# Connecting My Dots

While engaging online with a university professor about the computations involved in computing the forces produced by an iron cored electromagnet or solenoid, the question arose as to how the early engineers analyzed the magnetic circuits with any accuracy without the aid of computers and the attendant fea software. In particular, how was the non-linear relationship of H and B in iron integrated into the analysis? As the term "early" is relative it should be noted that the first U.S. patent for an iron core solenoid is around 1893[1] and the computational methods, if any, are unknown. My own early involvement began in the 1960's, still without computers. At that time I could have asked the same question but had no one to ask in spite of the determination to learn the secrets of magnetics. I have now concluded, after 55 years in the solenoid industry, that the early pioneers did not solve ferrous magnetic circuits with any great deal of accuracy and perhaps did not do so until much later when computers became available. The following is at least one engineer's path to solving this quest.

In a graduation commencement address Steve Jobs advised his listeners to "connect the dots", meaning to look at the past and see how events led to events that shaped the outcome of one's life's work. To graduating students this was a bit premature as he admits that they cannot look forward but only backward. He did not refer to the Psalms that promises that a good man's steps are ordered of the Lord. Nevertheless, the idea remains that one can connect the dots, as it were, to see how life has progressed to the present.

My dots include watching the power company at our house as a boy in the 1940's and seeing their mysterious test equipment, watching my uncle repair a radio with his electronic test equipment, and intrigued when given a burned out vacuum tube. My parents gave me a toy crane that raised and lowered a magnetic pickup that could be turned on and off from a flashlight battery and I learned the characteristics of residual magnetism from that little Marx toy crane. Still at a young age I sent off for a free catalog from Allied Radio Corp. in Chicago (which they continued for years), and saw the world of electronics by reading its pages, then buying a crystal radio from them and kits to make radios, amplifiers, and test equipment. My parents also gave me a book, The Radio Amateur's Handbook, which had schematics and instructions about ham radios and their circuits. And then an aunt found and gave me a newspaper ad for local radio technician classes (RETS) which I took for a year immediately out of high school. At church one evening an older friend described a "solenoid" product his company was making; it sounded like a place I would like to work. Previously, at school our 7th and 8th grade math teacher taught us advanced concepts of interpolation, imaginary numbers, and polar to Cartesian coordinate conversions, and the slide rule. My high school teacher, in addition to teaching algebra, geometry, and trigonometry taught us the fundamentals of calculus without ever mentioning the word calculus. I did not discover this until in college. I have to wonder how many students, percentage wise, benefited as much as I did from their teaching which later provided the key elements for not only the physics I later used but also mathematical modeling in differentials and impedance analysis of RLC circuits in polar and rectangular coordinate systems.

Just before college I applied at that solenoid company and got a job in the machine shop at age 18 in 1960 and then small order assembly with the goal of going into engineering. The solenoids we were assembling were the same basic construction that was on my toy crane and I immediately recognized how they functioned. At college I anticipated taking physics which would include the subject of magnetics. Here I apparently asked some difficult questions and the instructor quietly told me that I should be teaching the class instead of him. In about this same time period I also took a home study course from Cleveland Institute of Electronics which had excellent material in math (exponential notation) and motors and electronic circuit design. It guaranteed, after completion, the ability to pass

[1] I. A. Timmis; U.S. Patent 506,282

the FCC license test for commercial radio operators. I completed this one-year course in about 8 months.

