JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

# Study of Magnetostriction property of Barium Ferrite to design a transducer using simulation

Basuki Nath Mishra,[1] and Dr. Shuchitangshu Chatterjee.[2]

1. Research Scholar of RKDF University, Ranchi, Jharkhand, India ,
2. Vice Chancellor, RKDF University, Ranchi, Jharkhand, India,

Abstract:

We are familiar with humming sound produced by electrical devices like transformer, Refrigerator etc. this noise is heard by us due to a physical phenomenon. All materials respond to a magnetic field in different mode. On the basis of different mode of magnetization, the materials are classified into different types like ferromagnetic, paramagnetic, diamagnetic etc. Ferromagnetism is the strongest magnetic state. When a magnetic field is applied to a magnetic material, it experiences an alteration in the dimension of the specimen. This alteration in the dimension of the materials may continue till the state of magnetic saturation of the specimen. This phenomenon came into light by J P joule(1842). He was able to measure the change in shape of a piece of magnetic material during magnetisation. This phenomenon was named as the magnetostriction which is most popular in modern research . Our focus in this work is to study the magnetostriction in barium hexaferrite ($BaFe_{12}O_{19}$ ).

Keyword : Magnetostriction, Saturation , Tensor, magnetostrictive materials, susceptibility

## 1. Introduction :

Manetostriction is a phenomenon in which the dimension of a magnetic material changes with respect to change in its magnetisation. Conversely, it shows the change in magnetic states of the material under the influence of the mechanical stress [1].The corresponding materials are known as magnetostrictive materials. These materials exhibits coupling between ferromagnetic and ferroelectric parameters [2]. The magnetostrictive materials may be assumed as a collection of tiny magnets (ellipsoidal) . These magnets rotate due to torque ,which is developed by applied magnetic field. This rotation of tiny magnets results a change in dimension as well as free strain in the material [3]. The phenomenon of magnetostriction can be understood through the theory of quantum mechanics. At atomic level, the magneto- mechanical coupling is explained using theory of spin orbit coupling [4]

Barium ferrite ( $BaFe_{12}O_{19}$) is a hard magnetic material having fairly large magneto -crystalline anisotropy, good chemical stability, high Curie temperature, and large saturation magnetization [5]. It has a high packing density and it is a metal oxide[6]. Barium ferrite is understood and expressed as $Ba^{2+}(Fe^{3+})_{12}(O^{2-})_{19}$. It has a net magnetic moment of $40\mu_B$ . [7] The specific heat of Barium ferrite is temperature dependent. It shows no inconsistency with long range polar ordering in the temperature range from 1.90 to 300 K[8]. In present time, $BaFe_{12}O_{19}$ is a popular ferrite permanent magnet. The Curie temperature ( $T_C$ ) is about 720 K and above. It depends on various factors like method of synthesis, grain size etc. and it was proposed to exhibit quantum Para electric behaviour[7] . $BaFe_{12}O_{19}$ is hexagonal ferrites . Commonly, it is known as Hexaferrite. The Barium hexaferrite is discovered in 1950s [8] .In this paper, we have studied the magnetostrictive characteristics of Barium ferrite. To study the characteristics, we have designed a transducer using Barium ferrite with the help of simulation software "COMSOL MULTIPHYSICS**".**

## 2. Historical background :

Magnetostriction was first measured by Joule(1818- 1889). [9]He was able to measure the deformation in the shape of a piece of iron during the process of magnetisation. Internally, the iron, ferromagnetic material contains domain which has varying densities of magnetic moments. The magnetic moments are aligned with one other in a single direction and uniform magnetic polarisation occurs within each specific domain. The domain may be divided into two or more new domain by splitting up the internal magnetic fields. These new domains require less magneto static energy to store. These new domains have magnetic moments in different directions such that the required energy to maintain the magnetic field at rest is minimum. After joules work on magnetostriction, some of the effects come in the field of magnetism.

Villari effect (1864): The change in susceptibility of magnetic material changes with respect to applied mechanical stress is called Villari effect . This effect is also known as magneto elastic effect .It is regarded as inverse of magnetostriction. [12]

Matteucci effect : The creation of helical anisotropy due to the applied torque.

Wiedemann effect : The development of torque in magnetostrictive material due to applied helical magnetic field is wiedemann effect. This is regarded as inverse of Matteucci effect.

