A new understanding of the first electromagnetic machine: Joseph Henry's vibrating motor

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In 1831, Henry invented a battery-powered rocking-beam motor that he later described as the first electromagnetic machine. He repeatedly modified the design over his career, but only one version of a motor actually constructed by Henry is known to exist. This version is in a collection of Henry instruments at Princeton University. We found that the Princeton motor cannot have operated in the form that was displayed as early as 1884. We found evidence in several historical documents and in the instrument itself that the field magnet shown with the motor is a mistake. Instead of a single horizontal bar magnet, the motor was designed to use two elliptical magnets. We presume the error was made by whoever assembled the first public display. We modeled the dynamics of Henry's vibrating motor and compared our results to the operation of a replica motor. Modeling provides insight into how the motor is able to vibrate indefinitely even in the presence of energy loss due to friction.
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I. INTRODUCTION

Henry was one of the most important American scientists of the 19th century, and his work stimulated a number of significant engineering innovations, including the electromagnetic motor and the electromagnetic telegraph. His electric motor was the precursor of the modern day dc electric motor. Henry's most significant contributions were in electromagnetism. The international standard unit of electrical inductance, the Henry, is named in his honor.[1]

We focus on a particular Henry motor (hereafter referred to as the Princeton motor) that is on display at Princeton University. This motor is the only Henry motor known to exist and is a modification of the original one that he first described in 1831.[2] The earliest public display of this motor appears to have been in Philadelphia at the 1884 International Electrical Exhibition.[3] The Princeton motor was never described by Henry, and it seems that it has been assembled incorrectly. The earliest known description of the Princeton motor is an article by Pope in 1888,[4] which was published ten years after Henry's death.

To develop an understanding of the Henry motor, we inspected and tested it and constructed a working replica of the original 1831 motor. We also tested replicas of the Princeton motor armature to help us unravel details of the coil windings and the effects of induced currents in the armature core.

Henry identified his motor as the first electromagnetic machine.[5] Based on Henry's private correspondence and notes taken by his students in his natural philosophy course, we know that different versions of the motor were conceived and constructed.[6,7] The motor that survives to this day is part of an apparatus collection that Henry used as a faculty member at the College of New Jersey (now Princeton University).[8] The instruments in the collection were used for teaching and research during 1832–1848.

The Princeton motor differs from the 1831 version, and as we will show, the Princeton motor cannot operate. We believe that Henry never saw it in the form that was put on display. It is unlike any motor that he described in his research papers, lectures, court testimony, and letters.

In particular, we will show that the single horizontal bar magnet of the Princeton motor is an error. The 1831 motor used two vertical bar magnets with north poles pointing up. All the motors that Henry described used two field magnets and were based on pole reversal of a rocking electromagnetic armature.[9–11]

II. COMPARISON OF THE PRINCETON AND THE 1831 MOTORS

To understand motion in the 1831 motor (see Fig. 1), consider the forces on the iron armature when it starts with the right armature end down and the left end up. The armature is magnetized by current flowing in a helical coil wrapped around it. One end of the coil attaches to whisker *r-p*. The other end attaches to whisker *q-o*. Battery terminals *l* and *t* are zinc electrodes which are negative by convention. Terminals *m* and *s* are copper electrodes which are positive. The zinc and copper electrodes are immersed in a dilute acid. Whisker contact is made initially with the battery on the right. The battery terminals are thimbles filled with liquid mercury to allow low-friction electrical contact with the whisker leads.

When the whiskers are connected with the battery on the right, current (which flows in the positive to negative direction) moves in the armature coil in a counterclockwise sense (as seen looking along the armature axis as viewed from the right), so that the electromagnet end that dips down on the right is north and the end that rises up on the left is south.

Two vertical permanent bar magnets with their north poles up are underneath the armature ends. North poles are indicated by the painted stripes (or bands) on the magnets as seen at locations C and D in Fig. 1. Because like poles repel and unlike poles attract, the electromagnetic armature experiences a torque when connected to the battery on the right. This torque is due to the combined effects of like-pole repulsion (north-north on the right) and unlike-pole attraction (south-north on the left). As a result, the armature is accelerated to the left toward decreasing angles. As the armature rotates left, contact with the battery terminals is maintained until a limiting angle is reached when the whiskers lift out of the mercury. Current then stops flowing in the coil and the armature loses its magnetization.

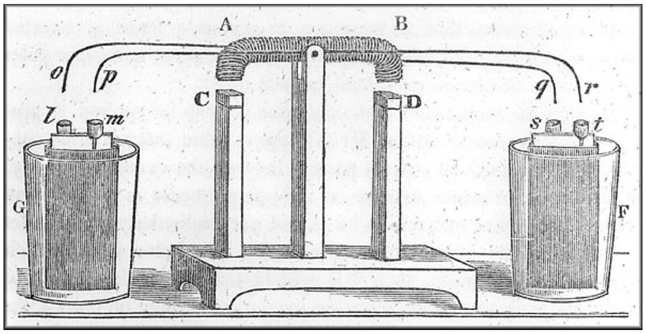

Fig. 1. Engraving of 1831 motor from Henry's paper (Ref. 2).

At the moment when the current stops, the armature is moving left and continues to coast. When the whiskers make contact with the mercury-filled thimbles on the left, current again begins to flow. The electrical polarity of the left battery is the reverse of the right battery, so that the current flowing in the armature winding is now clockwise. The left armature end becomes north and the right armature end becomes south, which is the reverse of the armature polarity of the right-dipping case.

With a north pole at the left armature end to repel the north pole of the left field magnet (and south-north pole attraction at the right armature end), the rotation of the armature decelerates until it eventually stops. After the armature stops, current is still flowing in the coil. As a result, the armature reverses direction and rotates right toward increasing angles. The armature continues to accelerate to the right until the whiskers lift out of the mercury-filled thimbles. The armature now coasts back to the right side and the process repeats.

Henry reported that his 1831 motor operated at 75 oscillations/min (1.25 cps) when used with dilute acid in the batteries and oscillations could be maintained for more than 1 h.[2] Normal operation of the 1831 motor was explained as the result of pole reversal of the electromagnetic armature. Note that the current in the armature is ac and reverses direction at the rocking frequency.

