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Modeling Of Inductor Using Ferrofluid Inside Core

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ABSTRACT

Nanotechnology Has Been A Boon In The Last Couple Of Decades And Significant Efforts Have Been Made To Develop Nanoparticles With Bottom Up And Top Down Approach. There Has Been A Tremendous Increase In The Number Of Research Papers And Patents In The Field Related To Magnetic Nanoparticles, Ferrofluids And Their Applications. The Physical And Chemical Properties Of These Materials Hold A Direct Correspondence To Size Dependency Of Magnetic Nanoparticles. Characterization And Measurement Of Nano-Particles Pose Interesting Analytical Challenges. This Work Is Carried Out For Modeling Of Inductor Using Ferrofluid In Core.

Keywords – Self Inductance, Susceptibility, Modeling, Permeability

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I. INTRODUCTION

A Ferrofluid Is Basically A Colloidal Suspension Of Single Domain Magnetic Particles Which Can Be Prepared With The Dispersion Of These Magnetic Particles In A Carrier Liquid And Stabilized By A Suitable Organic Surfactant. Ferrofluids Such As Fe3o4 Typically Have Sizes From 10 Nm To 200nm. Various Applications Are Designed Using Such Materials And Technological Interests In Ferrofluids Are Growing Since They Have Emerged As Reliable Materials Capable Of Solving Complex Engineering Problems.[1] There Are Numerous Applications Of Ferrofluids[2, 3, 4]

An Experimental Observation On The Dynamic Behavior Of Ferrofluid Was Carried Out For The Measurement Of Dynamic Magnetic Susceptibility Which Gave The Basic Response Mechanisms Of Nanoscale Ferrofluid [5]. The Magnetic Properties Of Particles In A Ferrofluid Under Suspension Can Be Described By Langevin Theory Of Paramagnetism Which Suitably Modifies To Take Account Of Distribution Of The Particle Sizes. A Single Domain Particle Can Be Considered In A State Of Uniform Magnetization With A Magnetic Moment **M** = **Ms.V** Where Ms Denotes The Saturation Magnetization And V Is Volume Of The Particles [6]. The Direction Of This Magnetic Moment Of Particles Will Fluctuate As A Result Of Thermal Agitation And The Spectral Density Of

Resulting Macroscopic Fluctuating Magnetization. This Fluctuation May Get Deduced Due To The Complex, Relative, Low Field Magnetic Susceptibility [7]. Initial Susceptibility Can Be Calculated At Each Temperature With The Help Of Measurement Of Particular Size Particles By Using A Vibrating Sample Magnetometer. In This Measurement Technique, Two Samples Of Ferrofluid In Small Applied Field Were Taken At A Temperature Between 100k And Room Temperature .These Samples Were Originally Frozen In Zero Field And Subsequently Were Warmed In Small Field.[8]. For Analyzing The Linear And Non Linear Susceptibility Of Superparamagnetic Fine Particles, Néel Relaxation Is Used, Which Is Basically The Difference Between The Susceptibility Of Same Particles In Solid Or Fluid[9].

Studies Have Been Carried Out On Performance Of Inductive Transducers With Magnetic Fluids And The Inductance Calculation Were Carried Out By Using Numerical Simulation Method [10].

In This Work, We Use The Method For Modelling Of An Inductor Where Inductance Was Calculated By Considering The Brownian Relaxation[11]. This Relaxation Was Due To Rotational Diffusion Of The Whole Particle In The Analysis Related To The Origin Of Permeability Of The Ferrofluid In The Core. Hence, An Attempt Has Been Made To Analyse Permeability And Susceptibility Of The Core Mathematically.

II. PREPARATION OF A FERROFLUID

A Ferrofluid Is Prepared From Respective Salts Of Fe^{2+} And Fe^{3+} Oxidation State By Mixing Them With Alkaline Solutions Thereby Giving Precipitation Of Magnetic Nanoparticles. Nanoparticles Start Forming After Nucleation And The Growth Is Controlled By Temperature, Concentration Of The Solution And Ph Value. The Surface Of Nanoparticles Can Be Treated Suitably So That A Proper Surfactant Adsorption Can Take Place At A Higher Temperature As The Process Is Chemisorption. Thus, A Particle Starts Giving Steric Repulsion Which Is Necessary To Form A Stable Colloidal Disordered Suspension. Since The Particles Are In A Few Nanometers, They Can Be Therefore Treated As A Single Domain Particle.