## 3. Mechanism of Magnetostrictive effect :

In 1842, Joule declared that a ferromagnetic sample changes its length with respect to applied magnetism [9]. This was the beginning of the new concept magnetostrictive. Quantitively, Magnetostriction can be measured by joule's magnetostriction coefficient. The magnetostriction coefficient is the fractional change in length during the increase of magnetization from zero to the saturation point. $\lambda = \delta L / L$, where $\delta L$ is the change in length after magnetizing the material from zero to saturation point. L is the original length [10]. Magnetostriction coefficient($\lambda$) is a parameter to study the magnetostrictive character of the material. $\lambda$ is a dimensionless quantity which is expressed in term of $\times 10^{-6}$ . Generally , It is written as ppm. [11] Basically, Domain migration and reorientation under applied magnetic field are the primary cause of magnetostriction under applied magnetic field[9]. Ferromagnetic materials show magnetostriction to different degree. A ferromagnetic material at a compressed state (initially) shows more pronounced magnetostriction . The simple relation between strain and flux density is Strain = Change in length per unit original length of the sample rod = $\frac{\partial l}{\partial x} = KB^2$ ; where B is flux density and K is material constant. It behaves like an indicator. If K is positive then the rod is expended while negative K indicates contraction .

The strain tensor due to magnetostriction ($\varepsilon_{ij}$) can be divided into two distinct parts: a. due to joule magnetostriction ($e_{ij}$) and b. Volume magnetostriction ($e^v$)

$$\varepsilon_{ij} = \hat{e}_{ij} + e^v\delta_{ij} \qquad \text{-----------------} (1)$$

$\delta_{ij}$ is kronecker tensor , and $e^v$ is volution dilation . $e^v = \frac{1}{3}\varepsilon_{ii}$

Therefore, $\hat{e}_{ij} = \varepsilon_{ij} - e^v\delta_{ij}$

The volume magnetostriction is considerable for very high magnetic field, the magnetic field far greater than magnetic saturation.

$$e^v = 0 , \qquad H < H_s$$
$$= a\,(H - H_s). \quad H > H_s;$$ $H_s$ is magnetic field at saturation point.

In joule magnetostriction, The strain is assumed as a function of intensity of magnetisation(M). therefore we have assumed $\hat{e}_{ij} = \hat{e}_{ij}(M)$. For an isotropic media, the strain has its maximum value along X- axis at saturation point.λ

Therefore, we can represent the strain in matrix form as $\hat{e}_{ij} = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & -\frac{1}{2}\lambda & 0 \\ 0 & 0 & \frac{1}{2}\lambda \end{pmatrix}$ where λ is the relative change in dimension at saturation.

If the material is assumed as linear between the demagnetized and saturation state,

then $\hat{e} = \lambda\ [|M|\ /\ |M_s|$, $M_s$ is magnetisation at saturation

Generally, In simple mechanical problem (without magnetic field), the elasticity problem is solved by principal of minimum energy []. Thus we can express the equation as :

$I(U_i) = \int_v w^e\,dv - \int_v f_i U_i dv - \int_{st} TiUi\,dS$ ------------------ (2) V : Volume of the body, $f_i$ = internal force, $T_i$ = stress, St :Surface on which the stress is prescribed, $w^e$ = density of elastic energy, it may be expressed as the quadratic form of the strain tensor. $w^e = \frac{1}{2} C_{ijkl}\ .\varepsilon_{ij}\ .\varepsilon_{kl}$ ; $C_{ijkl}$ is the Hookes tensor(order-4). This tensor can be derived into two independent component $C_{11}$ and $C_{12}$ for isotropic material. These two independent constants may be expressed in terms of Elasticity constant (E) and Poisson ratio (σ).

$C_{11} = E(1-\sigma)/(1+\sigma)(1-2\sigma)$ and $C_{12} = E\,\sigma/(1+\sigma)(1-2\sigma)$

If the magneto static energy is added to the simple mechanical problem, then magnetostriction effect has been found. Thus the equation (2) may be modified as

$I(U_i) = \int_v w^e\,dv - \int_v f_i U_i dv - \int_{st} TiUi\,dS - \int_v w^m\,dv$ ------------------ (3)

In this work , we have considered magnetostriction only. Therefore, We have neglected the forces which are not directly responsible for magnetostriction.