Now consider the Princeton motor shown in Fig. 2.[12] We determined experimentally that the armature of the Princeton motor is wound in one helical direction and is structurally similar to the armature in the 1831 motor. The field arrangement in the Princeton motor is different than that in the 1831 motor. The Princeton motor uses a single field magnet with north at the left and south at the right. The poles of the horizontal magnet are a large distance from the poles of the armature. As a result, the magnetic interaction between the armature and the field magnet would not be substantial because forces fall off rapidly with pole separation. In contrast, the 1831 motor uses two separate field magnets with north poles up. The poles of the vertical field magnets are very close to the poles of the electromagnet armature. Hence, the Princeton motor with its current configuration would not produce significant motion, or oscillations with successive pole reversals. Something is not right with the Princeton motor configuration.

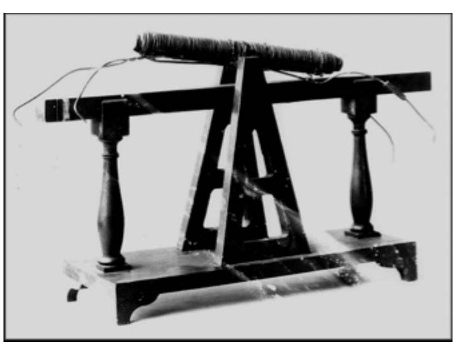

Fig. 2. Photograph of the Princeton motor, a modification of the 1831 motor, as displayed to the public since 1884.

To see if there is another way for the Princeton motor to operate, we examined its important parts. We did not find anything to alter our understanding of the Princeton motor. It cannot work as configured. Either the armature is wrong (for example, too short and wrong winding) or, what is much more likely, the horizontal bar magnet is wrong.

III. A DETAILED LOOK AT THE PRINCETON MOTOR

In the following we describe the components of the Princeton motor including the armature, the horizontal bar magnet, and the motor stand. We then discuss how it could have operated if the bar magnet was polarized differently or if the armature was wound differently. We also present two analytical models of oscillatory motion of Henry's vibrating motors: one that assumes instant magnetization of the armature core by a current in the coil and one that is more realistic with the core being magnetized over a short time as determined by armature inductance. We will show that the simple notion of pole reversing adequately explains oscillations but does not explain why oscillations are able to persist in the presence of frictional energy loss. To understand continuous operation, we will show that inductance and resistance need to be included in the analysis. We will see that a nonzero time constant is essential to give the rocking armature a push on each oscillation.

A. Armature

As in the 1831 motor, the armature is made up of multiple coils, an iron core, and whiskerlike leads that extend beyond either end of the core. Figure 3 shows the armature on the stand and when it has been removed for testing. Closeups show the insulating cloth liner at one armature end and a coil attachment to a whisker. Many qualitative features of the Princeton motor armature match those of the 1831 motor armature. In particular, the Princeton motor armature is simply wound with all wire loops circulating in one direction. The only significant difference between the two armatures is the shape of the iron core. The core of the 1831 motor is bent down at the ends so that the electromagnet poles are in close proximity to the poles of the vertical magnets. This shape contrasts with the shape of the core of the Princeton motor armature which is straight. The Princeton armature is much shorter than the horizontal bar magnet which is placed below it. The difference in length means that the poles of the armature are far from the poles of the horizontal bar magnet. The large separation between poles suggests that magnetic forces will be small.

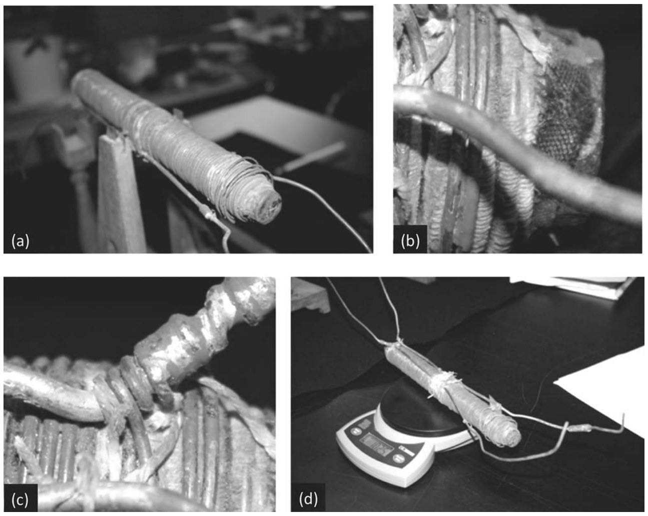

Fig. 3. Closeups of the Princeton motor armature: (a) appearance in its normal operating position on stand; (b) end of iron core showing cloth liner; (c) wire connection of one coil to a whisker; and (d) armature being weighed on a laboratory scale.

B. Armature windings

There are two distinct windings on the armature and both windings circulate about the core in the same direction. One end of each coil is attached to a whisker resulting in two points of attachment to each whisker. The whiskers therefore serve to connect the two coils in parallel. We established the direction of the current by passing 1 A through each coil and measuring the direction and strength of magnetic polarization of the iron core. We were able to excite each of the two coils separately because of a broken segment in one of the windings. The broken wire is about four loops of that surround one end of the armature. These loose loops can be seen in Fig. 3(a) on the armature end that comes out of the page. This armature end is marked with a green fabric liner. (The other armature end [see Fig. 3(b)] is marked with a black fabric liner.) We can match the ends of the broken wire of the loose loops in Fig. 3(a) to the points where they were once attached without ambiguity. By adding an electrical jumper to bridge the break, we were able to excite the armature with its intended parallel wiring of both coils.

Whiskers, made of 0.1 in. diameter bare ductile wire, are used to connect the coils to the batteries on the left and right of the motor. The 0.05 in. diameter wire used in the two coils is either wrapped with an insulating thread or painted. The painted wire loops are on the outside of the armature. Figures 3(b) and 3(c) show both painted wire loops and thread wrapped loops. Painted wire segments are spliced to the thread wrapped wire segments. The splices are twisted and soldered.

