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The Sound of Modern Design

Introduction to Transducer Motor Design

Richard Little

Director of Advanced Design

Tymphany HK Ltd.

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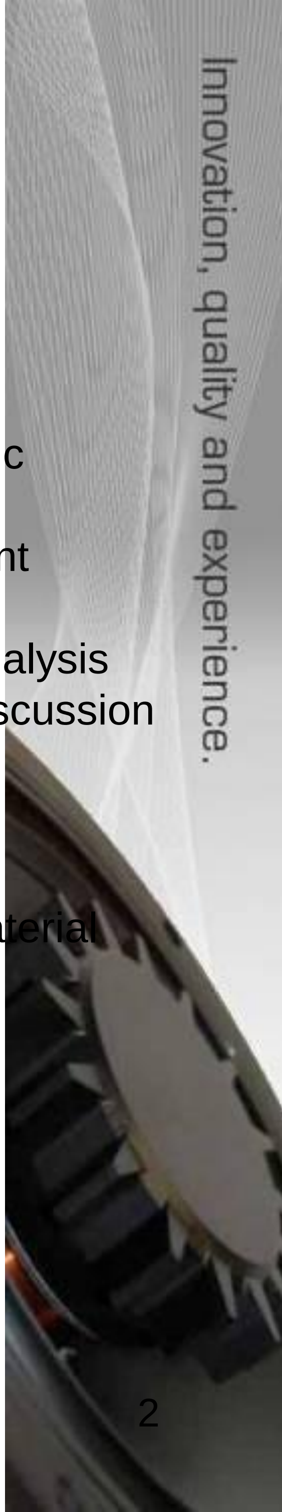
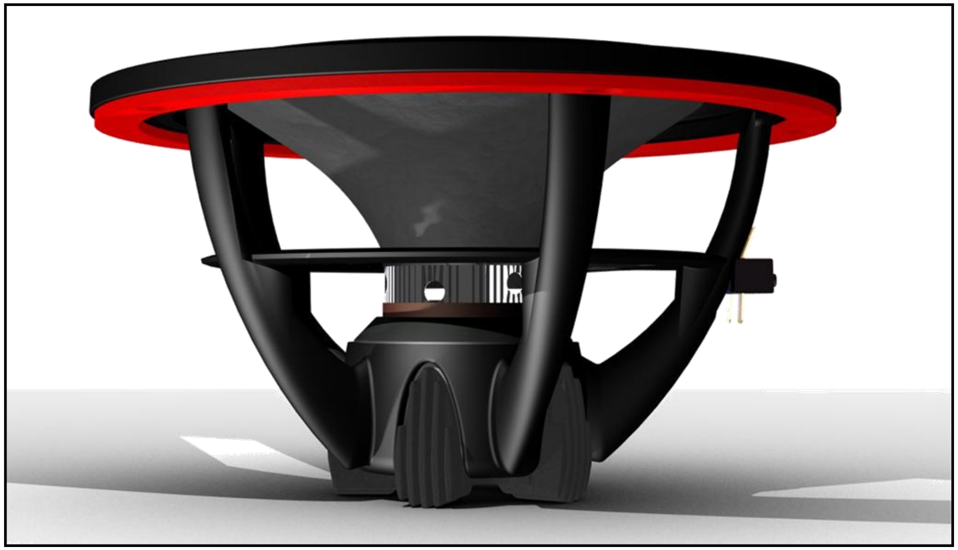


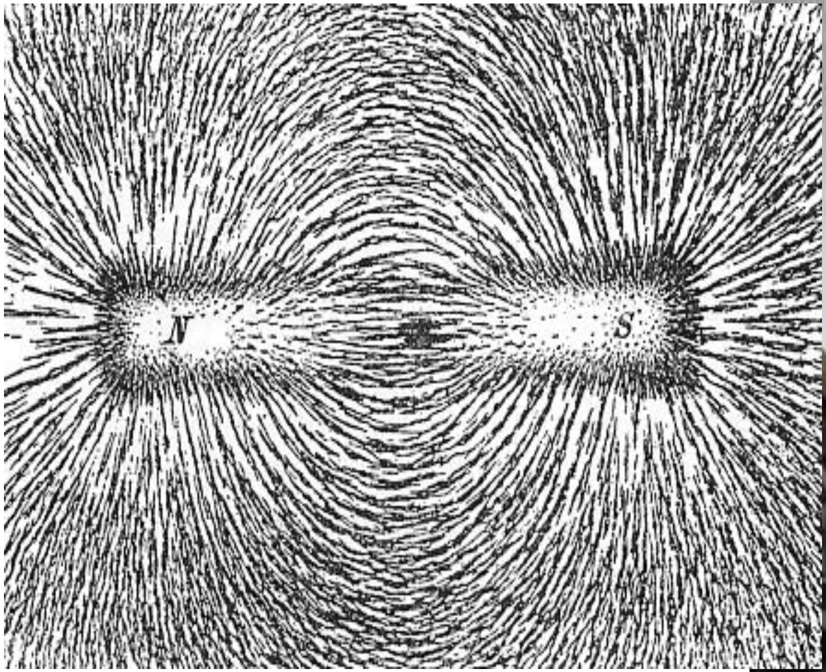
Introduction

- Transducer motors play the role in the transducer, to transform an electrical signal input into the transducer, into a mechanical force which drives the transducer's diaphragm and creates the outgoing pressure wave.
- In today's world, the components of a transducer motor tend to be the most costly.
- Therefore, it's of great benefit to understand transducer motor design principles and processes, so as to be more effective in designing the motors.



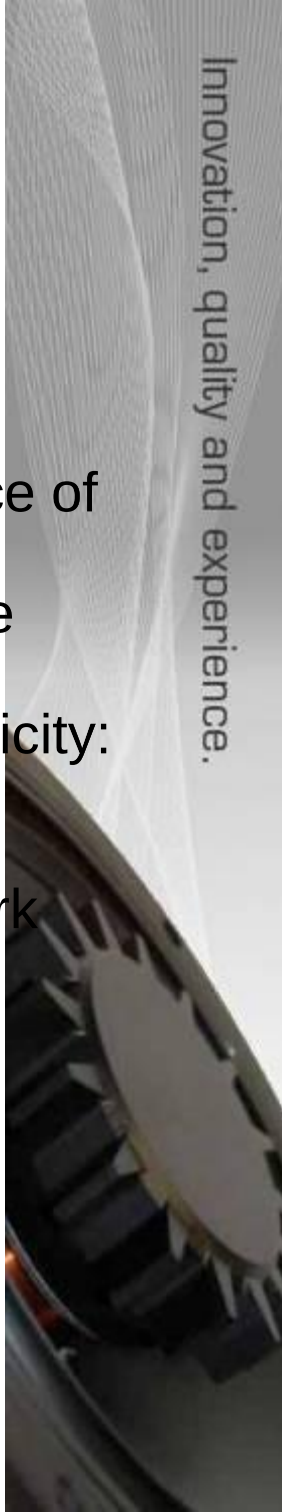
Magnetics history

- In ancient times, the phenomenon of “magnetism” came from the properties of “lodestones” and magnetite, being natural magnets composed of iron-rich ore.
- These magnets were used to make compasses. Compasses were invented in China, and dates back to the beginning of the first millennium AD. Such compasses eventually aided or supplanted celestial navigation.



Magnetics history (2)

- In 1820, Hans Christian Oersted, a professor at Copenhagen University, noted and reported an experimental finding, that the direction in which a compass pointed is affected by the presence of an electric current.
- Andre Marie Ampere then went on to demonstrate more linkage between current and magnetism, later that same year.
- Thus, we had at that time two separate forces linked with electricity: the electric force, and the magnetic force.
- Michael Faraday then went on to derive rules relating changing electric and magnetic fields, in experimental and theoretical work throughout the mid-1800s.

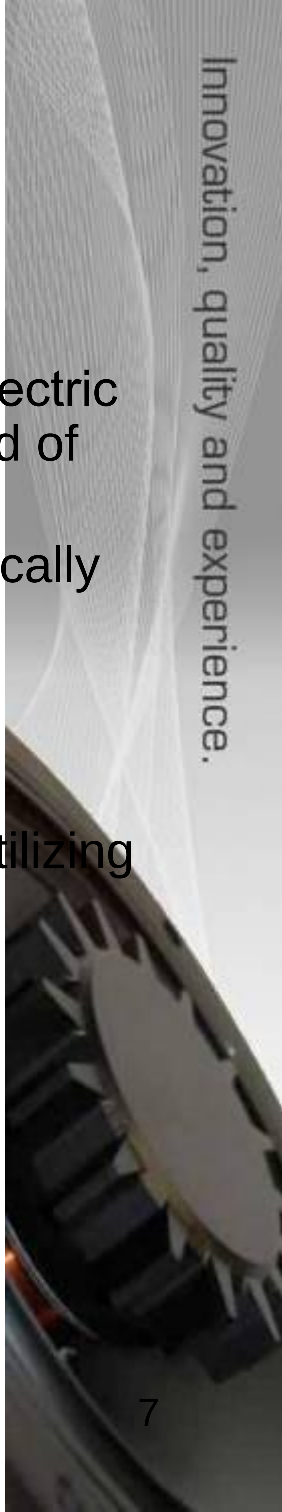


Magnetics history (3)

- It fell to James Clerk Maxwell, in 1864, to more properly link the two forces together, into one complete picture of electromagnetism. The picture included the result that disturbances in the electromagnetic field travel at the speed of light. This complete picture is known as Maxwell’s equations.
- In 1885, Heinrich Hertz verifies experimentally that Maxwell’s theory is correct, observing electromagnetic waves.

Magnetics history (4)

- Einstein’s 1905 theory of special relativity highlighted the linkage of electric and magnetic fields, as a result of the absolute constancy of the speed of light.
- In more modern times, magnetic materials have been studied theoretically and experimentally, allowing for the development of materials models (drawing upon the mathematics of statistical mechanics) for magnetic materials, and also allowing for the development of strong magnetic materials.
- Also, in modern times, the moving coil loudspeaker was developed, utilizing permanent magnet materials.



