and the instruments upon which it was played. During an investigation of the internal friction of several antique music wires by means of a torsion pendulum similar to the one invented by Coulomb and first described in the 1784 *mémoire* (Figure 1), it occurred to us to ask what Coulomb had used as the suspensions in his pendulum. His biographer, C.S. Gillmor, mentioned "harpsichord strings",[1] and in Coulomb's 1784 *Torsion mémoire* we found: *J'ai pris trois fils de clavcin, tels qu'on les trouve répandus dans le commerce, roulés sur des bobines, et numerotés* ("I used three harpsicord wires, such as one finds distributed in commerce, wound up on spools, and numbered").[2]

The spools of wire recently discovered in the stand drawer of a harpsichord in France fit Coulomb's description.[3] The instrument was built in Paris in 1732 by Antoine Vater, and the wire found with it was wound up on small wooden spools similar to spools for thread. The spool of red brass wire had a mark punched in one end and the spool of iron wire had the gauge size (*No 5*) written on it in ink, while the spool of yellow brass wire had neither mark nor number. Samples of the wires from these three spools, generally agreed to be of 18th century manufacture, were collected by J. Scott Odell of the Smithsonian Institution as part of a research project which he initiated into the physical properties of antique wire. With these samples in hand it was possible to measure certain of their properties and to compare these properties with those reported in Coulomb's *Torsion mémoire* in 1784. Since Coulomb's wire was undoubtedly of 18th century manufacture (a degree of confidence that we do not always have with collected samples), and the data were taken not long after the wire was drawn, comparison with the Vater wire allows us to detect if, during two centuries, significant changes occur in highly drawn wire.

Coulomb had invented the torsion balance in order to detect and measure small forces. In experiments to verify his theoretical derivation of its performance, he systematically varied the weight and the dimensions of the mass, the length of the suspension, and also the diameter and metal of the wire used as the suspension. From his comments in the *mémoire* we can presume that he chose harpsichord wire because of its consistently high quality.[4]

Composition

Coulomb reported the properties of two kinds of wire, *fer* (iron) and *laiton* (brass), each in three gauge sizes. Though he did not specifically identify the brass wire as harpsichord wire, as he did the iron wire, it seems clear from the context that the brass was also music wire. He writes: "Three brass wires were used, corresponding to the number and closely to the size, of the three iron wires that were just submitted to experiment."[5] The gauge numbers of both the brass and iron wire that he bought were *No 12*, *No 7*, and *No 1*, *No 1* being the coarsest and *No 12* the finest. Coulomb did not describe the alloys of his wires further, unless occasionally to refer to the *laiton* (brass) as *cuivre*, which could also mean "copper." French language of the time allowed interpreting both words as "brass," as in his use of *cuivre jaune* (yellow brass) on one occasion.[6]

Analyses of the samples from the Vater harpsichord identified the alloy described by Coulomb as *fer* as a highly refined, low-carbon, high-phosphorus iron.[7] The two brass samples from the Vater contained different amounts of zinc, the coarser wire (0.68 mm in diameter) containing only 7% zinc, while the finer brass wire (0.28 mm) contained about 28%.[8] It had been assumed from references to red and yellow wire in the 18th century literature that the red wire had been copper, since this was an accepted meaning for *cuivre*. However, attempts to restring instruments using wire of modern, highly refined copper which did not stay up to pitch suggested that there was a more appropriate meaning for *cuivre* in these contexts. Red brass, containing up to 15% zinc, makes a stronger, more stable string than copper alone while retaining copper's red color. Red wire was not used on every instrument and was strung only for the lowest notes that required the coarsest gauges. From the properties Coulomb reported for his brass wires when compared with those of the yellow brass wire from the Vater, it is clear that in the *mémoire, laiton* describes a yellow brass closely resembling modern cartridge brass.

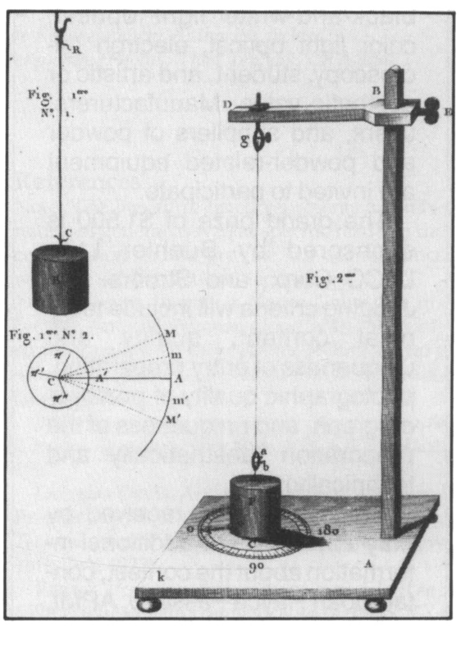

Figure 1. Coulomb's torsion pendulum as depicted in the Torsion mémoire *(Plate 1), 1784. (See Reference 2.)*

Diameter, Density, and Gauge Number

Coulomb measured the breaking loads for each size of brass and iron wire that he used as the suspension in his apparatus. He also made measurements of the pendulum such as the length of the suspension, the weight and dimensions of the mass, and the period. With these data it is possible to calculate the tensile strength and the rigidity of each wire if its diameter is known.