$\therefore\ I(U_i) = \int_v w^e\,dv\ - \int_v w^m\,dv$ ------------------------------------(4)

The density of magnetic elastic energy is $w^m = S_{ij}\ .\varepsilon_{ij}$ ; $S_{ij}$ is stress due to magnetostriction.

$W^m$ can be expressed as following (using Hook's Law)

$$W^m = \frac{3}{2}(C_{11} - C_{12})\,\hat{e}\,[\varepsilon_{11}(\alpha_1^2 - \tfrac{1}{3}) + \varepsilon_{22}(\alpha_2^2 - \tfrac{1}{3}) + \varepsilon_{33}(\alpha_3^2 - \tfrac{1}{3})] + 3(C_{11} - C_{12})\,\hat{e}\,[\varepsilon_{12}\alpha_1\alpha_2 + \varepsilon_{23}\alpha_2\alpha_3 + \varepsilon_{13}\alpha_1\alpha_3] + (C_{11} + 2C_{12})\,e^v[\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}];$$

$\alpha_i$ is the direction of magnetisation[].

Nonlinear magnetization in the magnetostrictive material is

$\mathbf{M} = M_s\,L(|H_{eff}|)\,H_{eff}/|H_{eff}|)$

Here L is the Langevin function.

$L = \coth(3\chi_m.\,/|H_{eff}|/M_s) - M_s / 3\chi_m.\,|H_{eff}|$

Where $\chi_m$ is the magnetic susceptibility ( initial linear region) and $H_{eff}$ is the effective magnetic field. Effective magnetic field has two terms. First term is related to magnetic field and the second term is associated with the mechanical stress contribution to effective field.

$H_{eff} = H + (\lambda_s / \mu_0 M_s^2)\,S_{ed}\,M$

Where $S_{ed} = dev(C_H\varepsilon_{el})$

The magnetization(**M**) and magnetic field(**H**) are associated with flux density (**B**) as

$\mathbf{B} = \mu_0(H + M)$.

## 4. Model definition and simulation :

In this work, we have studied the magnetostrictive nature of Barium hexaferrite using simulation .we have designed a virtual transducer using Barium hexaferrite with the help of simulation software COMSOL Multiphysics. Due to symmetric nature of geometry, the transducer is modelled in 2D axisymmetric mode in model wizard option (figure 1). This reduces the computation time. In this model, we have designed a drive coil

. this coil is enclosed by a steel housing .A piece of Barium ferrite is placed in the core of the coil. This works as an actuator . The magnetic field is created by passing a current through the drive coil.

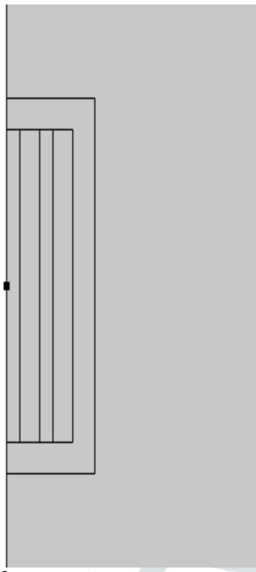

Fig 1 : Model of transducer in 2D axisymmetric mode in COMSOL Multiphysics

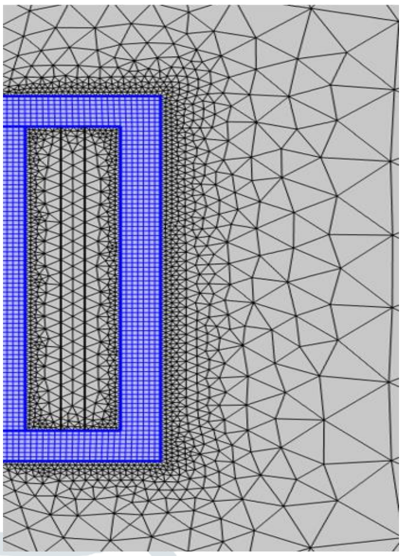

Fig 2 : Mesh used in the project

The following parameters are used to describe the nature of magnetostrictive material in the present work(Table- 1)