Magnetics relationships

- Magnetic fields are produced by electric currents. These magnetic fields can affect materials near the original current.
- Solid state magnetics is the study of permanent and non-permanent magnetization of materials (“magnetic materials”).
- Permanent magnet materials can remain magnetized in the absence of an external magnetic field. In other words, they generate their own internal magnetic fields, once magnetized.
- The governing equations for the fields inside a permanent magnet are described below:

$$B = \mu_0 (H + M)$$

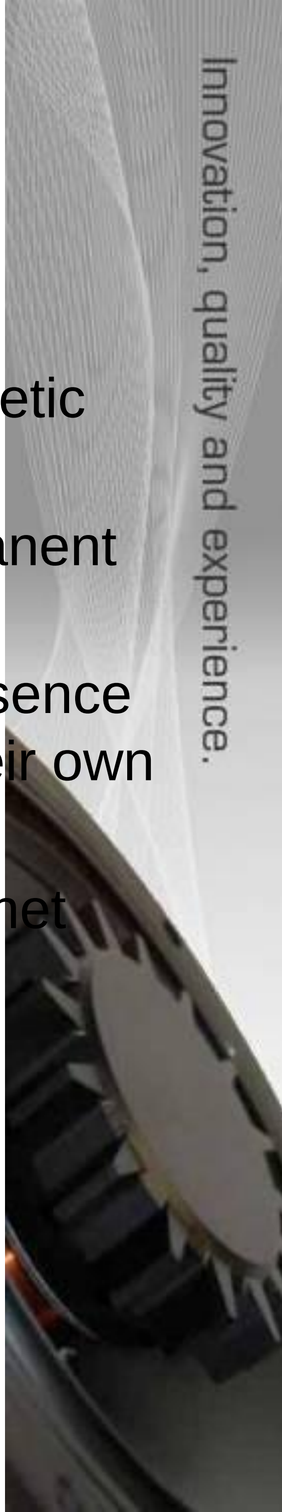
General case

$$B = \mu_0 H$$

Free space

$$B = \mu H$$

Isotropic linear magnetic medium



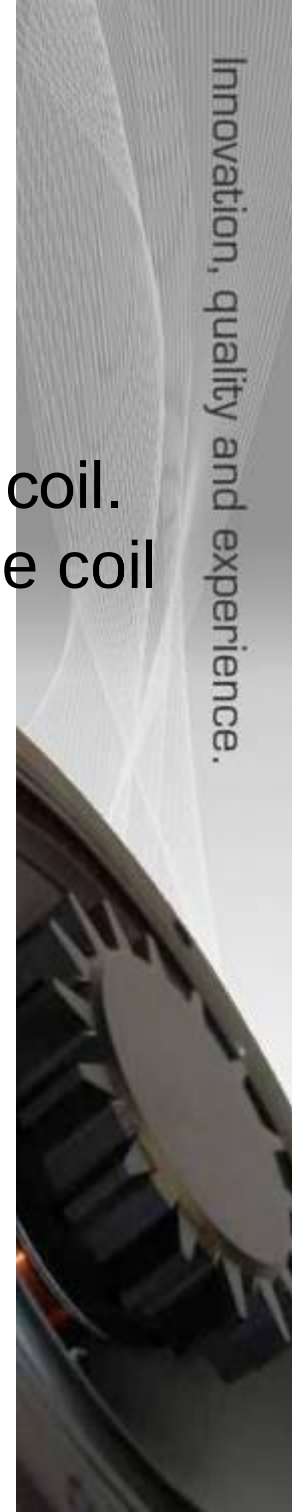
Magnetic relationships (2)

- H is called the *magnetic field strength*.
  - We tend to use H to designate the “driving magnetic influence” from externally applied currents (and internal currents). In other words, H is produced by currents.
- We call M the *magnetization* of the material in question.
  - The essence of what’s being conveyed by M, is a quantification of how strongly the magnetic material is self-magnetized. Self-magnetization can be thought of as a self-generated reinforcement of the externally applied field.
- We call B the *magnetic flux density*, or the *magnetic induction*.
  - B is the quantity which acts on currents immersed in a magnetic field.

Magnetic Relationships (3)

- Typical transducer designs operate by virtue of the magnetic field “delivered” to the location of the voice coil. When a current is run through the voice coil, the voice coil experiences a force acting upon it, according to the Lorentz force law:

$$F = (BL)I$$



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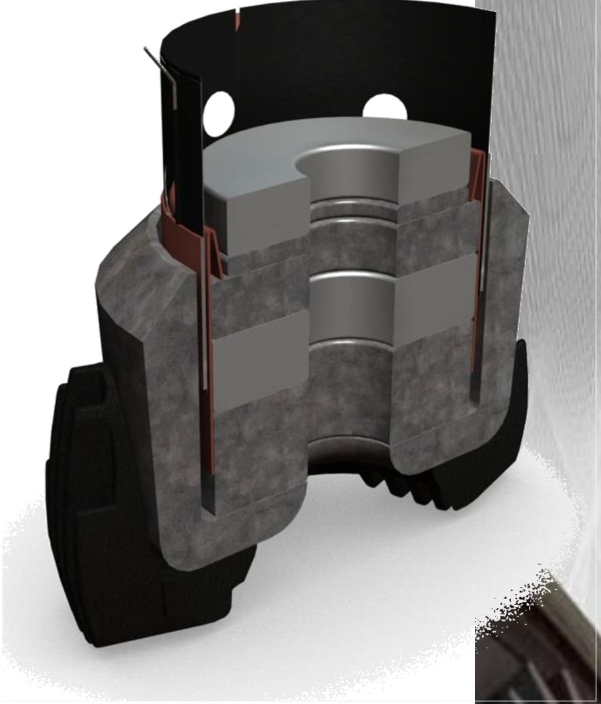
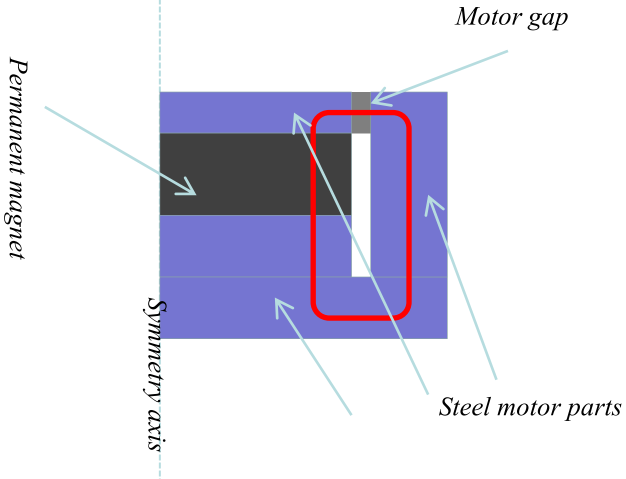
Basic Transducer Function

- Typical moving voice coil transducers operate by benefit of the Lorentz force law. The motor is constructed with a voice coil (essentially an inductor) placed inside it (in a location known as the motor gap). The motor delivers constant magnetic field levels to the position of the voice coil, in an orientation perpendicular to the current flowing through the coil. When the current does flow, a force results which moved the coil up and down.
- Typical transducer motor parts:
  - Voice coil
  - Permanent magnet(s)
  - Top plate (steel)
  - U-yoke or t-yoke (steel)
  - Copper cap or shorting ring





Basic Transducer Function (2)

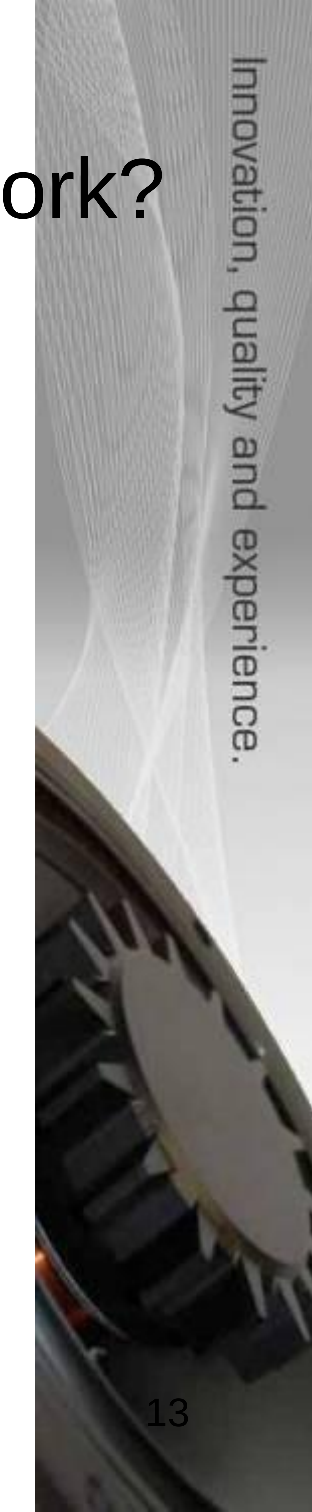
- The motor force factor BL (the coefficient of current in the Lorentz force law) is a function of motor and coil design, and is particular to each design.
- Transducer efficiency is related to the coil resistance and motor force factor through a well-known equation:

$$\eta_0 = \left(\frac{\rho_0}{2\pi c}\right)\left(\frac{(Bl)^2 S_D^2}{R_E M_{MS}{}^2}\right)$$

- The BL factor and coil resistance Re are key factors in motor design, as a part of overall transducer design and function.

Permanent Magnetization – how does it work?

- Permanent Magnetization – How does it work?
    - Permanent magnet materials
    - Magnetic domains
    - The magnetization process
    - Permanent magnet material properties



Permanent Magnetization – materials

- Typical permanent magnet materials:
  - Ferrite
  - Neodymium-iron-boron
  - Samarium cobalt
  - Alnico
- Each of these permanent magnet materials has its own particular chemical structure. They all result in material structures which produce permanent magnetization following exposure to an external magnetic field.

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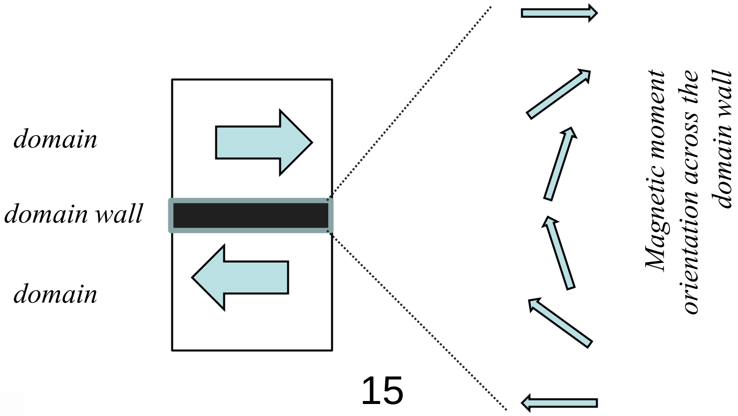
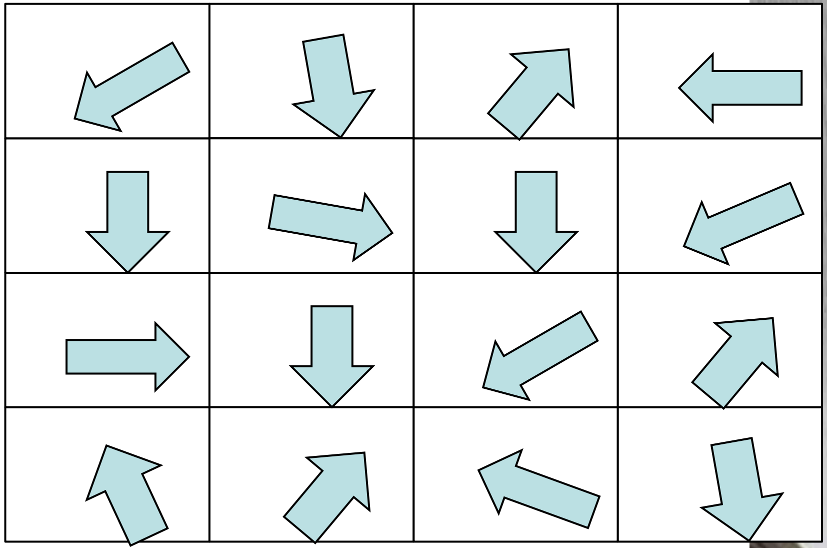
Permanent Magnetization – magnetic domains