We were able to determine that the coils wrap about the core in three layers of loops, which are indicated by comparing the diameter of the coil wrapped armature with the diameter of the core. If we allow for the thickness of the thread wrapping of the innermost wires in the windings, it was clear by our measurements that there were more than two layers and less than four layers of wire loops. By inspecting the outermost portion of the armature we counted about 130 loops per layer. Without unraveling the windings, we cannot be certain how precisely the wires were wrapped around the core. One possibility is that there is an inner coil of two layers (260 loops) and an outer coil of one layer (130 loops). This possibility is shown in Fig. 4. The other possibility is that each coil contains about one and one half layer. Given our determination that the resistance of each coil is about the same, this possibility seems more likely even though we initially thought otherwise. This second possible wiring is also supported by our magnetic pole strength measurements which reveal that one pole is stronger than the other when a single coil is energized. When both coils are energized in parallel, the pole strengths are about equal.

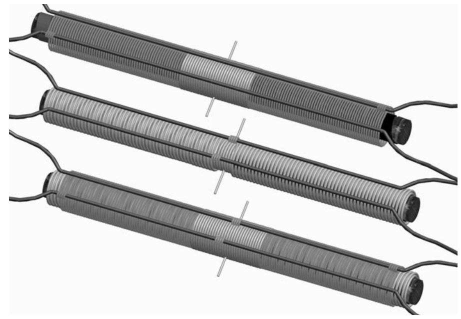

Fig. 4. Illustration of one of the two possible windings of wires in the Princeton motor armature showing iron core, whiskers, and coil attachments. At the top is the outer winding, in middle is the inner winding, and at the bottom are both windings.

The armature of the 1831 motor used three separate wire strands coiled in the same direction. The three coils were each 25 ft in length. Ordinary bell wire was specified, 0.045 in. in diameter. The wire in each coil was insulated with cotton thread.[2] Henry was known for his use of insulated wire to increase the number of turns in electromagnets. The combination of many loops and a parallel or series configuration based on the type of battery used (that is, high current or high voltage) allowed Henry to make the strongest electromagnets at that time. In the 1831 motor, all three coils were connected in parallel with one another. The coil ends were twisted and connected to whiskers to connect with pole-switched batteries on the left and right sides of the motor.

To test the Princeton motor, the armature core was magnetized by connecting either one coil, the other coil, or both coils wired in parallel to a current-regulated power supply (Good Will Instrument Co., model GPC-1850D). Typically, a 1.0 A current was used in our tests.

C. Replica armatures

To help check our measurements and our understanding, we made replicas of the Princeton armature. We wound the replica armatures with about the same number of loops as in our estimates for the inner and outer coils following the possibility shown in Fig. 4. For the replica cores, we used a 10.88 in. long, 0.75 in. diameter cast gray iron rod (from MacMaster-Carr Supply). We also made one core out of a bundle of about 100 painted thin rods of high-purity (soft) iron to help us understand the effects of eddy currents in the core. The bundle diameter was also 0.75 in. We tested replica armatures in the same way as we tested the original armature. The replica armature coils used 16 AWG (0.0508 in. diameter) enameled copper magnet wire. The armature replicas had 270 turns and 135 turns for the inner and the outer coils, respectively. The resistance of the inner coil replica was measured to be 0.27 Ω. A current of 1 A resulted in solid-core pole strengths that were measured at one armature end to be 40 G and 47 G at the other end. The replica of the outer coil had a resistance of 0.14 Ω. A current of 1 A in the outer coil replica resulted in solid-core pole strengths of 18.5 G at one end and 21.7 G at the other.

D. Coil resistance

The resistance of the Princeton motor armature with the two windings wired in parallel was 0.33 Ω. The resistance was determined by dividing the measured voltage drop by the operating current. We used a standard four-point measurement to eliminate the effects of lead resistance. A precision high-input-impedance voltmeter (Keithley multimeter, model 2000) was used to determine the voltage drop across the armature coils. This test was made with a current of 1 A.

The resistance of the one coil alone (the one that was the inner coil if the windings were of the type depicted in Fig. 4) was measured to be 0.47 Ω. The measured resistance of the other (outer) coil was 0.58 Ω. Based on its length and the winding possibility shown in Fig. 4, the outer coil should have a smaller resistance than the inner coil. This prediction disagreed with measurement. Perhaps, an internal connection is resistive or the outer coil wire is made of a material with a different resistance than that of the inner coil. We are not certain of the cause of the discrepancy.

How do these resistances compare with those that one could calculate? Following the winding possibility shown in Fig. 4 and using an estimate of physical dimensions and of the number of loops, we estimate that the length of the inner coil is 53.7 ft. The outer coil is 37.7 ft. The radius of the outer coil is larger than the inner coil, and therefore it is longer per unit loop than the inner coil. The relation $R=\rho\ell/A$, where ρ is the resistivity for copper, ℓ is the wire length, and A is the cross sectional area, gives the estimate 0.22 Ω of the inner resistance. The outer resistance should be 0.16 Ω. These estimates compare reasonably well with our replicas but disagree with the Princeton motor armature measurements by more than a factor of 2. We are not certain of the source of this discrepancy, but we suspect that the resistivity of the wire used in the Princeton motor is higher than that for high-purity copper.

E. Motor core

The Princeton motor armature core is a cylinder with diameter of 0.70 in. and length of 10.88 in. It is covered with a thin layer of what seems to be silk. There is also a mesh lining over part of the core that may be cotton. The fabrics insulate the coils from the electrically conducting core. Armature poles are marked with black fabric at one end and green fabric at the other.

We magnetized the core with a 1 A current with both windings connected in parallel. To wire in parallel, a jumper was used to bridge the break in the outer coil. We noted an intermittent short circuit between one whisker and a few loops of one coil. The origin of this short circuit can be seen by close inspection. Some of the cotton wraps on the coil have deteriorated. Care was taken in our testing to avoid the short circuit by adding a small piece of paper insulation or by pulling back on one whisker.

The pole strength was measured with a Pasco magnetic field probe (model CL-6520A with model 750 interface) set for axial field measurements on the ten times setting. This setting is recommended for measurements near but below 100 G. For a test current of 1 A, the pole strength of the north end was about 46 G. The pole strength measured at the south end was about 49 G. These pole strength values compare with those of the replica armatures.