III. ORIGIN OF PERMIABILITY IN THE CORE

When The Particles Are In The Suspension, Their Magnetic Properties Can Be Described By Langevin Theory Of Paramagnetism Suitably Modified To Take Account Of Distribution Of The Particle Sizes. Single Domain Particles, As Such Can Be Considered In A State Of Uniform Magnetization With A Magnetic Moment ***M*** Given By [6]

$$M = Ms.V \qquad (1)$$

Where **Ms** (Wb/M^2) Gives The Saturation Magnetization(*Ka*/M) And **V** Is The Volume Of Particle. The Magnetic Moments Are Fixed In Orientation Relative To The Particle Because Of Magnetic Anisotropy (K J/M^3) [14] Which Arises Out Of The Combination Of Particle Shape And Magnetocrystalline Anisotropy. The Direction Of Magnetic Moment Is Referred To As Axis Of Easy Magnetization. The Mean Magnetic Moment **M** Of A Particle In The Direction Of Field Is Described By Langevin Expression As Follows

$$M = Ms\,[\,\mathrm{Coth}\,\Xi - 1/\Xi\,] \qquad (2)$$

Where, $\Xi = (\underline{Mho/}\,Kt)$

The Behavior Of The Ferrofluid Depends Upon The Behavior Of Individual Particles Therefore The Study Related To Behavior Of The Particle Is Necessary. There Are Three Characterization Times Of The Particles Which Governs The Behavior Of An Individual Particle In The Applied MagneticField. Two Of These Are Carrier Liquid [12, 13]. There Are Many Related Works For Inductive Sensors Using These Ferrofluids In The Core. Whereas Less Work Has Been Carried Out On TheMathematical

Dependent On The Relaxation Of The Magnetic Moment Of Particle.

Firstly, The Equilibrium Of The Magnetic Moment Is Obtained By Physical Rotation Of The Particle The Time Associated With This Bulk Rotation T_b, Is The Brownian Relaxation Time[15].

$$T_b = 3\,V'\eta\,/\,Kt \qquad (3)$$

Where, **V'** Is The Hydrodynamic Volume Of A Particle And **H** Is The Dynamic Viscosity Of The Carrier Liquid.

Secondly, The Magnetic Moment May Change Or Reverse The Direction Within The Particle Without The Rotation Of The Particle. This Is Achieved By Overcoming The Energy Barrier (**Kv**) Where **K** Is The Anisotropy Constant Of The Material. The Probability Of Such A Transition Is Approximately Equal To e^{Σ}, Where **Σ** Is A Ratio Of Anisotropy Energy To The Thermal Energy .

This Reversal Time Or Switching Time Is Known As Neel's Relaxation Time T_n.

$$T_n = T_o\,e^{\Sigma} \qquad (4)$$

Where $\Sigma = Kv / Kt$ And $T_o \sim 10^{-9}$seconds. T_o Is Damping Or Extinction Time And In Fact Third Time Component To Be Considered. Further It Can Be Seen That For High And Low Barrier Energies Neel's Relaxation Time Varies[16]

$$T_n = (T_o / \sqrt{\Sigma})\,e^{\Sigma} \qquad \text{For} \quad \Sigma > 1$$
$$T_n = T_o\,.\,e^{\Sigma} \qquad \text{For} \quad \Sigma \ll 1\ . \qquad (5)$$

Under Equilibrium, The Magnetic Moment **M** And The Internal Field H_a Of A Particle Are Parallel, Any Deviation Of The Magnetic Moment From Its Equilibrium Position Would Result In The Precession Of The Magnetic Moment About Its Easy Axis With An Angular Frequency(Ω_o)

$$\Omega_o = M_o\,\Gamma\,H_a \qquad (6)$$

Γ Is A Gyromagnetic Ratio, H_a Is Internal Magnetic Field Equals To **2k/Ms** Where **Ms** Is The Saturation Magnetisation Per Unit Volume. In The Absence Of External R.F. Field The Precession Decays With Decay Time T_o Seconds.

$$T_o = Ms/(2\,M_o\gamma\alpha k) \qquad (7)$$

A Is A Damping Constant Generally Approximated To 0.1 Or 0.01, As An Example

$Ms = 0.4t, \quad \Gamma = 8.8x10^{10} sec^{-1} t^{-1}$

$K = 2x10^4\ J/M^3$

$T_o = 9x10^{-11}/A\ \ Sec$

$T_o = 9x10^{-10}\ \ Sec\ \ For\ \ A = 0.1$

$T_o = 9x10^{-9}\ Sec\ \ For\ \ A = 0.01$

$T_o = 9x10^{-9}$ **Sec** Plays Significant Role In Determination Of T_n.