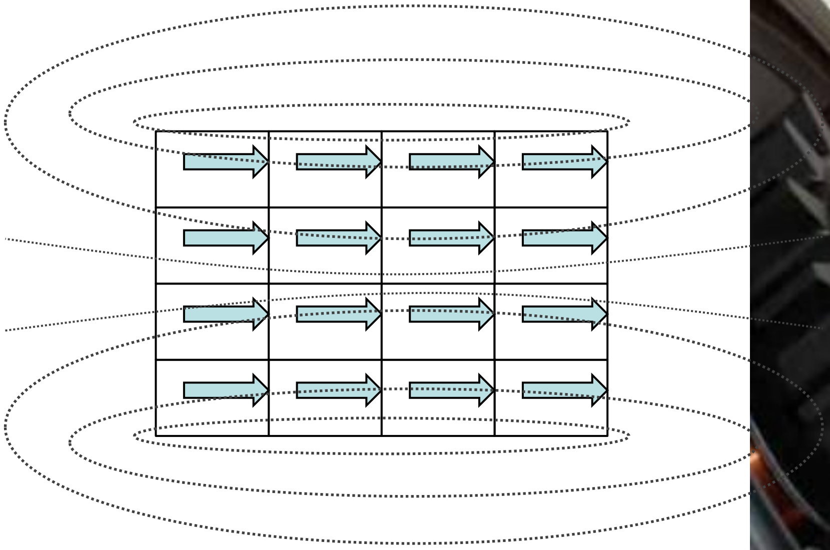
- For each of these magnetic materials, at a microscopic level the materials are organized into "domains". In a domain, the material's chemical lattice structure is organized so that there is a net current circulating on the surface of the domain.
- Because there is a net current circulating within each domain, each domain therefore has its own internally-generated magnetic field.
- At the junction between domains, domain walls represent a structural transition between two regions which have differing magnetic field orientations. This is illustrated in the following figure.



Permanent Magnetization – the magnetization process

- Through an application of the external magnetic field, the bound currents in each domain are re-aligned in a common direction.
- This sounds simple enough, but at a microscopic level this implies changes are going on in the crystalline structure of the material, with some domains growing, others shrinking, and so on. The domain walls move in a non-continuous fashion, moving between what are called "pinning sites".





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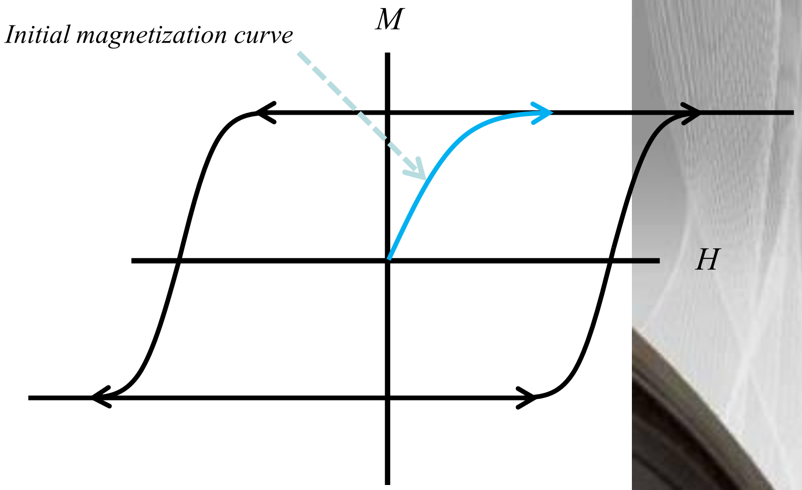
Permanent Magnetization – the magnetization process (2)

- Why does a permanent magnet stay magnetized?
  - The domain walls don't easily move back to their original locations—they tend to stay pinned at their pinning sites.
  - The magnetic field produced by each domain acts to reinforce the orientations of the other domains.
- So, we end up with hysteresis. The magnet stays oriented in one direction until such time as a large enough external field is applied to reverse its direction.
- The hysteresis properties of a magnetic material are clearly definable and measurable for the material.

- The figure at right shows an example MH curve for a magnet material, with an initial magnetization curve, and then an outer hysteresis loop.



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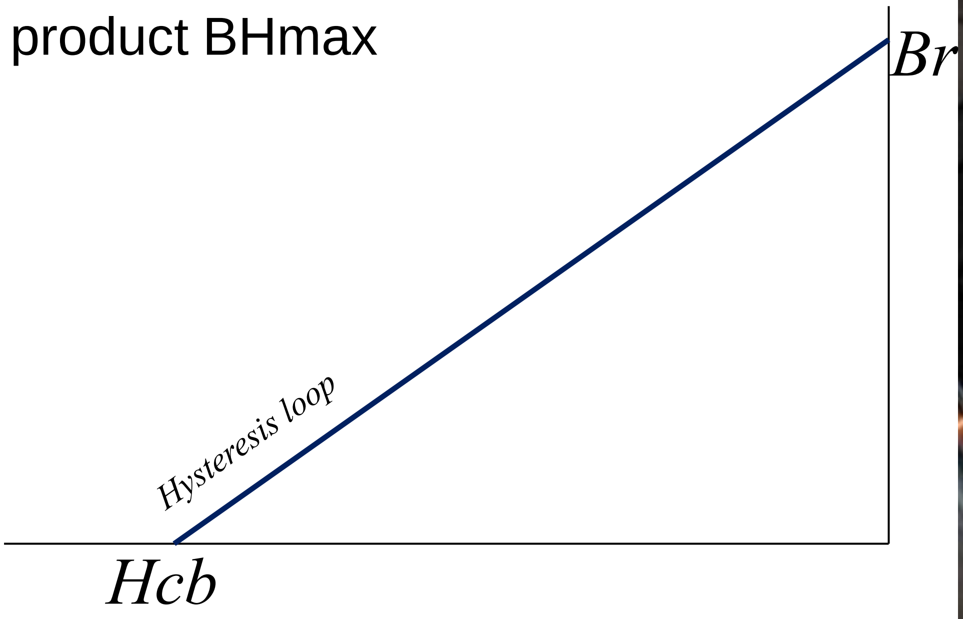
Permanent magnet material properties

- Magnet materials are typically characterized in their magnet performance by three factors related to the BH hysteresis loop curve:
  - The residual flux density Br
    - This is the intercept of the curve with the y-axis
  - The coercive force Hcb
    - This is the intercept of the curve with the x-axis
  - The maximum energy product BHmax



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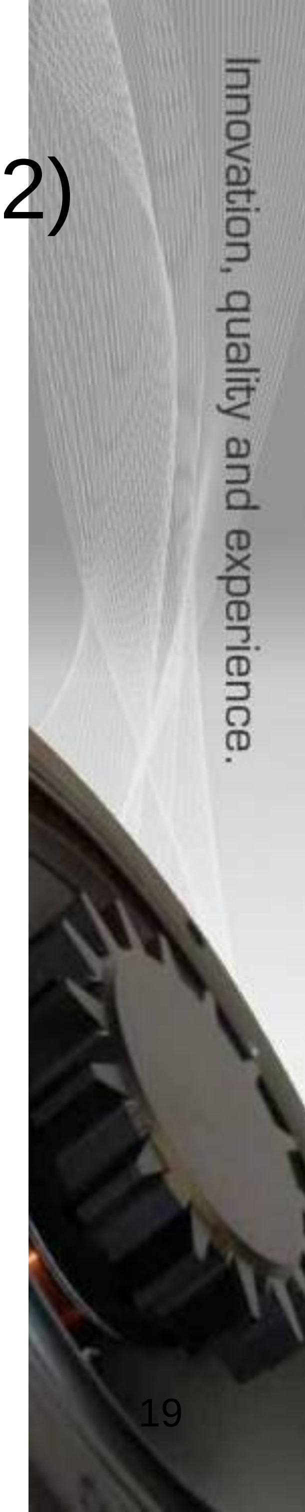
Permanent magnet material properties (2)

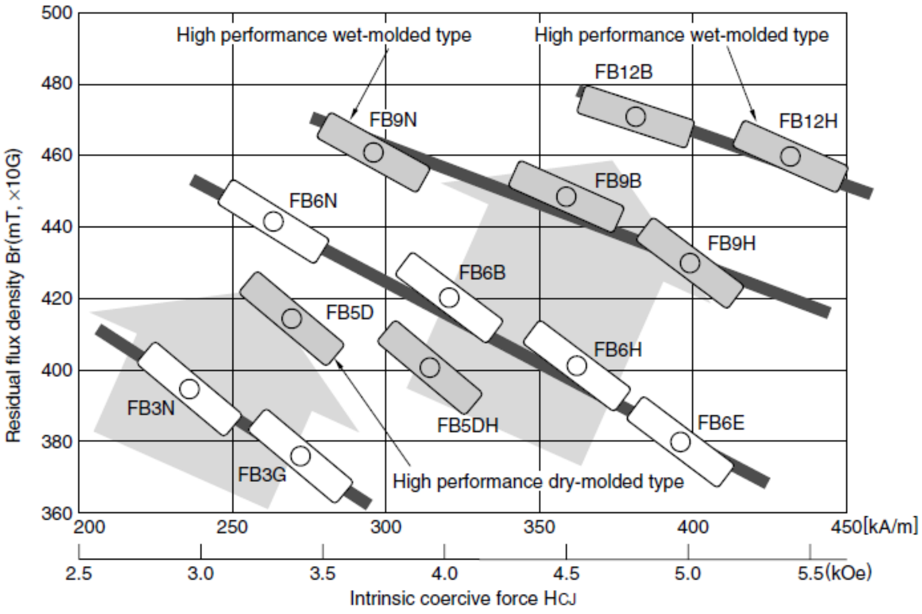
- Ferrite and neodymium-iron-boron magnet materials are the most common materials used in transducer motors.
- These materials come in different grades:
  - Varying amounts of maximum energy density
  - Variation in thermal stability in the performance of the material.
- The tradeoff for this variation is cost of the material.

- Thermal stability of magnet materials is represented graphically by showing the BH curves at different temperatures. This is important to understand in transducer design, as transducer motors see different temperatures based upon operation and environment.