Table 1: Basic constants /Parameter for barium ferrite

| Property | Symbol | value | Remarks |
|---|---|---|---|
| 1. Young Modulus | Y | $1.115 \times 10^{11}$ N/m$^2$ | Ref 10 |
| 2. Poisson's ratio | ν | $9.86 \times 10^{10}$ N/m$^2$ | ,, |
| 3. Density | ρ | 5.28 g/cm$^3$ | Wikipedia |
| 4. Electric conductivity | σ | $1.22 \times 10^{-2}$ S/cm | Ref -11 |
| 5. Relative Permitivity | $\varepsilon_r$ | 32 | Ref -12 |
| 6. Saturation magnetostriction | $\lambda_s$ | 9 ppm | Ref. 13 |
| 7. Saturation Magnetisation | $M_s$ | 44.65emu/gm | Ref 14 |

The mesh in this simulation software, COMSOL Multiphysics affects the result strongly . Actually , meshing is the most memory-intensive steps for finite element method. Meshing is important for correct result of the problem. We have used two types of meshing to get excellent result of the model- free squad and free triangular.

**5. Result and discussion :**

A. The results obtained by simulation software COMSOL are studied. The applied current density in the coil was $10^6$ A/m$^2$ . The electric current causes magnetic field. this magnetic field results magnetostriction in Barium hexaferrite. The variation of stress in Barium hexaferrite is studied. The data found in simulation using comsol is plotted. The variation of stress in Barium hexaferrite , as a surface plot is shown in figure 3 & 4. Figure 3 is 2d effect while figure 4 is 3d effect. This plot helps to understand that the developed stress in the piece of material due to magnetostriction is nonzero near the bottom surface only and uniformly zero except that region (the region near the bottom surface of the rod). This is caused due to the boundary condition applied to the rod . on the basis of observation we may conclude that free strain due to magnetostriction cannot produce any stress until the material is mechanically constrained.

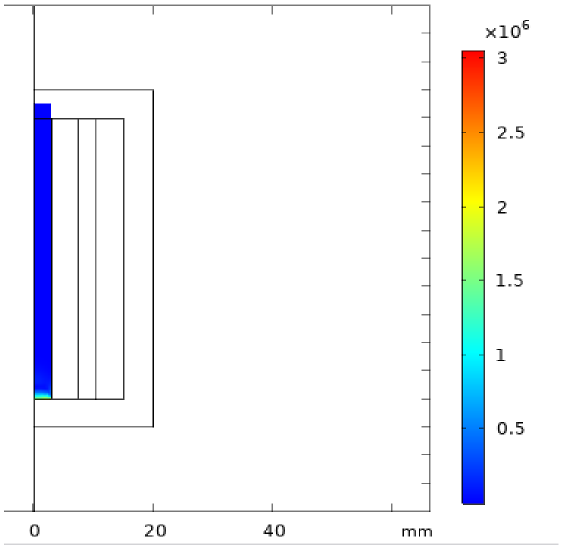


Fig 3 : variation of stress in COMSOL Multiphysics

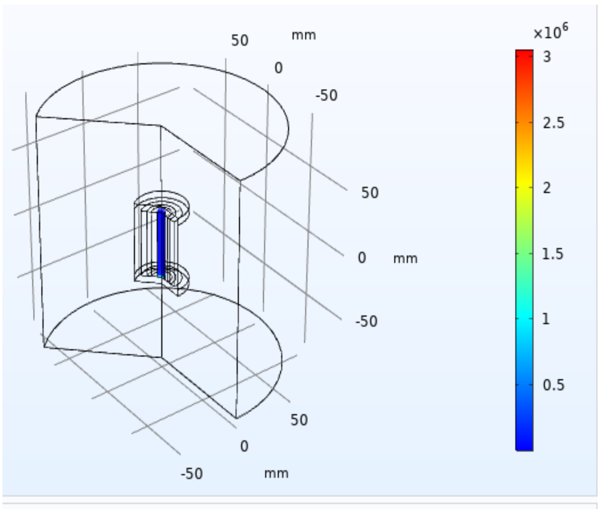


Fig 4 : variation of stress (3D) in COMSOL Multiphysics

B. The concentration of magnetic flux in the core due to designed steel housing is studied .the variation is shown in figure -5.The figure indicates that the magnetic flux density in the core of the coil (Barium hexa ferrites) is almost uniform. This is the validation of the Fringe effect. In the result, the bending of the flux lines towards the edge is seen at the end of the rod. In this region, majority of the magnetic flux is forced to curl into the steel housing. This is due to ferromagnetic nature of Steel. The 3D visualisation of variation is shown in figure -6 .