The Distribution Of Particle Size Implies The Existence Of Distribution Of Relaxation Time With Both The Above Relaxation Mechanism Contributing To The Magnetisation. They Do So With The Effective Relaxation Time $\mathbf{T_{eff}}$.

$$\mathbf{T_{eff} = (T_n . T_b) / (T_n + T_b)} \qquad \mathbf{(8)}$$

The Values Of $\mathbf{T_n}$ And $\mathbf{T_b}$ Are The Functions Of Particle Size. The Diameter Of The Particle Above Which The Physical Rotation Occurs Is Given Below[17]

$$\mathbf{Ds = (24kt/\Pi k)^{1/3}} \qquad \mathbf{(9)}$$

It Is Interesting That When $\mathbf{T_n = T_b}$ One Can Determine Critical Particle Radius Above This Radius The Brownian Relaxation Mechanism Occurs And Below This The Relaxation Is By Neel's Mechanism. These All Affects The Susceptibility Of The Ferrofluid In The Core Of The Test Cell And In Turn Changes Susceptibility ($\mathbf{X_i}$) And Permeability, Thereafter. The Change In The Permeability Changes The Inductance Of The Coil. The Susceptibility Of The Ferrofluid $\mathbf{X_i}$ Depends Upon Volume Fraction $\mathbf{\Phi_m}$ And Given By Equation 10.

$$\mathbf{X_i=(\Pi/18)(\Phi_m)(M_0 m_d{}^2 d^3/Kt)} \qquad \mathbf{(10)}$$

IV. MATHEMATICAL MODELING

Case I] Without Ferrofluid In Core

The Magnetic Field Inside The Solenoid Is Given By

$$B = \frac{\mu_0 \mu_r N I}{l}$$

The Total Flux Linked With The Solenoid Is Given By

Total Flux= $N{*}\phi_m$ = $N\iint B.ds$

The Total Flux = $N\left(\frac{\mu_0 \mu_r N I}{l}\right) A$

Now The Inductance $L = \frac{Total\,flux}{current}$

$$= \frac{\mu_0 \mu_r N^2 A I}{l I}$$

$$= \frac{\mu_0 \mu_r N^2 A}{l} \qquad \mathbf{(11)}$$

Case Ii] With Ferrofluid In Core

$$B = \frac{\mu_0 (\mu_r + \mu_r(i)) N I}{l}$$

Total Flux= $N{*}\phi_m = N\iint B.ds$ = N*B*A

Total Flux = $N{*}\frac{\mu_0 (\mu_r + \mu_r(i)) N I}{l}{*}A$

$$= \frac{\mu_0 (\mu_r + \mu_r(i)) N^2 A I}{l I}$$

$$L' = \frac{Total\,flux}{current}$$

$$= \frac{\frac{\mu_0 (\mu_r + \mu_r(i)) N^2 A I}{l I}}{I}$$

$$= \frac{\mu_0 (\mu_r + \mu_r(i)) N^2 A}{l}$$

$$L' = \frac{\mu_0 \mu_r N^2 A}{l} + \frac{\mu_0\ \mu_r(i) N^2 A}{l} \qquad \mathbf{(12)}$$

$$L' = L + \Delta l \qquad \mathbf{(13)}$$

Where $\mu_r(i) = 1 + X_i$ **(14)**

$$X_i = \left(\frac{\pi}{18}\right)(\phi m)\left(\frac{\mu_0\ \mu d2d3}{KT}\right) \qquad \mathbf{(15)}$$

$$\Delta l = \frac{\mu_0\left[1+\left(\frac{\pi}{18}\right)(\phi m)\left(\frac{\mu_0\ \mu d2d3}{KT}\right)\right] N^2 {*} A}{l} \qquad \mathbf{(16)}$$

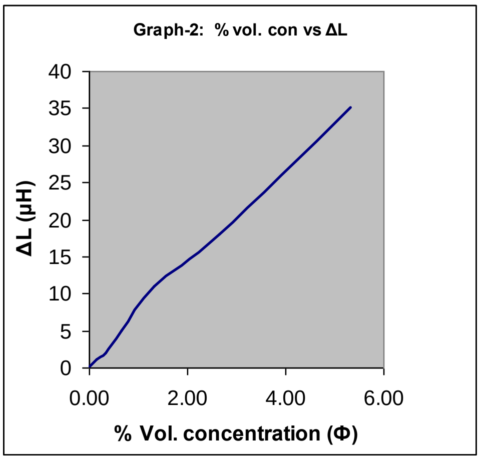

Fig.4.1: Inductance Value V/S % Volumetric Concentration.

CONCLUSION

An Attempt Has Been Made Stating Mathematical Relation Between Change In Inductance, Temperature, Volumetric Concentration, Domain Magnetisation And Size Of The Magnetic Nanoparticle As Shown In Equation (16).

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