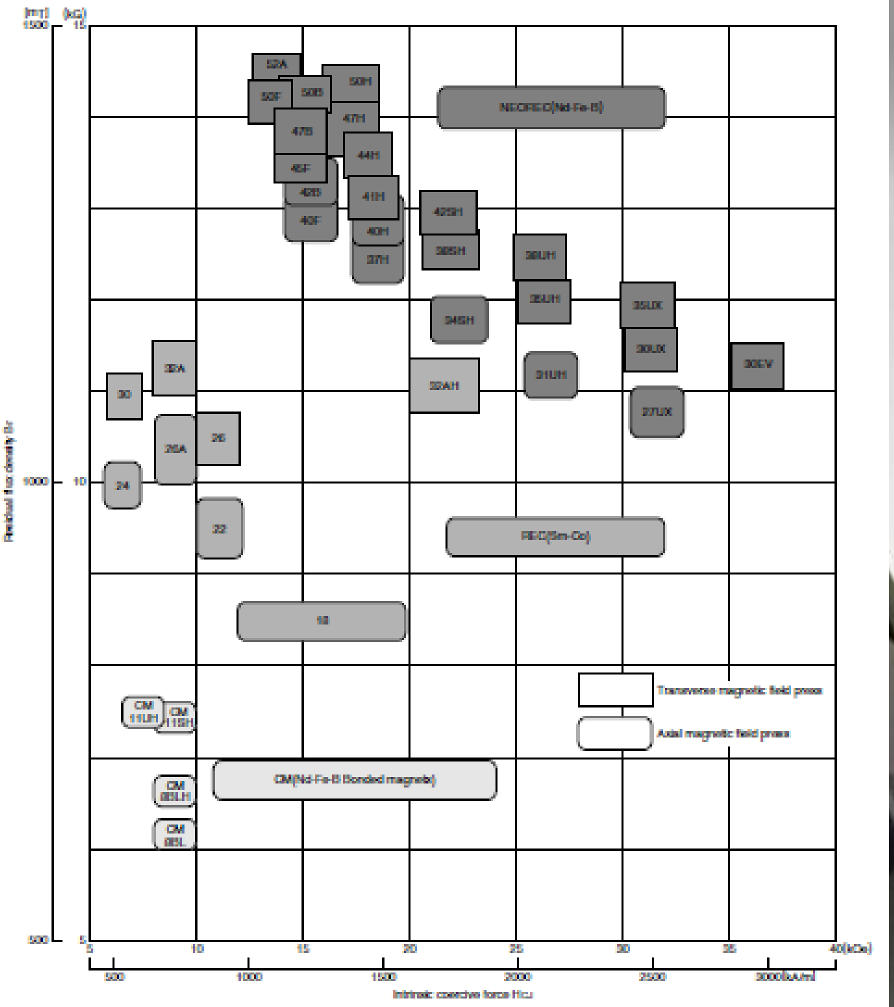


Permanent magnet material properties (3)

Ferrite material properties

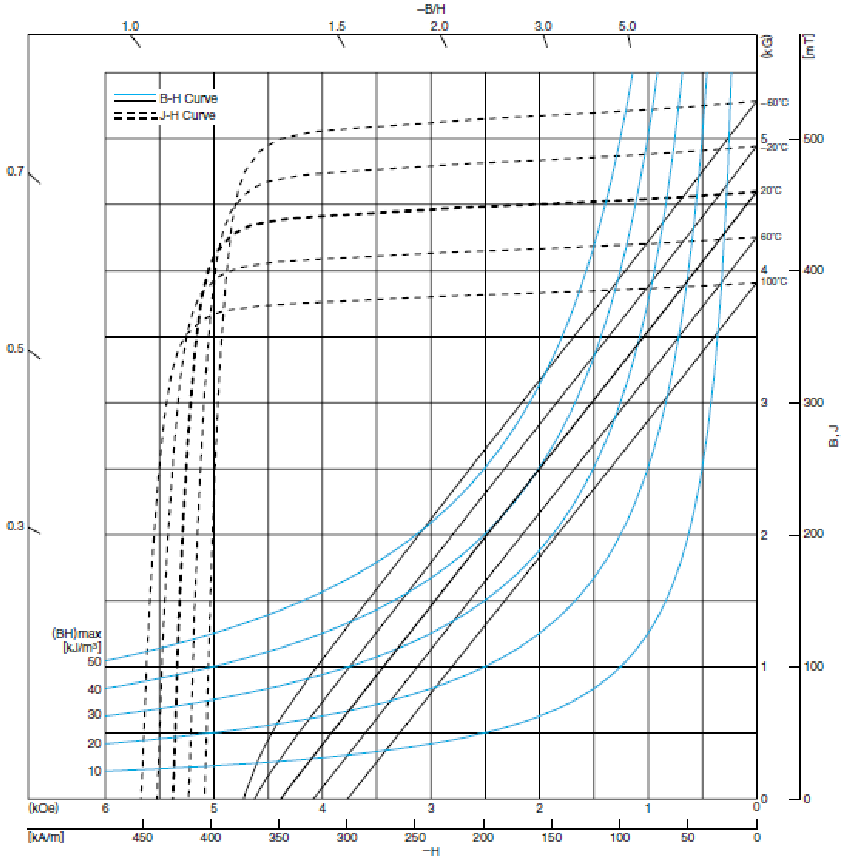


NdFeB material properties

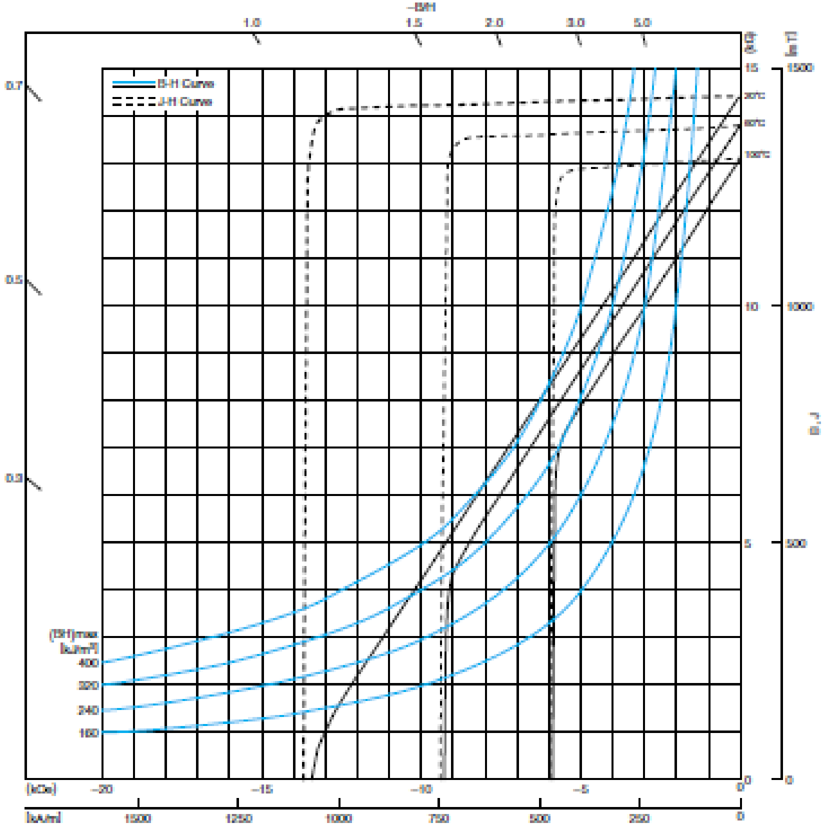


Permanent magnet material properties (4)

Ferrite material properties



NdFeB material properties



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Magnetic Circuits

- Magnetic Circuits
  - Magnetic circuit equation
  - Load line analysis

Magnetic Circuits – Circuit Equations

- Let’s say a permanent magnet has been assembled into a transducer motor, and magnetized. How strong is the magnetic field throughout the motor?
- The amount of magnetic field that the magnet produces is affected by its environment: air and steel adjoining the magnet.
- We can treat the magnet in a circuit analogy. The magnet itself operates something similar to a battery, and the environment acts like resistors.
- Voltage analogy:
  - Voltage must sum to 0 around any closed loop in a magnetic circuit.

$$\mathcal{F} = \int \mathbf{H} \cdot d\mathbf{l}$$

- Current analogy:
  - Magnetic flux must flow through the circuit without piling up anywhere.

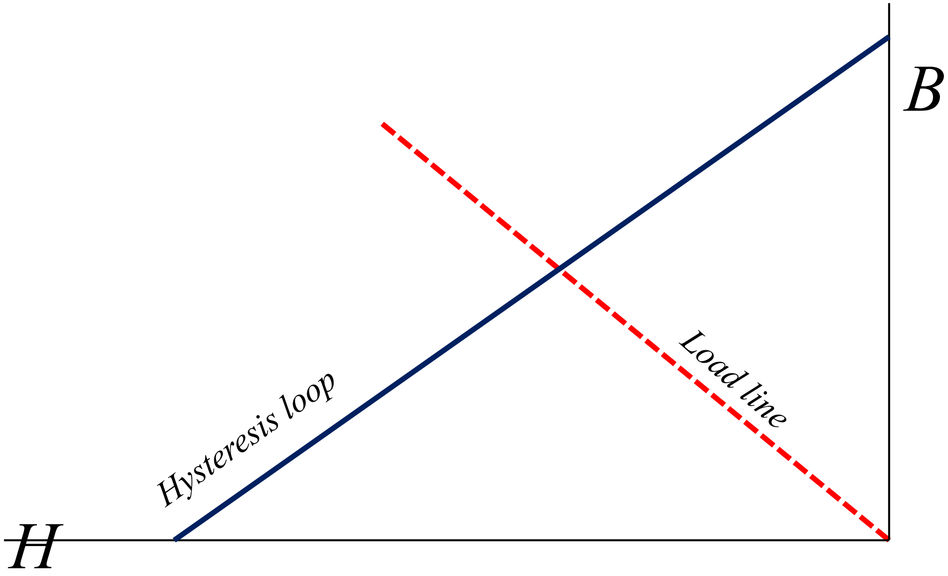
$$\oint \boldsymbol{B} \cdot d\boldsymbol{A} = 0$$

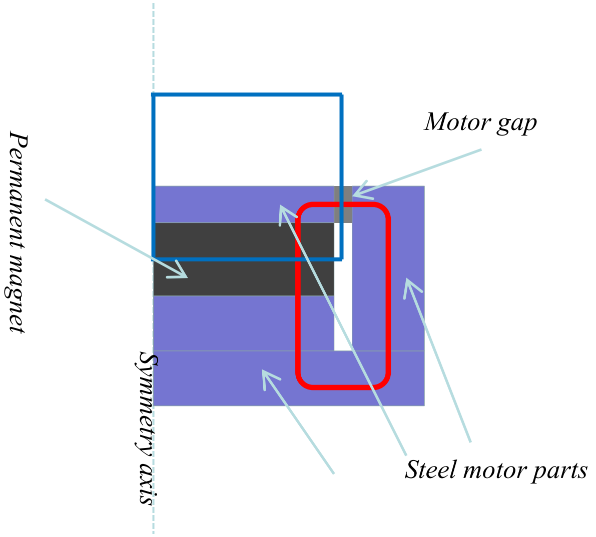
- Resistance analogy:
  - The magnetic resistance (“reluctance”) of any uniform element in a magnetic circuit is proportional to the length of the element, and inversely proportional to the element’s cross-sectional area.