While energized, the field direction of the Princeton armature was determined using a magnetic compass. The compass was moved slowly along a looping path that was roughly equidistant from the armature about the long axis of the core. The field direction followed what would be expected for a simple energized solenoid. At the position of the core midpoint, the field direction was parallel to the armature's long axis. We repeated this test for current in one coil alone, current in the other coil alone, and current in the parallel-wired coils. We also repeated these measurements with the electrical polarity reversed.

The Princeton motor core is described as soft iron by Henry and by students in his course on natural philosophy. Soft iron does not retain its magnetism after current stops flowing. Hard ferromagnetic materials such as tool steel retain their magnetization.

Polarization of the Princeton core was observed to fall abruptly as soon as the current was removed. A small residual magnetization (less than 15% of the maximum pole field) remained. If the core was made of a hard magnetic material appropriate for permanent magnets, a much larger magnetization would have been retained. Our conclusion is that the Princeton motor armature is made of soft iron.

F. Coil inductance

We determined that the inductance of the Princeton armature is ≈4.3–4.6 mH. This determination was made with both coils connected in parallel. We used a series LR arrangement, forcing the circuit with a voltage step. The series resistor, R, was 0.25 Ω (rated at 10 W). We selected a low-inductance resistor, and its inductance was separately determined to be less than 0.002 mH, small enough not to interfere with the principal inductance measurement. The power source was the GW power supply used earlier but this time in the voltage regulated mode. The voltage across R was measured with an oscilloscope and the voltage transient was fit to the form $A(1-e^{-t/\tau})$, where time constant $\tau=L/R_T$. R_T, the total resistance, is the sum of the resistances of the series resistor, the resistance of the armature coil, the internal resistance of the power supply, and the resistance of the leads. We determined its value by dividing the power supply steady-state voltage by the power supply steady-state current. The measured transient is shown in Fig. 5. The voltage step was applied by turning on the power supply. An internal relay in the power supply closes to apply the voltage. After the relay closure, it takes ≈3 ms for the power supply voltage to reach steady state, so we did not use the first 3 ms of the measured transient in our curve fit.

Our method for measuring the inductance followed several attempts which gave conflicting results. The source of the conflicts was tracked down to eddy currents in the iron core. We found that eddy currents persist for times on the order of 300–400 μs. In our earlier transient measurements, which gave conflicting results, we used a series resistance of either 50 or 8 Ω. Because the time constant τ was less than 1 ms,

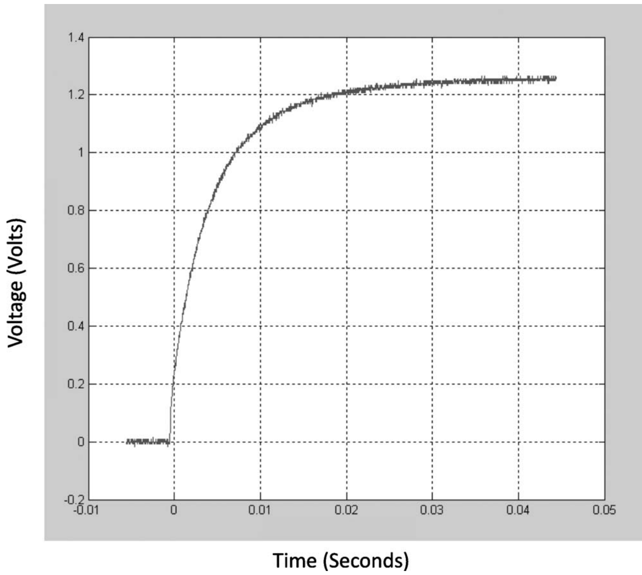

Fig. 5. Voltage versus time across R in the series LR circuit showing an exponential rise; a fit to this curve is used to determine a value for L.

the transients were masked by these eddy currents. The method that we used ultimately involved slower transients obtained by employing a smaller series resistance. As a result, our final measurements were only weakly modified by the eddy currents.

The indicator that flagged a problem with our earlier measurements was that the observed transients were not characterized by a single exponential. We also tried frequency-based methods to determine the inductance based on an inductance bridge and used both series and parallel resonance circuits. These frequency-based methods also gave inconsistent results. In hindsight, we realize that frequency-based methods would have worked better if we used test frequencies below 10 Hz. Our original frequency-based methods used test frequencies in the range of 100 Hz–1 kHz.

How does the measurement of $\approx$4.3–4.6 mH compare with what would be calculated for the inductance? The inductance L of a solenoid with a ferromagnetic core is $L=\mu N^2 a/l$, where μ is the relative permeability in units of $\mu_0=4\pi\times 10^{-5}$ G/A cm, N is the number of loops, a is the solenoid area, and l is the solenoid length.[13] If we use $N=135$, $a=\pi(1.1\ \text{cm})^2$, $l=24$ cm, and $\mu=100\mu_0$ for the outer coil, we find an inductance of about 3.6 mH, which is more than a factor of 2 less than the 6–8 mH range of values of the inductance that we measured for the Princeton armature and the replica armature using the outer coil alone (assuming the winding possibility of Fig. 4). Our guess of a value of 100 for the relative permeability in these calculations falls in the expected range for magnetic iron. The actual value might be higher. These calculations were in the same spirit as the resistance calculations, that is, only to check orders of magnitude. We are satisfied that the calculated inductance is in the range of values expected.

G. Physical dimensions

The diameter and length of the armature core are 0.70 in. and 10.88 in., respectively. With windings, the outer diameter increases to 1.05–1.10 in. If the coil is tightly wound with bare 0.05 in. diameter wire, the diameter is

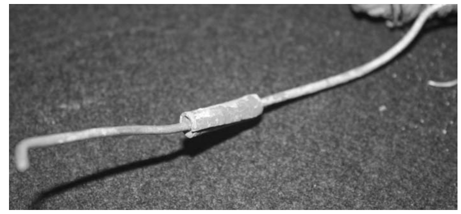

Fig. 6. Whisker weight that seems to have been added to statically balance the armature.