At work one day, still in small order assembly, an engineer came into my department to see why a dielectric tester was shocking some users. I showed him the offending tester and suggested that maybe it just needed an isolation transformer. He was surprised which led to a short conversation about my interests and hopes of going into engineering. He said that when the opportunity came he would put in a good word. The opportunity soon came and I was tested and selected over other applicants, yet without a college degree. As an assistant engineer I was paired up with a mechanical engineer. The company then had no electronics products except the manufacturing of selenium rectifiers, soon to be obsoleted by silicon diodes. We had no electronic calculators; computers were scarcely found only in universities and corporate administrative services, and calculations were largely done by slide rule or manually. But technology was now rapidly on the move. We obtained the early 4-function calculators causing the slide rules to disappear virtually over night. I encouraged my engineer to accept a black box project for Boeing Aircraft that would require electrical (emi) interference filters, which we did, and was the first step in moving our products forward in technology. Then came the Mariner IV camera shutter solenoid, Surveyor stepping motor for on-the-moon antenna orientation, and Apollo docking solenoids. At college I negotiated with my computer instructor to allow me to take advanced Basic programming instead of the routine mix of Fortran and Basic. And suddenly in 1982 the early Commodore computers, hard wired for Basic, appeared in our local K-Mart store and I immediately bought one. I started programming for routine coil calculations at work which resulted in the startup of procuring engineering computers in our company.

Along with learning about and designing electronics which had been my main focus since childhood, it became apparent that no one in engineering knew how to mathematically design a work solenoid from scratch to fit a specified size, power level and force & stroke envelope nor even how to accurately measure the inductance of an iron core inductor. This was because iron core devices typically run at a 60 Hz. frequency instead of the 1000 Hz. inductance bridge frequency. Also there were the many facets of magnetic design that needed to be understood. Whether our predecessors had labored in the magnetics when starting the company is unknown but it is equally likely that they picked the recognized NEMA motor sizes as a starting point, made solenoid models (both axial and rotary), tested and documented their performance and those became the market selections. Naturally, design decisions were necessary to produce their noted efficiency. But in the 1930's and 40's there was no assistance from a computer or software to do the tedious repetitive mathematics required to design from scratch and only approximate calculations could be made manually.

When I set about to figure out magnetic design sometime in the 1970's, there were no engineering computers, no commercial software to design the coils, no BH equations to ease the effort of equating the solenoid steel's flux density with its reluctances (for each component), much less even the recognition that it needed to be done. This overall effort became my private challenge. I dabbled with the known equations at that time and slowly began to understand their roles. Our company president had the same sense that a solenoid company needed a documented procedure for producing predictable magnetic designs and hired a Ph.D to do the research and show proof. After three months the consultant admitted failure and left. I soon found that to relate the iron's B and H I had to consult a graph many times just to get into the ballpark for a reasonable flux level. This was very tedious and time consuming and would not be suitable for a computerized routine. I would need an equation of the appropriate steel to compute the steel magnetizations (H) after calculating the flux density (B) for each steel component. The B&H relationship is highly non-linear and different for each steel alloy. Only BH graphs were available but no equations were to be found (of course)[2] but are essential for computerized calculations.

[2] The Feynman Lectures on Physics, Vol.II, 1964 - p. 36-7 "Now all we need is an equation which relates H to B. But there isn't any such equation." P. 36-10 "We still have two unknowns. To find B & H we need another relationship - namely the one which relates B to H in

Besides, my computer had very limited memory and would not tolerate even a rudimentary lookup table. Thus I developed my own curve fitted algebraic equations shortly after acquiring that first computer which allowed computing for any flux density from zero up to magnetic saturation of the steel. Prior to this I had already made a coil winding program that sized the magnet wire in terms of its awg number and the number of turns and resistance based on the bobbin dimensions. My major hurdle was just how to predict the solenoid force when even the flux level was an unknown for a given solenoid size and coil power level. Flux level and output force are interdependent; one dictates the other, a classic problem having two unknowns that must be solved simultaneously. Finally it dawned on me that just as an electrical circuit of series resistors has the same current thru each resistor, in a solenoid the flux level is the same thru each steel component, being in series in a loop. Then by (mathematically, in a computer program) beginning the calculations with an arbitrary flux level, finding the flux density for each component and computing H from my equation, the total ampere turns of the loop components can be found (also termed as losses). Now, having previously established the coil's ampere turns at some fixed power level, the total ampere turns in the steel (losses) and across the air gaps can be compared to the ampere turns in the coil and the flux adjusted (reiterated) within the program until the two values converge. The convergence identifies the true flux for the model and the force is then computed by equating the flux energy in the working air gap to its equivalent work energy (force x distance).