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A}$$

Magnetic Circuits – Load Line Analysis

- Our simplistic magnetic motor is shown to the bottom right.
- Using the analogies described previously, the magnetic flux flowing through the air gap of the motor is the same as generated by the permanent magnet. (blue curve)
- Also, the magnetic "voltage" in the circuit must sum to zero. (red curve)
- Given these relationships, a straight line relationship can be derived between B and H for the magnet material. This straight line relationship is dependent upon the lengths and cross-sectional areas of the air gap and magnet only, assuming that the steel parts do not contribute any magnetic resistance to the circuit.
- The intersection of the load line and the magnet's BH hysteresis loop represents the operating condition of the magnet.



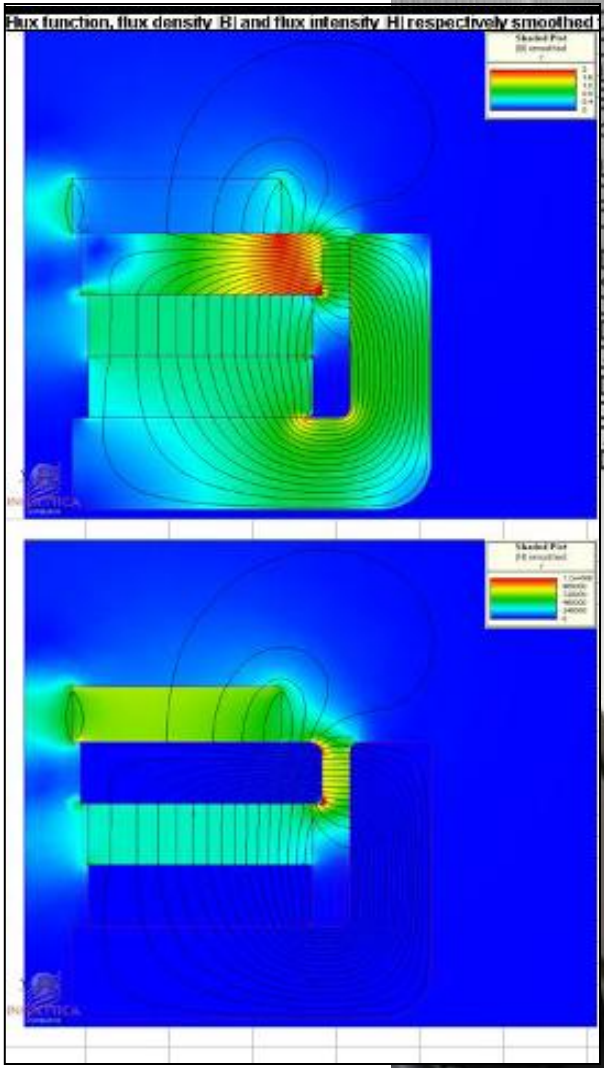


Finite Element Analysis

- Finite element analysis
  - How finite element analysis works
  - Outputs from FEA analysis
  - Typical software packages
  - FEA accuracy

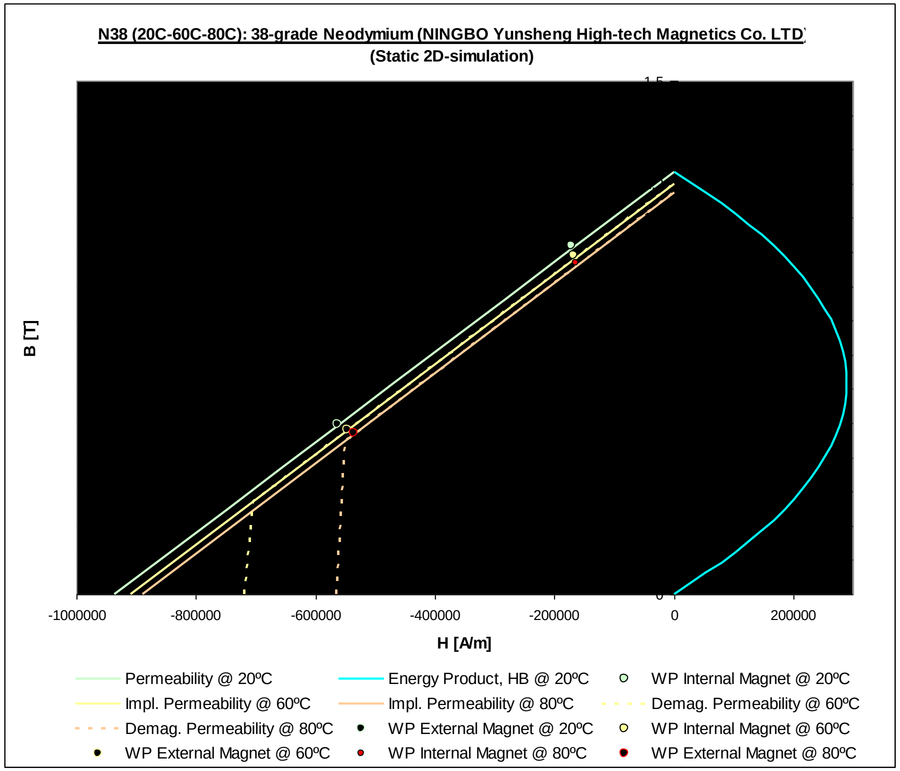
How finite element analysis works

- The load line analysis is a good way of understanding the basics of what drives the performance of a magnetic circuit.
- However, now that computer technology is advanced, the most common way of performing this analysis is by finite element analysis on computers. See example to the right.
- When conducting finite element analysis, the magnetic material properties (the BH hysteresis curve) must be provided.
- Determining the load line that the magnet is operating along, can be accomplished by understanding the BH properties of the magnet, and reviewing the average magnetic flux levels (B) within the magnet as predicted by FEA.
- Determining the BL which the transducer motor is providing to the voice coil, is often determined by simulating a small current running through the voice coil, and studying how much force is exerted on the voice coil as a result.
- Optimizing the motor shape is conducted iteratively, though simple reviews of the magnetic field patterns also contribute to the process by identifying visually areas of the motor which can be trimmed away.

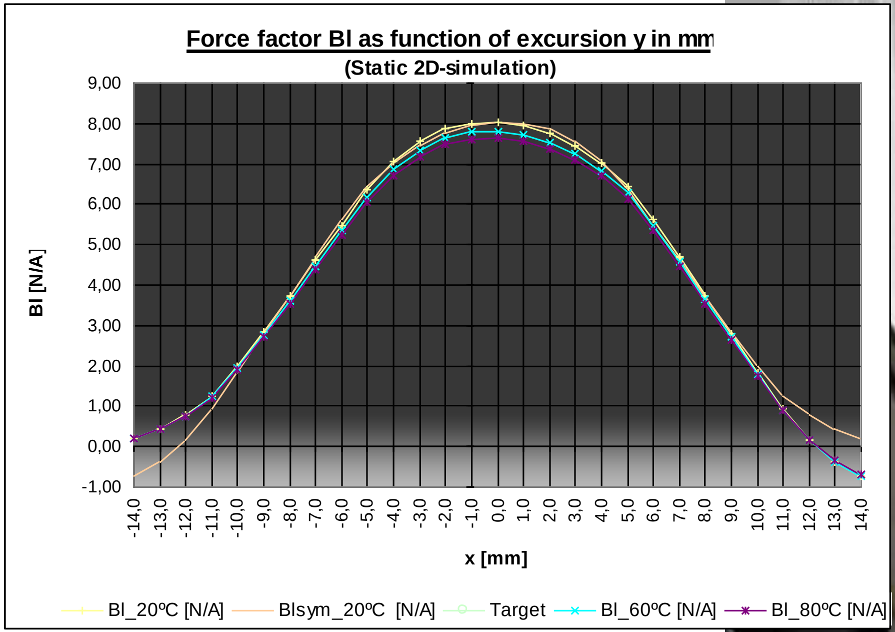


Outputs from FEA analysis

Load line analysis



BL curve (BL as a function of coil position)



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Magnetic FEA software

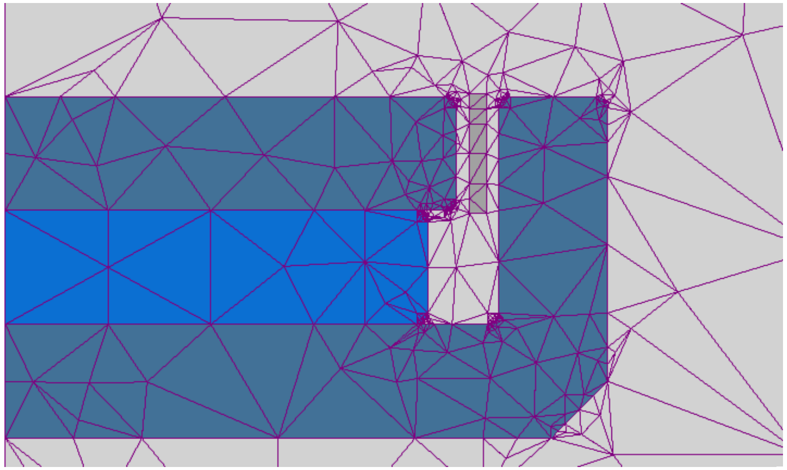
- ANSYS
- Infolytica – Magnet
- Vector Fields – Opera
- COSMOS
- COMSOL
- Ansoft – Maxwell
- FEMM
- FineMotor
- others

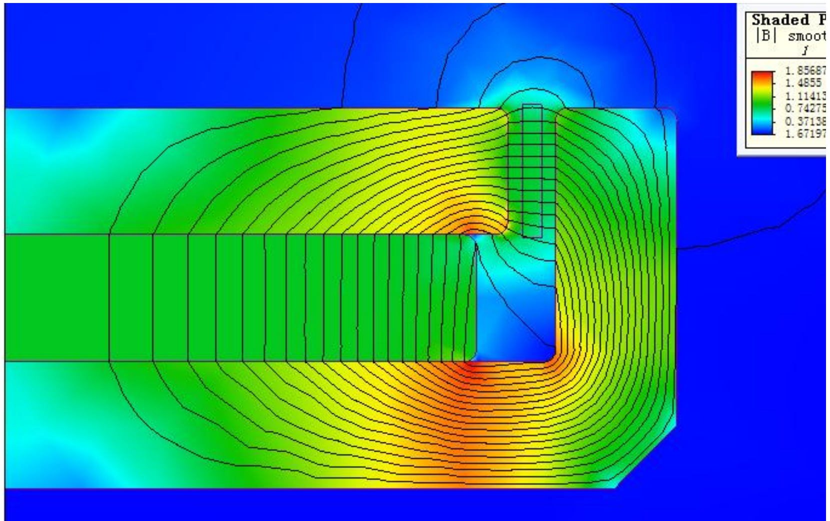
FEA accuracy

- Finite element analysis primarily works by breaking up the motor and surrounding air into a set of very small pieces, and iteratively solving the magnetic field equations for all of these pieces, until the level of change from iteration to iteration has become fairly small.
- This set of very small pieces is usually called the “mesh”. The smaller these pieces are, the finer or denser the mesh is.
- A finer mesh pattern will lead to more accurate FEA results for the magnetic field pattern within the motor. Accuracy in this case means that magnetic flux lines appear smooth, and magnetic field distributions also look smooth.
- Nowadays, running FEA analyses with a finer mesh pattern only takes a matter of a few minutes…there’s little reason not to obtain accurate results.