Coulomb did not report the diameter of

his wires directly. Instead he measured the weight of a six-Paris-foot length (1.849 m) of each wire.[9] This was a customary procedure in the 18th century, and one followed, for example, by Sauveur, who declared, "I prefer to know the weight of a fixed length of string to that of its diameter."[10] The length to be weighed seems not to have been standardized; Sauveur used 40 astronomical inches (1.104 m). Six Paris feet was then a unit called the *toise.*

To calculate the diameter of the wires from the data given by Coulomb, their densities must be known. The densities of the Vater wires were measured, and each had a density somewhat less than that of the same alloy in bulk form. Several properties of wire are sensitive to the degree of their reduction, and among them are the tensile strength and the density. Coulomb reported the breaking load for each gauge and so must have been aware of the change in tensile strength as a result of work hardening during reduction. He does not, however, consider the effect of drawing in slightly lowering the density of wire. He suggested values for the densities of iron and brass, in modern units 7.71 Mg/m^3 for *fer* and 8.31 for *cuivre jaune.*[11] These values were taken from Musschenbroek and were nearer the measured values of the Vater's wires than the modern standard values used by later commentators.[12]

As a test of the accuracy of calculating the diameter from measurements of length, weight and density, the diameter of each Vater wire calculated by one author was compared with a series of 40 micrometer measurements along the length of each wire by the other and were found to be in close agreement (Table I), even though the wires from the Vater were very much shorter than the lengths weighed by Coulomb. The measured densities of the Vater's yellow brass and iron wire[13] were used as a closer approximation to the actual values than those suggested by Coulomb in calculating the diameters represented by the gauge numbers of his wires (Table II). Coulomb reported that his *No 12* iron wire had a diameter of nearly a 15th of a *ligne,* that is, nearly 0.151 mm.[14] There was also very little difference between the results of our calculations and those of Bell[15] for the iron wires (0.51 mm for *No 1*). The diameters calculated for Coulomb's *No 1* and *No 7* bracket the measured diameter of the Vater's iron wire, whose gauge size, *No 5,* was marked on its spool.

The sizes of the brass and iron wires of the same gauge number were, as Coulomb had reported,[16] closely similar but not exactly the same (Table II). This had been postulated independently by Rémy Gug of Strasbourg.[17] According to Sauveur, the coarsest music wire was one-third of a *ligne* (0.75 mm) in diameter. The diameter of the red brass wire from the Vater (0.68 mm) was larger than Coulomb's *No 1* gauge brass wire. In the gauge system then used in Paris it would have had a gauge number between 0 and 4/0. The Vater's yellow brass wire, which was from an unmarked spool, upon measurement was found to have the same diameter (0.28 mm) as that calculated for Coulomb's *No 7.*

The meaning of the old gauge numbers in terms of diameters has obvious importance in restringing, especially for antique instruments where gauge numbers were recorded for specific strings. Standardization of wire gauges tended to be geographically limited in the 18th century. The diameters associated with the gauge numbers reported by Coulomb can be assumed to apply to Paris gauges. Keeping that proviso in mind, it was possible on the basis of Coulomb's data to identify the gauge number of the yellow brass wire from the Vater as *No 7* in the Paris gauge system.

Tensile Strength and Hardness

Coulomb measured the breaking load for each of his six wires as another method of characterizing the wire he used in the

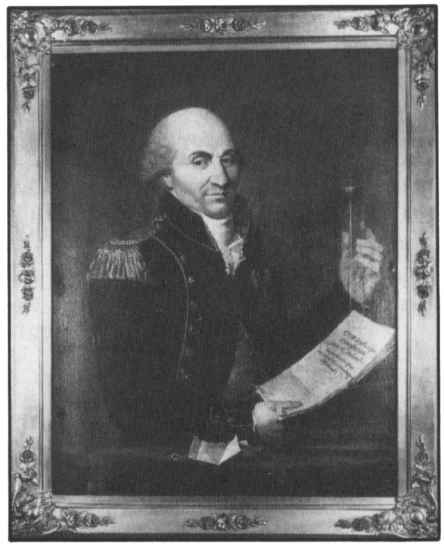

Figure 2. Portrait of Charles Augustin Coulomb (1736-1806) with his torsion balance, painted by an unknown artist, probably between 1803 and his death in 1806, and now the property of his great-great-grandson. Photograph courtesy of C. Stewart Gillmor, reproduced with the permission of the Coulomb family.

