Inductor Fabrication and Characterization

Developers
J Mitchell, K Meehan, and Y Xu.

Objectives
The objectives of this experiment are to design and construct a solenoid inductor and determine the complex permeability of its ferrite core.

Preparation
Read the section on inductance in your textbook (Section 9.10, pages 292 – 299). Also read the section on inductance in your Fundamentals of Electric Circuits book (Section 6.4, pages 226 – 230) and in your Lab-in-a-Box manual (Section 2.10, pages 37 – 40).

Background

Inductance (L), or self-inductance, is the ratio of the linkage magnetic flux to the current (I) producing the flux (Edminister 169). Flux linkage is the product of the number of turns (N), and the magnetic flux ($\phi$) linking each of those turns. Inductance has units of henries (H), where one Henry is equal to one Weber-turn per ampere ($\frac{Wb}{A}$). Equation 1 shows the formula for inductance.

$$L = \frac{N\phi}{I}$$  \hspace{1cm} (1)

Note that Eq. 1 is applicable only to linear media, in which the flux is proportional to the current (Buck 293). Inductance can also be defined as the property whereby an inductor exhibits opposition to change of current flowing through it (Alexander 226).

Inductor

An inductor (the terms coil and choke are also used) is a circuit element designed to store energy in its magnetic field. Technically, any conductor through which current flows can be considered an inductor. However, inductors usually are made by wrapping several turns of conducting wire around a cylindrical core.

The inductance of an inductor depends on its number of turns (N), its length (l), its cross sectional area (S), and the permeability (μ) of its core. The core may be made of air, iron, plastic, or steel. Because iron, for example, is a magnetic material, an inductor with an iron core can have an inductance several thousand times larger than one with an air core. A diagram of a typical inductor is shown in Figure 1.

![Figure 1: Typical form of a solenoid inductor](image-url)
The inductance of a long solenoid is

\[ L = \frac{\mu N^2 S}{l} \]  

(2)

The inductance of a toroid with a circular cross section is

\[ L = \frac{\mu N^2 S}{2\pi r} \]  

(3)

When current flows through an inductor, the voltage across it is equal to the product of its inductance value, and the rate of change of the current with respect to time (Eqs. 4).

\[ v = L \frac{di}{dt} \]  

(4)

**Ideal vs. Non-ideal Inductor**

The ideal inductor does not dissipate energy. It stores power taken from the circuit when storing energy in its magnetic field and delivers power to the circuit from its magnetic field when returning the energy. In practice, however, all inductors are non-ideal.

Non-ideal inductors have a significant resistive component which arises from the resistance of the conducting wire used to wrap the core. This resistance is called parasitic resistance, or winding resistance. This parasitic resistance appears in series with the inductor and causes the inductor to become an energy dissipating device. Non-ideal inductors also have parasitic capacitance, or winding capacitance. Parasitic capacitance arises from the capacitance coupling between the conducting coils of wire. Parasitic capacitance appears in parallel with inductance and parasitic resistance. It can be neglected in most cases, except at high frequencies. The equivalent circuit for a non-ideal inductor is shown in Figure 2.

**Quality Factor**

Quality factor (Q) of a circuit is the ratio of its center (resonant) frequency to its bandwidth. Quality factor is dimensionless and should not be confused with reactive power which uses the same symbol Q. As shown in figure 3, the higher the quality factor, the more selective the circuit is and the smaller its bandwidth. Selectivity of a circuit is its ability to accept certain frequencies and reject all others. A Q of 10 or greater is considered to be a high Q (Alexander). The Equation for Q is shown in Eqs. 5, where B is
bandwidth and \( f_0 \) is center frequency.

\[
Q = \frac{f_0 L}{R} = \frac{f_0}{B}
\]

(5)


- 1 ea “ANDY” board
- 1 ea dual trace Oscilloscope
- 1 millimeter
- Magnet Wire
- 1, ¼” diameter bolt
- 1, ¼” diameter iron core
- 1, ¼” diameter heat shrink tubing
- 1, 1k \( \Omega \) resistor (shunt)
- 1 ea ruler

Create a solenoid inductor, shown in figure 1., by first placing an iron core inside a heat shrink tube and then by wrapping magnet wire around the bolt and heat shrink. The inductor should have between 100 and 200 turns of magnet wire. To make an electrical contact with the magnet wire, the coating must be scraped off.

**Modeling:**

1. Build your Inductor and calculate its inductance with an (a) iron and (b) air core.
2. Measure the resistance of the inductor.
3. Calculate the Q of your inductor.
4. Using MATLAB graph the Inductance vs. relative permeability of the core. Use the values of your inductor for length, cross-sectional area, and number of turns.

5. Using PSpice, create 2 high pass filters using your calculated inductances for (a) an iron core and (b) an air core. Remember to add the measured parasitic resistance into the simulation.

6. Determine the cutoff frequencies of your filters.

**Measurements:**

1. Using the Velleman oscilloscope, determine the value of your inductor. (Hint: use the voltage drop equation).

2. Using the Circuit Analyzer tool on the Velleman software, obtain a Bode plot (magnitude and phase) for both of your high pass filters where the frequency range is from 1 kHz to 1 MHz.

3. Compare the measured value of your inductors to the calculated values.

4. Compare the calculated Q values to your measured Q value.

5. Compare the measured cutoff frequency of the inductors to the cutoff frequencies determined from PSpice.

6. What is the reason for the differences between calculated and observed values?

**Frequency Dependence and Complex Permeability:**

Losses which occur because of a medium’s response to a magnetic field are modeled through a complex permeability. Shown in Eqs. 6 is the equation for complex permeability. Where \( \mu' \) is the real and \( \mu'' \) is the imaginary.

\[
\mu(\omega) = \mu'(\omega) + j\mu''(\omega)
\]

Using your Velleman oscilloscope and MATLAB, determine the complex permeability of the metal core.