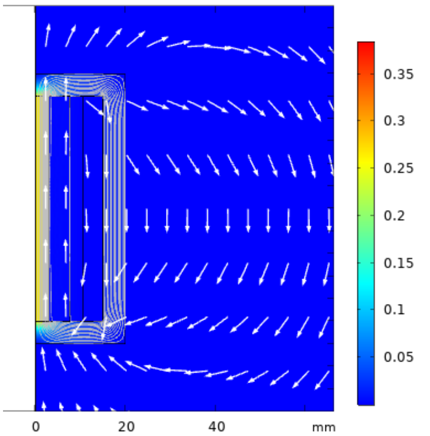


Fig 5 : magnetic flux density in Barium hexaferrite using COMSOL Multiphysics

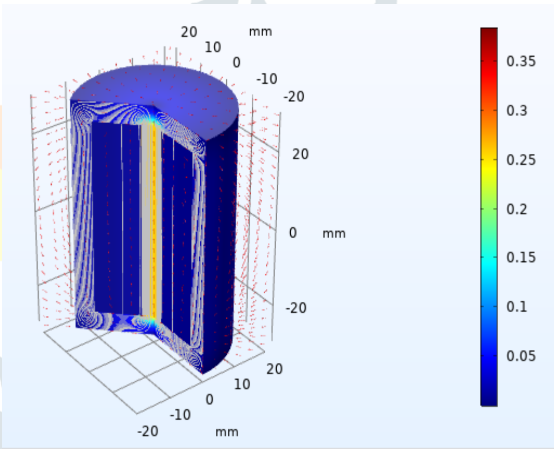


Fig 6 : magnetic flux density in core of the coil using COMSOL Multiphysics

C. **Magnetostriction curve :** magnetostriction curve of Barium hexaferrite obtained from the parametric study which is simulated a quasi-static ramping up of the current density (about $10^6$ A/m) in the coil is shown in fig 7. This figure indicates that the experimental material, Barium hexaferrite ($BaFe_{12}O_{19}$) exhibits nonlinear magnetostriction. While most ferromagnetic materials exhibits the linear magnetostriction. The large magnetostriction means high level magneto mechanical coupling. This Coupling arises due to orientation of magnetic moments on interatomic spacing [21]. The curvature under figure-7 shows positive magnetostriction of the Barium hexaferrite . It indicates and verifies the elongation of the sample irrespective of the direction of the rotation of magnetic moments