Table I: Calculated and measured diameters of wire samples from 1732 Vater spare stringing stock.

Alloy	Length (cm)	Weight (g)	Specific gravity (Mg/m^2)	Calculated diameter (mm)	Measured diameter (mm)
Red brass	16.4	0.5323	8.68	0.69	0.68
Yellow brass	18.5	0.1125	8.24	0.31	0.28
Iron	57.6½	0.3687	7.69	0.33	0.31

Table II: Gauge numbers and diameters of 18th century music wire.

Source	Alloy	Gauge Number	Weight* (grains)	Diameter (mm)
Coulomb	*fer*	12	5	0.15
"	"	7	14	0.25
Vater	iron	5		0.32
Coulomb	*fer*	1	56	0.50
"	*laiton*	12	5	0.14½
"	"	7	18½	0.28
"	"	1	66	0.52½

*Weight of six-Paris-foot length (1.849 m): the *grain* was 0.053 g. Conversion factors from Ronald Edward Zupko, *French Weights and Measures before the Revolution,* (Indiana University Press, Bloomington, 1973).

Table III: Breaking loads and tensile strengths of 18th century harpsichord wire.

Source	Alloy	Gauge No.	Diameter (mm)	Load, as reported	Tensile strength (MPa)
Vater	iron, annealed	5	0.32	*	552 Mpa
Coulomb	*fer*	1	0.50	33 *livres*	800
Mersenne	iron	–	0.38	19 *livres*	821
Vater	iron	5	0.32	*	938
Coulomb	*fer*	7	0.25	10 *livres*	965
"	"	12	0.15	3 *livres*, 12 *onces*	1014
Coulomb	*laiton*, annealed	1	0.52½	12–14 *livres*	263–307
"	*laiton*	1	0.52½	22 *livres*	483
"	"	7	0.28	14 *livres***	**
"	"	12	0.14½	2 *livres*, 3 *onces*	634

*Sample not broken: tensile strength estimated from hardness tests.
**This datum is an obvious misprint; 14 *livres* corresponds to a tensile strength of 1,097 MPa.

Table IV: Rigidities of 18th century harpsichord wire, measured in the 18th and 20th centuries. In these calculations each modern cycle is equivalent to two *oscillations* in the *mémoire*.

Source	Alloy	Gauge No.	Ridigidty (GPa)
Coulomb	*fer*	12	74.9
"	"	7	79.0
Vater	iron	5	75.3
Coulomb	*fer*	1	66.6
Potier (1884)	iron	*	76.3
Coulomb	*laiton*	12	25.3
"	"	7	28.8
Vater	yellow brass	7	33.2
Coulomb	*laiton*	1	27.1
Potier (1884)	brass	*	27.8
Vater	red brass	(0.68 mm)	10.2

*Potier did not indicate which iron wires were the basis for his calculation; he calculated the value for brass using the ratio 3.34 given by Coulomb for the rigidities of iron to brass. Potier also assumed the specific weights to be 8.6 for brass and 7.8 for iron, although Coulomb quoted from Musschenbroek a ratio between them of 77:83.

suspensions of his torsion balance. Unfortunately, the breaking load published for *No 7 laiton, 14 livres*, is clearly a misprint. This is one of many in the *mémoire* but one we were unable to rectify.[18] Such misprints occurred so often in his publications that Coulomb was moved to complain that the publications were "so incorrect that it is not possible to read them."[19]

The tensile strength of each wire (Table III) was calculated by dividing the breaking load data by the calculated diameters in Table I. The increase in tensile strength from the coarsest wire to the finest is evidence that the drawing schedule proceeded through these reductions with no interruption for annealing, which would have softened and also weakened the wire.

The earliest data on the breaking loads for music wire had been published by Marin Mersenne in 1636.[20] He reported breaking loads for brass, iron, silver, alloyed gold and pure gold wires, all of one-sixth *ligne* (0.38 mm) diameter. Because he reported brass wire nearly as strong (801 MPa) and silver and gold wires stronger (990 MPa) than iron (821 MPa), doubt justifiably has existed concerning all these data.[21] By comparison with Coulomb's breaking loads however, Mersenne's datum of a 19-*livre* breaking load for his iron wire (Table III) is acceptable.

Samples of antique wire as long as those from the Vater (10 to 30 cm) are scarce, and we were not willing to subject them to a breaking load test for comparison with Coulomb's data. Besides resulting in two shorter pieces of wire, such a test would have also vitiated the measurement of internal friction, a property highly sensitive to its subsequent handling. Instead, a few millimeters were used for microhardness tests. In iron alloys an approximate tensile strength may be inferred from the hardness.[22] The hardness of the Vater's iron wire (291 kg/mm^2) gave an estimated tensile strength of 938 MPa, used in Table III.