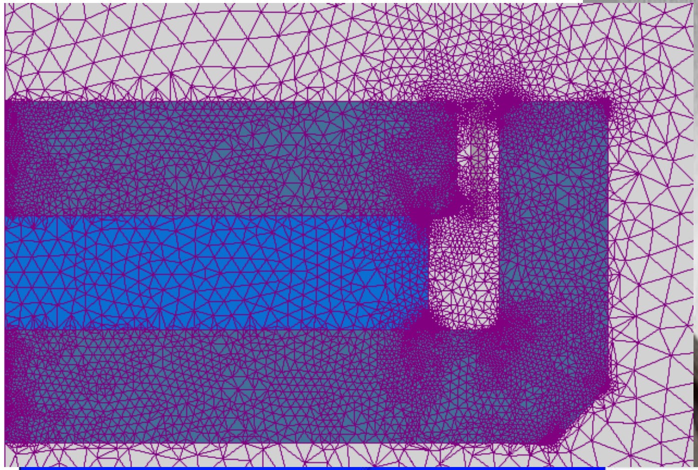
FEA accuracy (2)

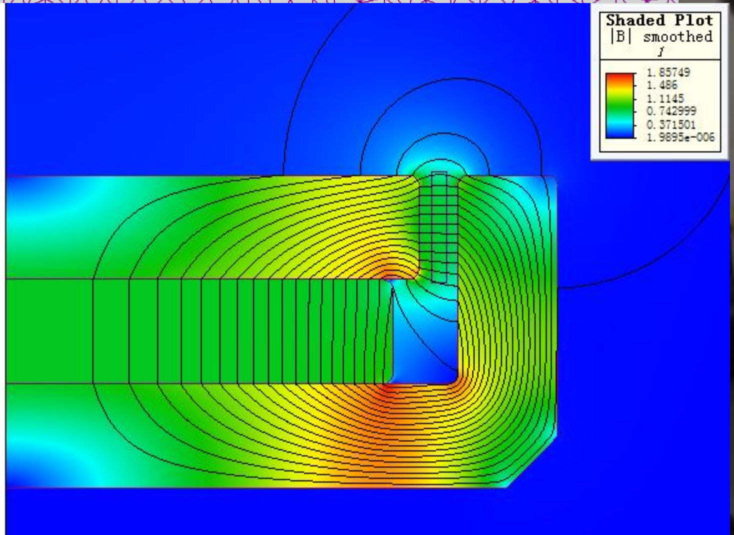
Original mesh pattern and results





Fine mesh pattern and results





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FEA Accuracy (3)

- The accuracy of FEA results also depends upon an accurate knowledge of the magnetic material properties representing the motor parts. For this, we are reliant upon accurate information from our suppliers.
- Finally, the accuracy of the results depends upon accurately drawing the intended shape of the parts. For more accurate results, round off the corners of the parts, just as they will be delivered by the suppliers.

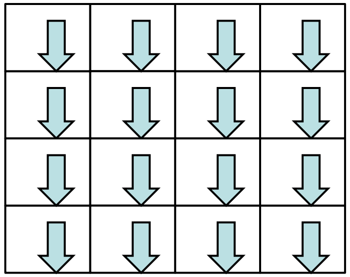
Temperature Effects

- Temperature Effects
  - Thermal agitation of magnetic domains
  - Material properties at different temperatures
  - Thermal demagnetization analysis
  - Thermal demagnetization discussion

Thermal agitation of magnetic domains

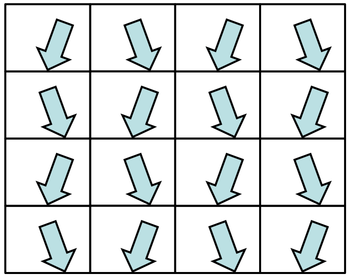
- As the temperature increases, the magnetic domains are affected in two fashions:
  - The orientation of the magnetic field starts to randomly jostle from side to side, due to thermal agitation.
  - Occasionally, enough thermal energy is delivered to a domain to cause that domain to permanently change its orientation…even flip to the opposite orientation.

A



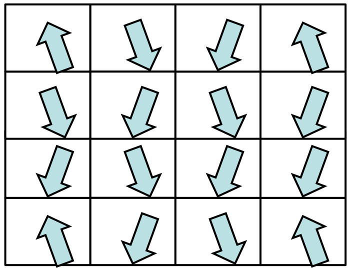
Room temperature domain structure

B



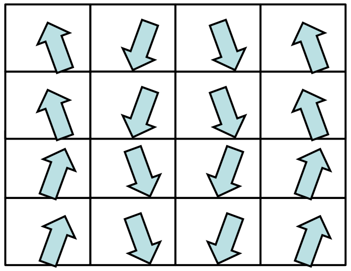
Higher temperature domain structure – non-permanent loss in magnetization strength

C



Even higher temperature domain structure – 50% permanent loss in magnetization strength

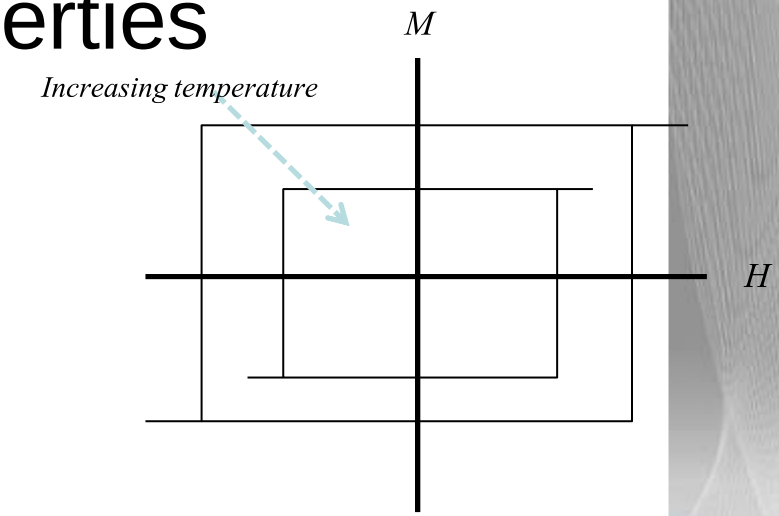
D

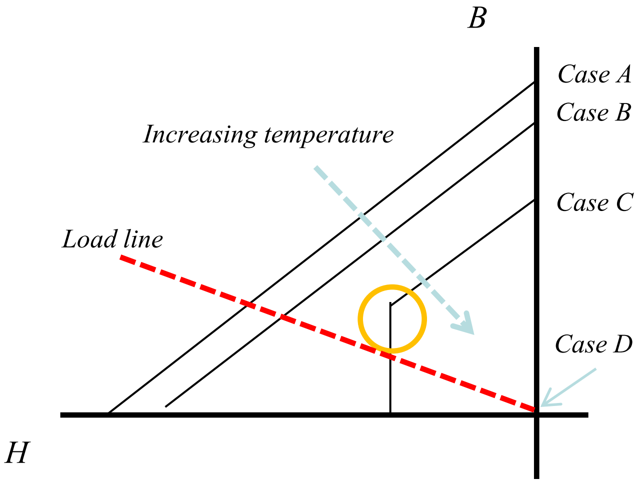


Temperature at which 100% permanent loss in magnetization strength is reached

Temperature Effects – changes in material properties

- The result of the thermal agitation is that the hysteresis loop starts to “shrink” as temperature increases. See figures at right.
- The permanent magnet is not able to generate as much magnetic flux as before, not because the load conditions have changed, but because the magnetic material is less effective at generating the flux, as was illustrated on the previous slide.
- If the load line ever falls below the yellow circle location, which we call the “knee” in the BH curve, then some permanent demagnetization, due to domain flipping, will occur.





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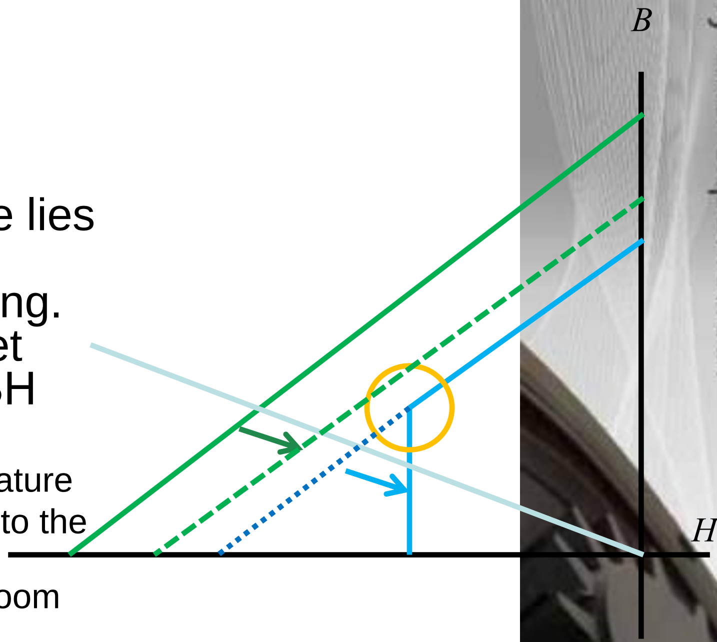
Temperature Effects – changes in material properties (2)

- Let's run through how to study thermal demagnetization through an iterative process, by using FEA. Please refer to the graph at right.
- The lines:
  - Red = load line
  - Green = room temperature BH curve
  - Blue = higher temperature BH curve
- When the intersection of the load line and the BH curve lies "below the knee" (yellow circle), some permanent demagnetization is going to occur, due to domain flipping. Because the changes are permanent, when the magnet returns to room temperature, it has a new, "de-rated" BH curve.
  - Light blue arrow = amount of demagnetization at elevated temperature
  - Dark green arrow = that amount of demagnetization applied back to the room temperature BH curve
  - Dashed green line = new "de-rated" BH curve for the material at room temperature, because of the partial demagnetization.
- When performing finite element analysis to study the effects of thermal demagnetization, it is the dashed green line which must be used to represent the magnet material properties following exposure to temperature.
- Procedure:
  - Perform initial FEA to find load line.
  - Perform graphical analysis at right to determine new room temperature BH curve.
  - Repeat FEA to determine how much motor performance has been lost.