1.00 in.$(0.7+6\times 0.05)$ for three wire layers. This value is consistent with our assessment that there are three wraps of 0.05 in. diameter wire, that is, two wraps for the inner coil and one for the outer coil as shown in Fig. 4.

H. Moment of inertia

The mass, M, of the armature is 1025 g. If we assume the thin rod approximation and spinning about the center, the moment of inertia J should be $Ml^2/12$,[14] which gives $J=0.0061$ kg m^2. The error introduced by approximating the 0.70 in. diameter solid cylindrical core as thin is less than 20%.

I. Whisker weight

One of the whiskers has an appendage, which is rolled and soldered metal. We think that this appendage is an added weight to statically balance the armature. The armature seems to be well balanced (Fig. 6).

J. Bar magnet

The horizontal bar magnet is made of a hard ferromagnetic material and is 0.95 in.$\times$0.95 in.$\times$20 in. The bar magnet is considerably longer than the 10.88 in. armature (see Fig. 7). Also shown for comparison is the armature laying on its back. The magnet is end polarized, with the striped end being north. The residual pole field strength was measured to be about 23 G. The polarization of the bar magnet was checked with a compass that was slowly circulated about it. The compass needle rotated as we would expect for a simple dipole magnet with the compass needle being parallel to the bar's long axis when it was at the half-way point between the two magnet ends. The poles of the bar magnet were clearly seen to be opposite and the pole strengths as measured with the magnetic field probe were about equal. We conclude that the bar magnet is a simple dipole and is end polarized.

Fig. 7. Horizontal bar magnet with white stripe marking the north pole. The armature is shown for comparison and illustrates its much shorter length.

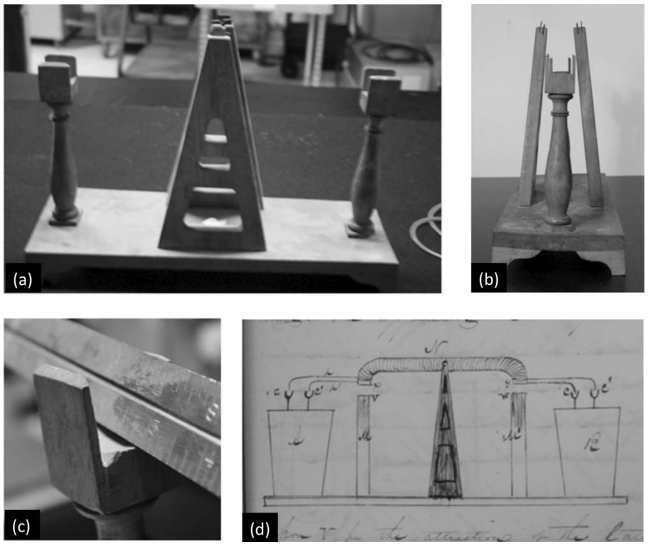

Fig. 8. Stand that supports the rocking armature: (a) front view; (b) side view; (c) wooden support for holding magnet; and (d) 1842 sketch from a student notebook showing the A frame.

K. Stand, pivot bearings, and magnet supports

The shape of the support for the rocking-beam armature is a truncated wooden pyramid made of two A-frame sides (see Fig. 8). The A frames lean inward with an internal angle of about 85°. At the top of the A frames are slotted metal plates to act as pivot bearings. The shape of the slots is between the letters U and V. There are also solid metal back-up plates on each side to keep the armature centered. The pivot back-up plate is 0.5 in. × 0.5 in. × 0.035 in. The bearing plate is 0.875 in. × 0.5 in. × 0.055 in.

The A frame is 4.13 in. at its base and 0.63 in. thick. The internal separation between A frames at the base is 2.87 in. and the internal separation at the top is 1.38 in. The armature's central axis is 8.9 in. above the base plate. The design is stable and allows the armature to rock with little friction. The A frame first appears in a student notebook in 1842.[15] The student's sketch is given in Fig. 8(d) and shows the 1831 motor configuration with a bent armature and vertical field magnets.

We note the elegant structure that Henry created. It is simple, functional, stable, and well proportioned. It has no unnecessary parts and its components are well integrated. Henry once worked as a civil engineer and as a watchmaker's apprentice. At Princeton College he taught a course in architecture, as well as one in natural philosophy. His talent for structures and aesthetics shows in this design. Even the wooden structures that support the magnet to the left and right of the A frame are artistic and functional.

As part of our examination of the stand, we removed the bar magnet and discovered that the internal supporting surface of each of the wooden magnet holders was rounded. The rounding is seen relative to a metal scale in Fig. 8(c). The rounding would not be necessary if a flat bar magnet was the one intended. Instead, the rounded supporting surface suggests two curved magnets were to be cradled. This discovery led us to learn about Henry's suggested motor modifications. Prior to this observation, the focus of our study was to make

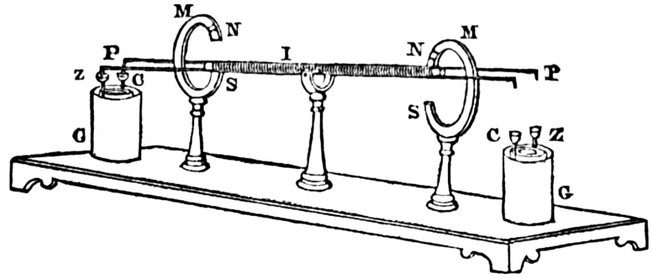

Fig. 9. Vibrating motor figure in a 1835 textbook on natural philosophy (Ref. 16), following a sketch provided by Henry.

sense of the motor's operation. Once we saw the curved surfaces we began to doubt seriously whether the long bar magnet was correct.

A search of the literature first revealed Henry's letter in 1834 to his friend and colleague, Green,[6] then a notebook entry of an electromagnetic engine by a student in 1845,[7] and finally a description in 1835 of the vibrating motor in a textbook on natural philosophy.[16] All three sources described motors using curved field magnets. The curved magnets are specified as having the same pole at the lower elevation and the opposite pole at the upper elevation. In the sketch from the textbook (Fig. 9), the poles in the lower position are both south. As noted in a footnote, the figure was based on a drawing provided to the book editors by Henry in 1835.