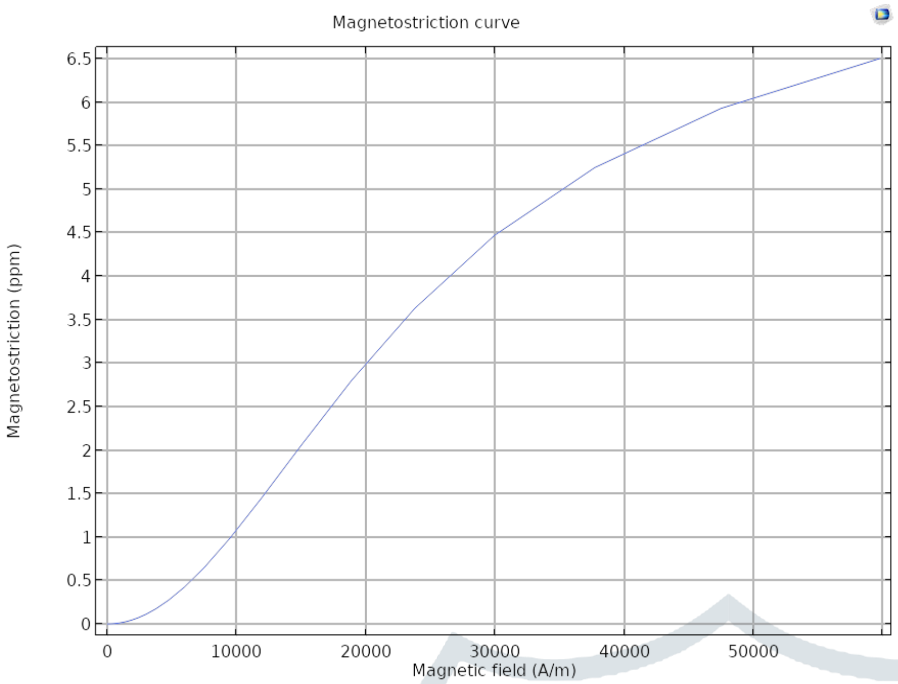


Fig 7: Magnetostriction Vs Magnetic field

D. **B H Curve** : The B H curve is the visualisation of relationship between magnetic flux density and magnetic field intensity of a ferromagnetic material. The slope of the BH curve results the value of permeability of the material. The ideal magnetic material (lossless) shows BH curve in the form of straight line. In real world, the magnetic flux density (B) in the material is limited to maximum value due to magnetic saturation. This results non – linear BH curve [22] . The B-H curve of barium hexaferrite as per observation during simulation is shown in figure 8. In this graph ,we have considered only z- components of corresponding vectors, B as well as H. this is due to the fact that, the magnetic field is oriented along the axial direction. The significantly non-linear behaviour of B-H curve is found in the region 20 KA $>H_z>$ 5 KA.

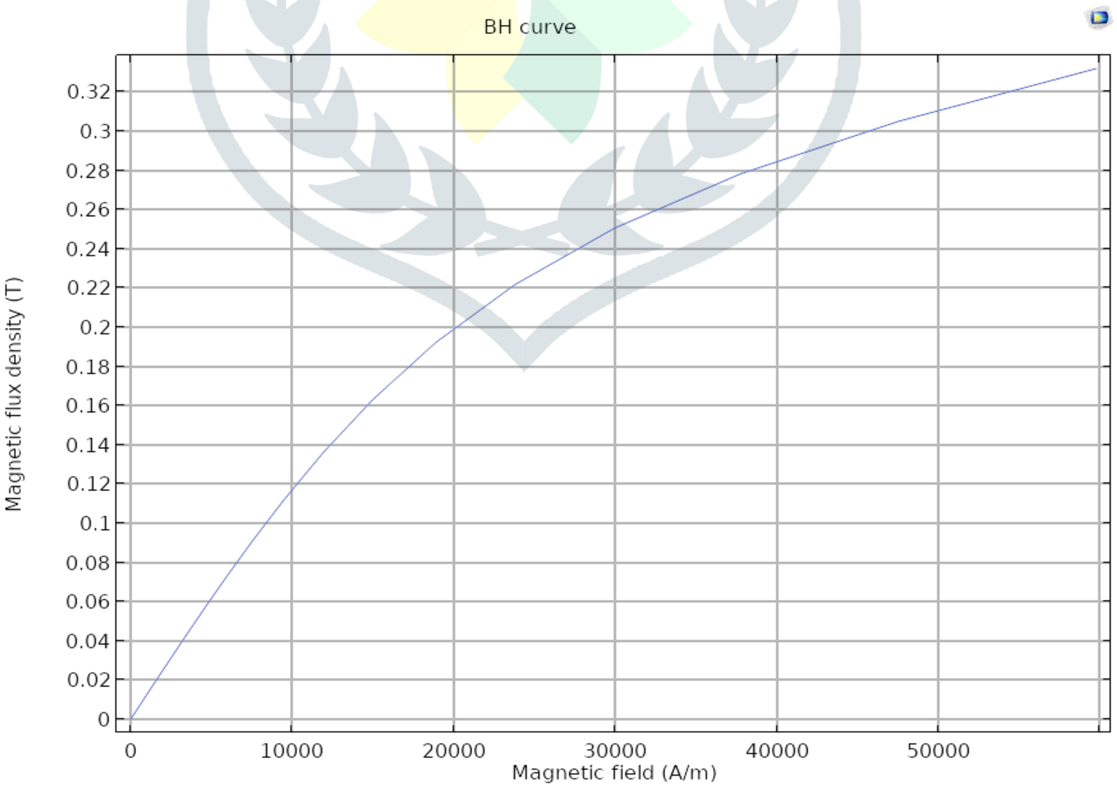


Fig 8 : BH characteristics of barium hexaferrite

## 6. Conclusion :

The Simulation software COMSOL Multiphysics is used to study the behaviour of Barium hexaferrite as magnetostructive transducer. In the observation, we found the positive magnetostriction in the material which indicates the elongation of the sample irrespective of the direction of the rotation of magnetic moments. The B-H curve of the sample is nonlinear monotonic curve. This indicates the magnetic saturation of the material, Barium hexaferrite. The total magnetic energy in this transducer is 78.62 µJ, while the electrical energy is zero. Total reaction moment is (0,0,0) in (r, φ, z) coordinate system. The referential impedance is 50Ω. This observation indicates that the response of transducer designed with barium ferrite may be increased by doping some elements or molecule in Pure Barium ferrite.