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Temperature Effects – changes in material properties

- Exposure of transducer motors containing permanent magnets to high and higher temperatures will result in thermal demagnetization, and increasing levels of loss of motor efficiency.
- Unless the temperature is raised high enough to change the chemistry of the magnet material, permanent losses due to thermal demagnetization can be recovered by remagnetizing.
- Magnets can be remagnetized to their original state, after exposure to high temperatures.
- Exposing the magnet to successively higher temperatures will produce the same result as one would get by exposing the magnet to the highest temperature first. There are no historical/cumulative effects due to exposure to temperature.

Demagnetization discussion

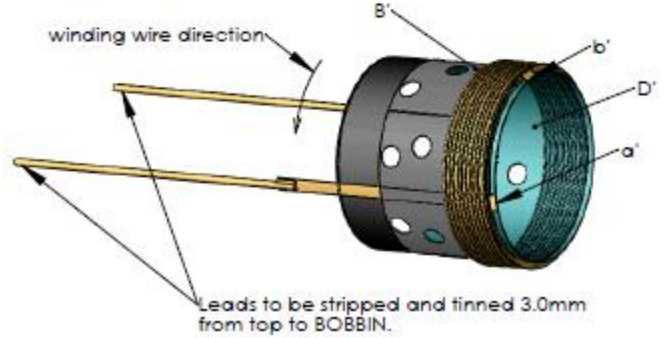
- Sources of demagnetization in normal speaker operation:
  - Heat from the voice coil
  - Ambient air conditions (hot cars, heat from the amplifier or television)
  - Validation test requirements (run power test at 85C)
- Effects:
  - Loss in speaker efficiency – less B being provided to the voice coil
  - Thermal “overload” of the speaker – the coil motion is decreased due to a lower level of B field delivered to the coil, so the coil can’t cool itself as much as it should, and it overheats.
- How to prevent in design?
  - Keep the load line slope high
  - Pick a magnet material with the knee below the operating point of the magnet, at the expected maximum temperature.

Voice coil design

- Voice coil design
  - Coil topology
  - Wire materials
  - Motor efficiency and wire material properties
  - Voice coil inductance

Coil topology

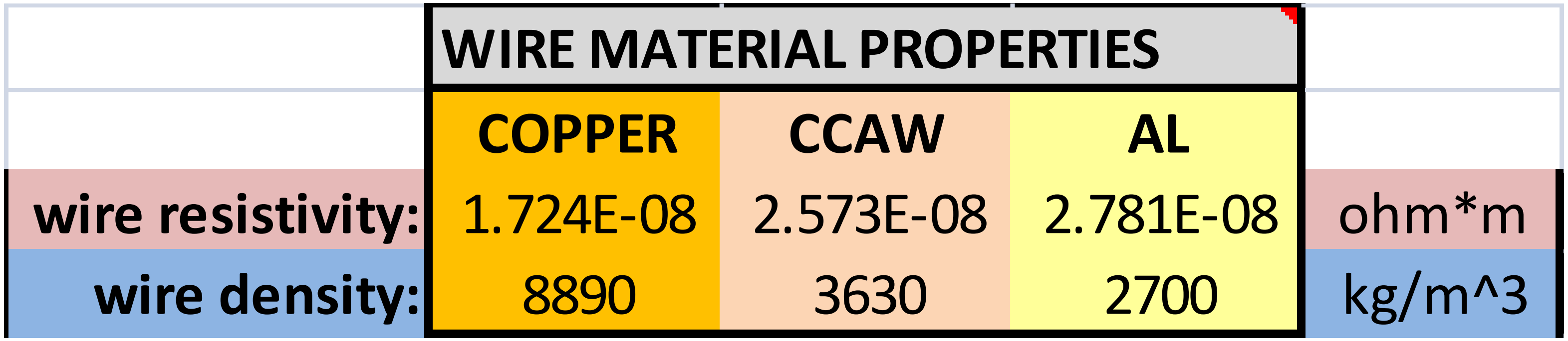
- Voice coils, as mentioned previously, are inductors, with wire(s) wound onto formers.
- The former (or bobbin) is typically thin, and made of aluminium or kapton (or equivalent). It may have holes in it, to aid in air circulation and coil cooling during operation of the transducer.
- The windings are typically wound only onto the lower part of the former. The upper part of the former is attached to the transducer's cone and spider.
- The wire itself is typically round, but can be square or rectangular in cross-section. The wire is coated in insulation and bonding adhesives, which are rated to perform up to certain temperatures (the higher the temperature, the higher the price).
- The windings are laid out in one or more lavers.



Leads to be stripped and tinned 3.0mm from top to BOBBIN.

Wire materials

- Typical wire materials are copper, copper-clad aluminium, and aluminium.
- Key material properties are listed below.



	WIRE MATERIAL PROPERTIES			
	COPPER	CCAW	AL	
wire resistivity:	1.724E-08	2.573E-08	2.781E-08	ohm*m
wire density:	8890	3630	2700	kg/m^3

Motor efficiency and wire material properties

- We previously had listed out the transducer efficiency relation:

$$\eta_0 = \left(\frac{\rho_0}{2\pi c}\right)\left(\frac{(Bl)^2 S_D^2}{R_E M_{MS}^{\;2}}\right)$$

- The quantity $(BL)^2/Re$ is known as beta (β), the motor efficiency. Through some math, we can state a relationship for beta:

$$\beta = \left(\frac{(Bl)^2}{R_E}\right) = B^2 V_C \sigma$$

- Here B is the magnetic flux density averaged over the voice coil windings, Vc is the volume of the conductor in the voice coil, and σ is the conductivity of the conductor.

Motor efficiency and wire material properties (2)

- In some transducer designs, the amount of moving mass available for the voice coil windings is limited. In those cases, it can be useful to examine the relationship between beta and the mass of the conductor (windings):

$$\frac{\beta}{M_C} = B^2 \cdot \left(\frac{\sigma}{\rho} \right)$$

- Here Mc is the mass of the coil windings, and ρ is the density of the windings.
- Given material properties of the various types of wires, this means that sometimes aluminium wire is a smarter choice than copper wire, in some designs.

Wire type	ρ (grams/cc)	σ (Ωm)	σ/ρ
Copper	8.96	$5.88*10^7$	$0.656*10^7$
Aluminium	2.7	$3.85*10^7$	$1.43*10^7$

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Voice coil inductance

- Voice coil inductance in free air is typically calculated by a complex formula derived by Wheeler:

$$L = \frac{\mu_0 \cdot \pi \cdot r^2 \cdot N^2}{h} \cdot \left(\frac{0.31831 \cdot h}{r}\right) \cdot \left(\ln\left(1 + \frac{\pi \cdot r}{h}\right) + \frac{1}{(2.3004 + \frac{1.622 \cdot h}{r} + 0.4409\frac{h^2}{r^2})} \right)$$

L = inductance (H)
r = average radius of coil (m)
N = number of turns
h = wind height of coil (m)

- When placed into a motor, the inductance is affected by the magnetic steel core, and increases accordingly. Wheeler's formula serves as a useful lower bound on the coil inductance.
- Because voice coil inductance increases due to the steel motor, sometimes a copper cap is placed on top of the pole in the motor, or a shorting ring is placed inside the motor. These parts serve to reduce the voice coil inductance, which decreases distortion and extends frequency response of the transducer to higher frequencies.

Motor design topology

- Motor Design Topology
  - Magnet material selection
  - Typical motor geometries
  - Top plate thickness vs. pole diameter

Magnet material selection

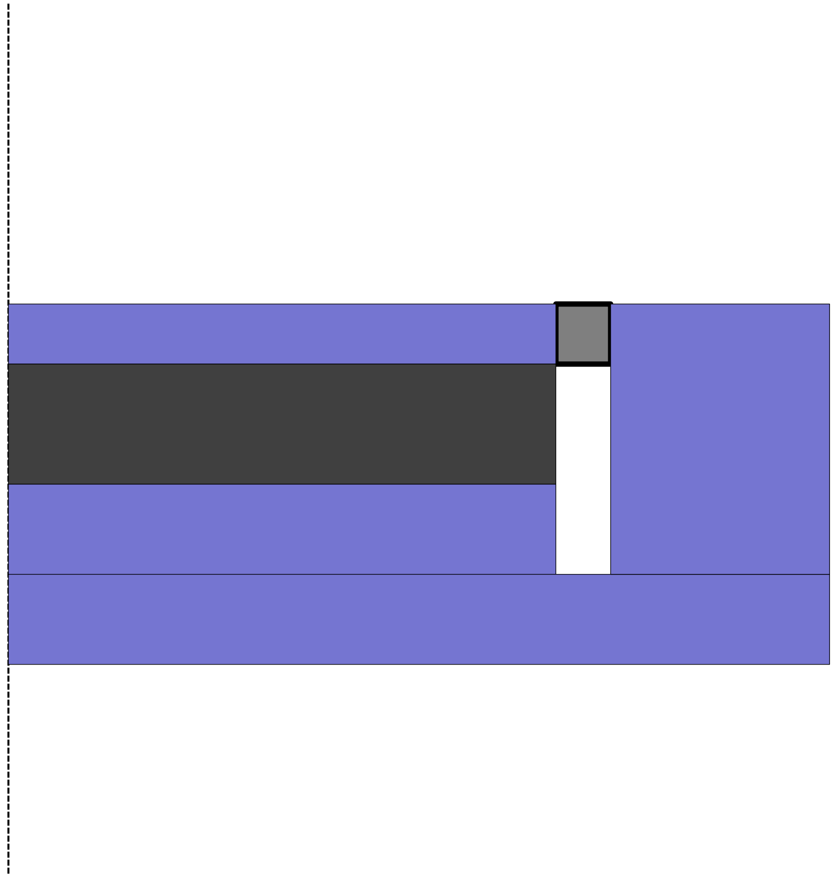
- Material selection is dominated by the price/performance trade-off.
- Performance:
    - NdFeB is far more energetic than ferrite magnet material. Motors can be smaller with NdFeB magnets.
    - NdFeB material grades labeled “H” or “UH” have high thermal stability.
- Price:
    - NdFeB is highly expensive material, compared to ferrite.
    - NdFeB grades with energy products greater than 40 MGOe can become expensive.
    - NdFeB grades labeled “H” or “UH” are also more expensive, due to the additives in their chemistry which boost thermal stability.
    - NdFeB is in limited supply and in high demand, and this has resulted in price increase in the last year.