IV. C-SHAPED ELECTROMAGNET FOUND

We failed to find C-shaped permanent magnets at Princeton, at the Smithsonian, at the Jefferson Medical College (where Henry's colleague, Green, was a Professor of Chemistry), and at the American Philosophical Society in Philadelphia. However, we did come across an electromagnet of the correct shape in the Princeton collection. This electromagnet fits the wooden holders in the Princeton motor stand very well and is the correct size, and its construction closely matches the armature. When in position, the two poles of the C-shaped electromagnet are near the pole of the armature end. The armature is also free to swing over a reasonably large range of angles. The wire in the coil of this C-shaped electromagnet is similar to the wire in the Princeton motor.

The C-shaped electromagnet has a double wrap that starts at one pole, proceeds to the other pole, where an insulating layer of silk is used and the pitch reverses, but continues to wrap in the same circulating direction back to the starting point. Each end is equipped with thimbles for mercury contacts with a battery. The ends of the C-shaped magnet are colored black and green in the same manner as the Princeton motor armature. The motor with this C-shaped electromagnet is shown in Fig. 10 and a sketch from his 1834 letter[6] to Green is shown in Fig. 11. A second nearly-identical electromagnet has been located at the American Museum of Radio and Electricity in Bellingham, Washington. Purchased from a private dealer, its provenance is unknown.

V. OTHER POSSIBLE INTERPRETATIONS

We started these measurements to learn how the Princeton motor could have worked with a long horizontal bar magnet.

Fig. 10. Princeton motor with the C-shaped electromagnet. Note the proximity of the poles of the armature and the poles of the electromagnet. Note also the wide range of angles possible if the armature was rocking.

We found nothing to help us and concluded that the horizontal magnet was an error. Nevertheless, it is useful to ponder other possibilities.

What if the Princeton motor was not based on pole reversal but instead on pole interruption? We can consider the field arrangement that we would have with the questionable horizontal end-polarized magnet, that is, north at the left and south at the right. In this hypothetical pole-interrupted case, the batteries would be arranged so that the electromagnetic armature when energized by dipping either left or right would have the same pole alignment as in the horizontal bar magnet, that is, north at the left and south at the right. All forces on the armature when dipping left or right would be due to pole repulsion only. Because pole repulsion increases inversely with the distance squared, the closest poles would primarily determine the net torque. When dipping right, the dominate repulsion would be south-south. When dipping left the dominate repulsion would be north-north. The equilibrium position would be horizontal. As soon as the closest poles separated enough so that the whiskers lifted out of the mercury cups, the electromagnetic armature would become unpolarized and would coast to the other side. As the armature dips on the other side, it would again become polarized with the same polarization as before, closest pole repulsion again would dominate and kick the armature back, and so on. Because oscillations would be based on pole repulsion only, the net torque would be less than the pole-reversed case where both repulsion and attraction contribute to the motion.

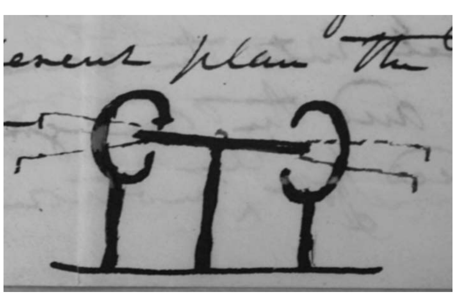

Fig. 11. Henry sketch of motor with C-shaped permanent magnets from his letter to Green in 1834 (Ref. 6).

We think that this field arrangement was never considered by Henry, but it is possible and it could be used to explain the horizontal magnet.

What if the horizontal magnet was polarized differently? Perhaps it could have been polarized so that its top surface was north and its bottom surface was south. This polarization is possible, although achieving large pole strength would be difficult. It could explain the excessively long length of the horizontal bar. However, the horizontal magnet has the characteristic stripe that Henry was known to have used to mark the north end. The presence of the stripe and the fact that our measurements show that the existing bar magnet is end polarized makes this possibility highly unlikely.

What if the armature was wound differently? Sherman suggested this possibility some years ago.[12,17] A different armature winding, with like poles at the two ends and unlike poles at the middle, could work using pole reversal. There are entries in student notebooks from Henry's classes about electromagnets with such windings. However, our tests show that the Princeton motor armature is not wound this way. Thus, the wealth of evidence leads us to conclude that the horizontal magnet is wrong and the correct configuration involves two C-shaped field magnets. In summary, our conclusions include the following:

(1) The horizontal magnet is end polarized and hence will not produce oscillation with a simply wound pole-reversed armature.
(2) The wooden supports for the field magnet are curved upward and these surfaces would cradle curved magnets.
(3) C-shaped magnets are described for a motor that was under construction by Henry when he wrote to Green in 1834.[6]
(4) C-shaped magnets are described for a working vibrating motor in a natural philosophy textbook.[16] A drawing incorporating these C-shaped magnets was provided by Henry.
(5) C-shaped magnets are described by a student from a Henry lecture at Princeton in 1845.[7]
(6) C-shaped magnets oriented with common poles at the same elevation will produce oscillations when used with a horizontal pole-reversed armature.
(7) The poles are too far from one another. The horizontal end-polarized bar magnet is 20 in. long and the armature is only about 11 in. long. The poles of the electromagnet are so far from the poles of the long horizontal field magnet that forces of attraction or repulsion would be quite small.
(8) C-shaped electromagnets of the correct size and shape to work with the Princeton motor have been located and are constructed in a manner that is very similar to the armature.