Coulomb's breaking load for *No 1* brass wire after annealing (12 to 14 *livres)* is a useful indicator of the amount of drawing in the brass wire which was required to reach a diameter of 0.54 mm. When compared with that of the wire before annealing (22 *livres)*, it measures the amount of strengthening of this wire attributable to work hardening during drawing. *No 1* wire was the coarsest wire of the set and so the least drawn, yet drawing had raised its strength at least 176 MPa above the strength conferred simply by alloying copper with zinc.

By annealing a sample of the Vater's *No 5* iron wire, as Coulomb had annealed his *No 1* brass wire, the strength attributable to the alloy alone could be measured, and when compared with the strength of the wire as drawn yielded an estimate of the amount of strengthening due to work hardening during drawing. In the *No 5* wire from the Vater, the hardness of the annealed iron was 190 kg/mm^2 which indicated an approximate tensile strength of about 552 MPa. The iron is harder, as a consequence of the phosphorus content, than annealed low carbon steel. Type 1008 steel, for example, has a hardness of about 100 kg/mm^2. The increase in strength due to work hardening of the Vater wire was nearly 400 MPa.

Coulomb was the first to report the breaking loads of music wire as a function of gauge number as well as of composition, showing his cognizance of the increase in tensile strength brought about by work hardening during drawing. Seventy years earlier Sauveur had assumed the tensile strength of wire to be a function solely of the alloy.[23] Coulomb's data on the strength of iron can be used to verify one datum from Mersenne's otherwise suspect breaking loads, that of one-sixth *ligne* iron wire at 19 *livres*, or a tensile strength of 821 MPa. Tensile strengths are of interest not only in estimating the mechanical loads antique instruments were designed to bear but also in discussing the changing pitch standards of the 17th and 18th centuries.[24]

Rigidity

Coulomb derived the equation still used for stiffness in torsion, the rigidity modulus, in his *Torsion mémoire* and reported data from which the rigidity of each of his six wires could be calculated (Table IV). He believed the rigidity to be invariant for a given alloy, as did the editor of the 1884 centennial edition of the *mémoire*, Alfred Potier, who published a single rigidity for the iron wires (7,480 kg/mm^2) and one for the brass (2,730 kg/mm^2).[25] Potier's calculations were also based upon the specific weights of modern brass and iron (8.6 and 7.8), rather than those suggested by Coulomb, which we have found by comparison with those measured in the wire samples from the Vater to have been more nearly correct.

The rigidities of the Vater wires in Table IV were measured in a torsion balance of the same general design as that of Coulomb, except that the measurements were taken in a vacuum, dictated by our interest in measuring internal friction. Coulomb estimated the effect of air resistance on his measurements of rigidity and found it to have been negligible. Comparisons of the two sets of rigidity data, one taken in the 18th century and the other in the 20th, suggest that if any effect of the passage of two centuries on the Vater's wire exists, it is very small.

That there were no significant changes in rigidity in two centuries is a particularly useful result since the aim of our research into the properties of antique wire is the establishment of specifications to reproduce this wire as faithfully as possible. It is the premise of this research that strings made from modern wire having the same properties as the antique wire can be assumed to give the same sound as harpsichord strings played and heard in the 18th century. Wire with properties typical of 18th century wire would represent one more step in the authentic recreation of baroque music, one not subject to the vagaries of modern taste.

For example, the stiffness of the wire is an important variable of string sound. Along with the builder's choice of string diameter, it determines the inharmonicity of the upper partials produced by the string. The stiffness of presently available replacement wire can be too high or too low. We measured the stiffness of some modern red brass wire of a composition (11% zinc) and size (0.60 mm diameter) similar to that from the Vater. The Young's modulus of the modern red brass wire was 64 GPa, lower than that of the red wire from the Vater, which was 86 GPa. On the other hand, modern steel wire of a sort commonly used for restringing harpsichords was found to have a Young's modulus of 219.2 GPa, higher than the iron wire from the Vater, which was 178.5 GPa.[26]

The discovery of Coulomb's measurements of harpsichord wire significantly enlarges the data base on antique music wire being accumulated by measurement of surviving examples. It was particularly unexpected to find them in the proceedings of the French Academy, as a bibliography of its citations on musical subjects had already been compiled[27] in which Coulomb's *Torsion mémoire* had not been listed. Further uncited data on music wire of the 17th or 18th centuries may exist in the literature on scientific instruments of the period.

Music wire was, and still is, the strongest fine wire available in commerce and has often been put to other than musical uses. For example, in 1890 Lord Kelvin mentioned "pianoforte wire at present in use for deep-sea soundings."[28] Music wire is another instance of the demands of art encouraging the development of materials to a very high standard. As we have seen from Coulomb's work, music wire of the 18th century was of such quality and reliability that it was useful not only to musicians but also to science.

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