- The best approach to material selection is to design and evaluate several options, and choose the correct one for your application.

Typical motor geometries

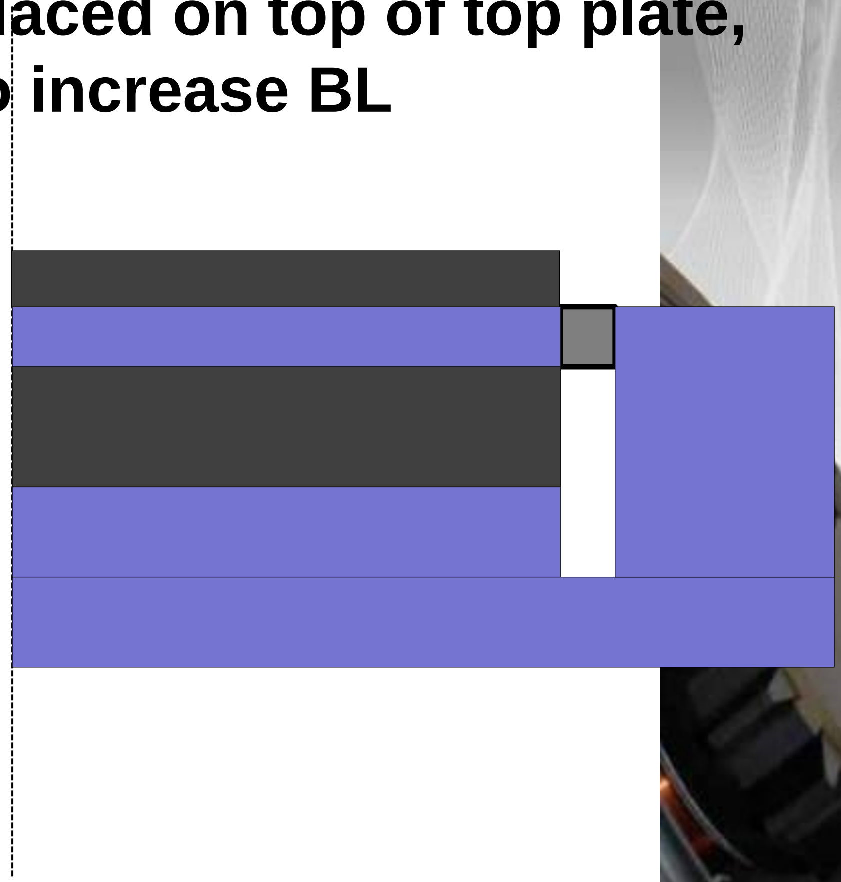
NdFeB magnet motor

Magnet located in pole



NdFeB magnet motor

Secondary bucking magnet placed on top of top plate, to increase BL



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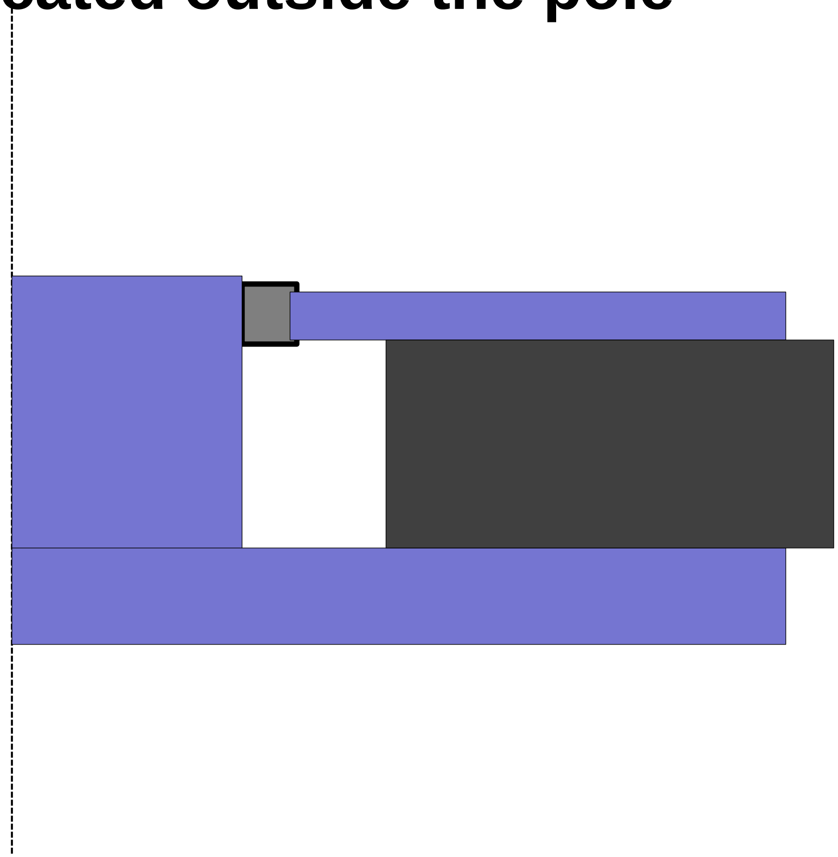
Typical motor geometries (2)

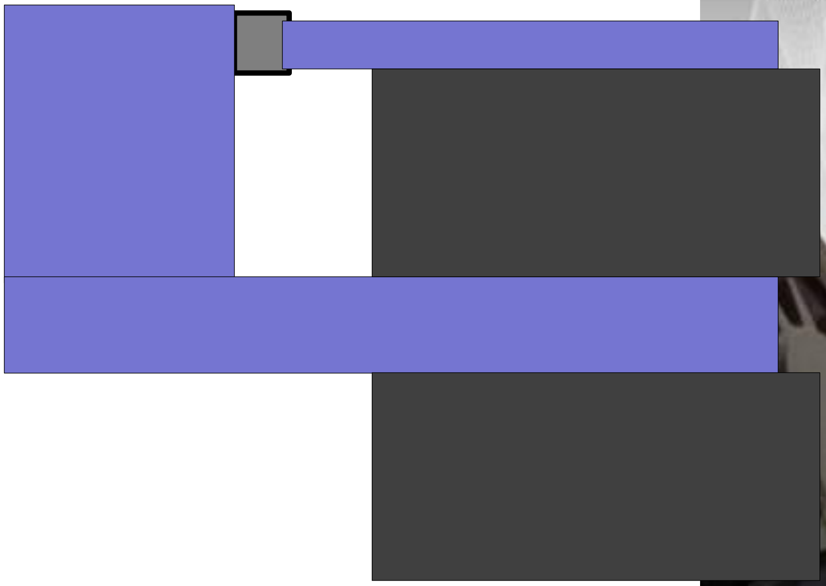
Ferrite magnet motor

Magnet and top plate located outside the pole



Ferrite magnet motor

Secondary bucking magnet placed on the bottom of the back plate, to increase BL

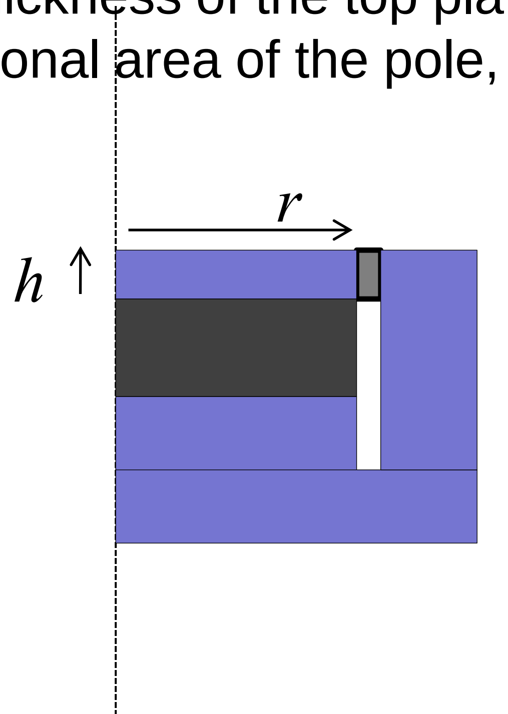


Top plate vs. pole diameter

- In our motor designs, magnetic flux is carried through the motor’s pole, through the voice coil, and out into the top plate. The magnetic flux levels are often highest in the pole section of the motor…the pole limits the amount of magnetic flux flowing through the magnetic circuit.
- With this in mind, it is possible to derive a relationship between the diameter of the pole, and the thickness of the top plate. This is done by equating the cross-sectional area of the pole, to the cylindrical area of the top plate.

$$\pi \cdot r^2 = 2\pi \cdot r \cdot h$$

$$h = \frac{r}{2}$$



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Top plate vs. pole diameter (2)

- This relationship explains typically selected thicknesses for top plates, given particular voice coil inner diameters.

VCID (mm)	r (approximate)	h (approximate)
19	9.5	4-5
25	12.5	6
32	16	8
38	19	10
50	25	12

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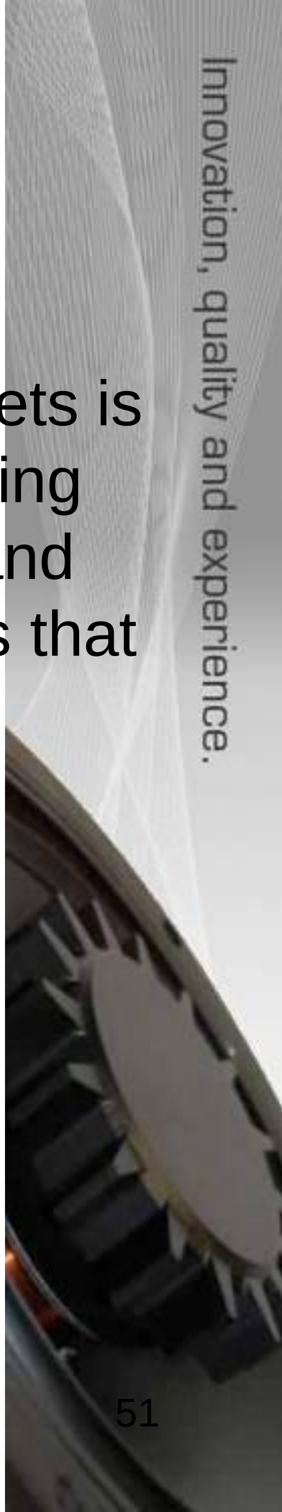
Design challenges

- Designing transducer motors to meet performance targets is a complex process, involving material selection, designing with computer software to determine part geometries, and weighing design options to select cost-effective designs that perform as desired.

- More advanced design challenges not yet discussed:
  - BL Distortion, Xmax, non-constant BL
  - Inductive distortion, DC offset
  - Skin effects



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