VI. A QUANTITATIVE ANALYSIS OF THE HENRY VIBRATING MOTOR

A. Instant armature polarization

Consider a mechanical model in which the armature is instantly polarized when current is applied and is instantly depolarized when current is removed. (This behavior follows Henry's assertion that polarization and depolarization of the armature are immediate.) We solve Newton's equation of motion,

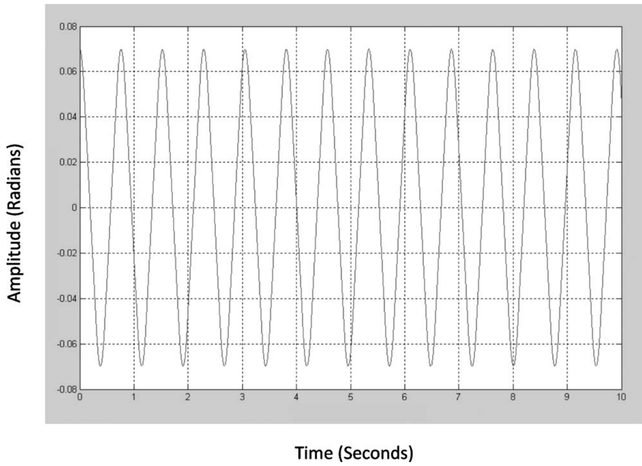

Fig. 12. Graph of armature angle versus time showing the oscillations according to a simple mechanical model of the motor.

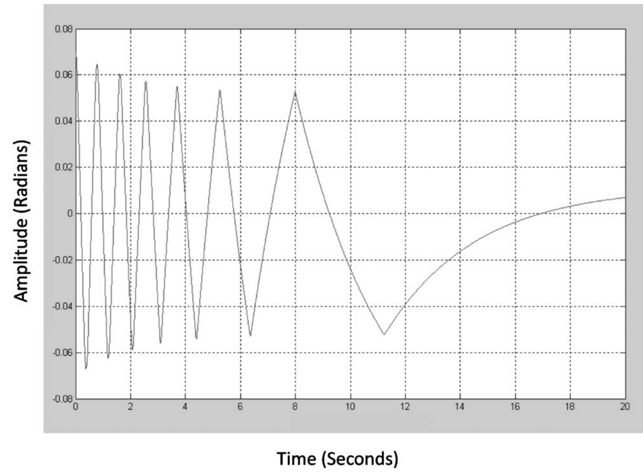

Fig. 13. Graph of armature angle versus time when started at a large angle for the case where friction is added to the simple model. Note that the armature rocks only for a short time before slowing to a stop.

$$\frac{d^2\Theta}{dt^2} = \frac{T}{J}, \qquad (1)$$

where J is the moment of inertia of the armature and Θ is the armature angle. The armature angle is zero when it is horizontal and T is the external torque. We assume that the torque is the result of magnetic attraction and repulsion of poles. For the purpose of illustration, consider the condition that when $\Theta \geq 3°$, T/J instantly becomes negative with a magnitude of -6 N/m kg. A value of 3° is a plausible but arbitrary estimate of the angle that corresponds to the whiskers just making contact with the right battery (including factors such as whisker length and thimble depth). The value -6 N/m kg for the torque is also arbitrary and is chosen so that the rocking frequency is about 75/min. A value of $T/J=-6$ means that $T \approx 0.037$ N m. This magnitude is reasonable for the torque given the pole strengths that we measured. We use the moment of inertia of the armature, $J=0.0061$ kg m^2, estimated in Sec. III H. We assume that the restoring torque is independent of angle and is applied instantaneously as soon as the rocking angle threshold is reached. If $\Theta \leq -3°$, T/J instantly becomes positive and has a magnitude of 6 N/m kg. This torque stops the rotation to the left and serves to reflect the armature back to the right side. When $-3 \leq \Theta \leq 3°$, T/J is assumed to be zero. We assume also that the system is conservative (no energy loss due to friction) and is linear. The linearity assumption is not exact, but the small error introduced by this assumption does not change the nature of these solutions. For the linear case, the dynamics are solved analytically but piecewise as battery connections are made and broken. When the batteries are disconnected and the armature is coasting, the angle increases or decreases linearly in time. When the batteries are connected, the angle is reflected following a parabolic trajectory in time. This solution to the linear model for the motion of the beam is shown in Fig. 12.

The model shows that oscillations continue indefinitely. However, if linear friction is added, the amplitude decreases in time and eventually stops. Figure 13 shows this behavior when a $0.3 d\Theta/dt$ damping term is added to $d^2\Theta/dt^2$ on the left-hand side of Eq. (1). Henry's motors did not slow down and stop—something more is needed to compensate for energy loss.

To help understand the effects of friction further, we tested our replica of the 1831 motor (see Fig. 14). The replica can be started in the extreme right rotated position. In this case, the motor armature just rocks back and forth indefinitely with a large angular swing. The replica armature can be started at a small tilt angle that just barely makes contact with the battery brushes. The motor armature starts slowly and then picks up speed and amplitude. The ability to oscillate more strongly cannot be understood with the simple model.

B. Electrical factors considered

We assume that the armature has inductance, resistance, and capacity to generate voltage as a back emf. All of these properties are known to be important in permanent magnet dc motors.[18] The equation for the motor becomes

$$L\frac{dI}{dt} + IR + V_{\text{emf}} + V(t) = 0, \qquad (2)$$

where $V_{\text{emf}}=-kd\Theta/dt$ and k is a constant which depends on the pole strength of the field magnet, the length of the wire that cuts magnetic field lines, the number of turns, and the geometry. Here $V(t)$ is the voltage supplied by a battery with a polarity that is determined by the rocking angle Θ. If Θ is between the limiting angles of battery contact, the $V(t)$ term is absent. When $V(t)$ is absent, the electrical circuit is not complete. To complete the circuit we replace the $V(t)$ term in

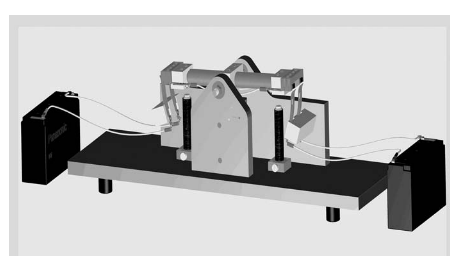

Fig. 14. Replica of the 1831 motor using brush-type contacts instead of mercury-filled cups constructed to test motor dynamics.