I used this technique over a number of years for old and new products and meanwhile the computer software industry was hard at work doing what I had done; writing commercial software for producing BH identities, not from equations, but from tables of data points and by interpolation[3] and then to do the magnetic calculations by means of the new Finite Element Analysis (contrasted to my macro element method).

When industrial companies and universities could afford to purchase the computers and commercial software for designing electromagnets of every variety (solenoids, motors, transformers, chokes, etc.) the students and users no longer were exposed to the details of equating H vs. B or of computing the design; i.e., setting an arbitrary flux starting point, computing the coil parameters, understanding the role of convergence of the dependent and independent mmf levels, etc. They didn't need to because all was done within the software.  Therefore, in a very short window of time the understanding of the designers of solenoids and motors who followed using programmed commercial tools were separate from their predecessors who had tediously dealt with BH relationships and the manual convergence of the mmf parameters. As fea software became predominate many or most university students "learned" magnetics via commercial fea programs in the classroom without experiencing the attendant non-linear BH foundations and mmf convergences.  As time inevitably passed, fewer individuals appreciated the earlier practices although the knowledge is retained in the fea software and used with great benefit for designers and their employers.  Many of those students who later became university teachers and professors themselves either overlooked these details or later had to catch up to understand what the software was doing. Some went on (quite naturally) to write articles on some aspect of magnetics which were published without question because of their educational status but were incomplete by the absence of what they did not know. Their writings, couched in Maxwell's and Faraday's equations, which they repeated in their writings, did little to enlighten the many who desired to understand the logical progression of a start to finish analytical process unique to iron cored devices.

With the onset of computers at engineer's desks much progress was made immediately and from then on. But for the engineer who, early on, could write software, no longer was it necessary to consult tables and charts of physics for moments of inertia, mass, battery life and thousands of things

the iron."

[3] How the B-H Curve Affects a Magnetic Analysis; Lipeng Liu; 2019 - " Multiphysics usually uses an interpolation function with a local table to define the B-H curve."

mechanical, electrical, and dynamic; and no longer did he have to manually calculate complex physics in many circumstances for variables that could be programmed. Little did I know that what I was doing in the early 1980's and onward was in parallel with the technology upswing across the country. Nor did my employer, at that moment, who compensated and promoted me beyond my expectations. It was one of those opportune periods when change was possible, rapid, largely unexpected and detrimental only to those who did not grasp what was occurring or did not have the resources to benefit. For them progress had to await the development of commercial software. What were the benefits? Industry, as a competitor, depended largely on prior product knowledge along with the slow development of new products being manually computed, put to paper, developed in a model shop, tested, and eventually approved for production. Development and testing were the key and a number of iterations were likely until the product met approval. The early computer-aided designs, on the other hand, integrated (read calculus) ohm's law, newton's laws, physics, trigonometry and algebra and disclosed early any deficiencies in dynamic performance, energy distribution, weight, cost, and manufacturability before incurring the costs of the first physical model and its associated testing. This was the competitive advantage.

Again, referring to the early engineering pioneers; they did not have the instrumentation necessary to accurately produce the test data for the iron's B and H characteristics. They had no curve fitting software for any data they may have had. And no computers to do the numerous and tedious convergence steps to solve for the circuit flux. Perhaps they did not even have a need to predict with any great accuracy a solenoid's force profile at that early stage. Here we can appreciate Newton's tribute of standing on the shoulders of giants. My experiences were unique only to myself but probably in common with many others. Nevertheless, they were challenging and enjoyable throughout.

All of the above circumstances, along with others, were my dots that fulfilled some childhood want, even expectancy, to experience and contribute to things technical. These were the biblical desires of the heart, fulfilled as promised, inserted into a niche of time that encompassed the space race, the electronics revolution, computerization, and in a company poised for a boost in technology.