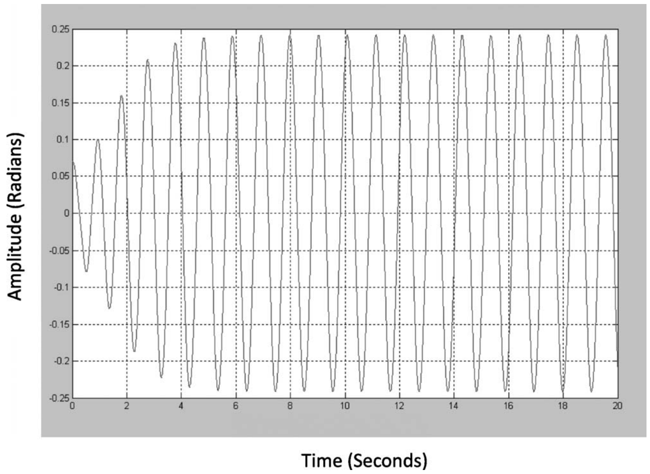

Fig. 15. Graph of armature angle versus time according to the improved motor model, showing the ability to speed up and increase its amplitude.

Eq. (2) with a resistive load term IR_L that models $V(t)$ as a sink rather than a source. R_L is arbitrarily taken to be 1000 Ω. This load allows the voltage across the inductor to return to zero. To analyze the motor dynamics we note that the torque T that appears in Eq. (1) is proportional to the current I. We will use the same constant of proportionality as the back emf, that is, $T=kI$. We thus have a coupled set of equations to solve, one mechanical and one electrical. The solution for the armature angle versus time is solved by numerically integrating the coupled equations (using the ODE45 function in MATLAB). The solution is shown in Fig. 15.

With this improved model we match the curious observation of the replica motor speeding up and the amplitude rising when started from a small angle. We also find that the motor will continue to oscillate in the presence of linear friction. We see that the back emf term is needed for the motor to reach a steady-state amplitude. If the back emf term was omitted, the motor speed and amplitude would increase without bound.

We now understand the motor in much greater depth. The motor armature receives a kick on each oscillation. After contact is made with the battery, the armature pole strength rises over a short time interval on the order of L/R. The work done on the armature is the force of repulsion times a distance. It takes work to stop the armature, and it takes work to increase it. The average repulsive force on the stopping stroke is lower than the average repulsive force on the boosting stroke. The stroke lengths are the same, and as a result, the work done on the boosting stroke is greater than the work done on the stopping stroke. The kick is the difference between the two. The boost on each oscillation here is analogous to the situation in mechanical clocks where a pendulum is kept in motion by a boost on each tick from the asymmetrical contact interaction between the verge and the escape wheel.

VII. CONCLUSIONS

We have argued that the horizontal bar magnet displayed in conjunction with the Princeton motor for more than 125 years is an error. There is evidence that instead of the horizontal magnet, two C-shaped field magnets were very likely used with the Princeton motor. We also showed that an electrical time lag due to inductance and resistance of the armature coil and internal resistance of the battery is essential to keep the motor oscillating when there is energy loss due to friction.

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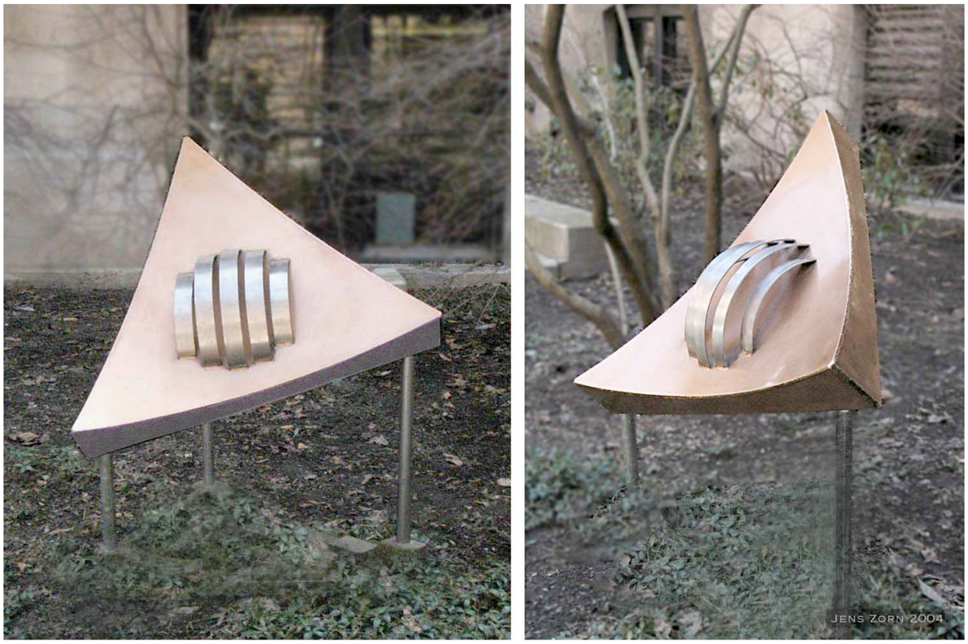

Quantum Tunneling In NH3 and the Origins of Microwave Spectroscopy

Ammonia, NH3, is a tetrahedral molecule in which a nitrogen atom is displaced from a plane defined by three hydrogen atoms. In 1932, David Dennison and George Uhlenbeck at the University of Michigan made the first quantitative prediction of tunneling phenomena: that the nitrogen atom would tunnel back and forth through the barrier at a rate of 23 GHz. In 1934, Michigan experimentalists Neil Williams and Claude Cleeton were able to see this transition in absorption of radiation generated by their magnetron oscillator; they were the first to use microwaves for spectroscopic measurements on atoms or molecules. In 1949, Harold Lyons, a Michigan graduate then at the National Bureau of Standards, used this narrow spectral line as the basis for the first atomic clock. In 1954, James Gordon, Herbert Zeiger and Charles Townes at Columbia University used this transition as the basis for the first demonstration of amplification by stimulation of emitted radiation, a process soon extended into the optical regime in the development of lasers.

This bronze and steel sculpture at the University of Michigan depicts the incipient passage of the nitrogen through the barrier presented by the plane of the hydrogen atoms. This sculpture was created by Jens Zorn, Professor of Physics at the University of Michigan.