## 7. Acknowledgement :

We have taken a lot of efforts to complete this research paper. However, it would not have been possible without the effective support of many individuals. We would like to extend our sincere thanks to all of them.
We are highly indebted to RKDF, university for providing necessary facilities in completion of this paper. We would like to extend our thanks and appreciation to all people who are directly or indirectly support us in completion of this article

## References:

1. Buschow, K.H.J. and de Boer, F.R., 2003. Magnetostrictive materials. In *Physics of Magnetism and Magnetic Materials* (pp. 171-175). Springer, Boston, MA.
2. eng Z, Dapino MJ (2017) Review of magnetostrictive vibration energy harvesters. Smart Mater Struct 26(10):10300
3. Chikazumi, S. and Graham, C.D., 1997. *Physics of ferromagnetism* (No. 94). Oxford university press.
4. GusEv, A.A., 1956. The Quantum Theory of Magnetostriction. *SOVIET PHYSICS JETP*, *2*(1).
5. Babu, V. and Padaikathan, P., 2002. Structure and hard magnetic properties of barium hexaferrite with and without La2O3 prepared by ball milling. *Journal of magnetism and magnetic materials*, *241*(1), pp.85-88.
6. Pullar, R.C., 2012. Hexagonal ferrites: a review of the synthesis, properties and applications of hexaferrite ceramics. *Progress in Materials Science*, *57*(7), pp.1191-1334.
7. Cao, H.B., Zhao, Z.Y., Lee, M., Choi, E.S., McGuire, M.A., Sales, B.C., Zhou, H.D., Yan, J.Q. and Mandrus, D.G., 2015. High pressure floating zone growth and structural properties of ferrimagnetic quantum paraelectric BaFe12O19. *Apl Materials*, *3*(6), p.062512.
8. S. P. Shen, Y. S. Chai, J. Z. Cong, P. J. Sun, J. Lu, L. Q. Yan, S. G. Wang, and Y. Sun, Phys. Rev. B **90**, 180404(R) (2014).
9. Joule, J.P., 1842. On a new class of magnetic forces. *Ann. Electr. Magn. Chem*, *8*(1842), pp.219-224.
10. Hristoforou, E. and Ktena, A., 2007. Magnetostriction and magnetostrictive materials for sensing applications. *Journal of Magnetism and Magnetic Materials*, *316*(2), pp.372-378.
11. Decocker, R., Kestens, L. and Houbaert, Y., 2002. Modelling the magnetostriction coefficient of polycrystalline ferromagnetic materials with a cubic structure by means of the finite element method. *Journal of magnetism and magnetic materials*, *242*, pp.1218-1220.
12. Villari, E., 1864. Intorno alle modificazioni del momento magnetico di una verga di ferro e di acciaio, prodotte per la trazione della medesima e pel passaggio di una corrente attraverso la stessa. *Il Nuovo Cimento (1855-1868)*, *20*(1), pp.317-362.
13. Li, W.X., Yu, K. and Cheng, D., 2000. Super magnetostrictive material of rare-earths--a study. *Mining and Metallurgical Engineering(China)(China)*, *20*(3), pp.64-67
14. Dapino, M.J., 2004. On magnetostrictive materials and their use in adaptive structures. *Structural Engineering and Mechanics*, *17*(3-4), pp.303-330.
15. J. J. Went, G. W. Rathenau, E. W. Gorter, and G. W. Van Oosterhout, Philos. Technol. Rev. **13**, 194 (1952).

16. Reddy, B.P.N. and Reddy, P.J., 1974. Elastic moduli of some ferrites at low temperatures. *Philosophical Magazine*, *30*(3), pp.557-563.
17. Gu, H., Zhang, H., Ma, C., Sun, H., Liu, C., Dai, K., Zhang, J., Wei, R., Ding, T. and Guo, Z., 2019. Smart strain sensing organic–inorganic hybrid hydrogels with nano barium ferrite as the cross-linker. *Journal of Materials Chemistry C*, *7*(8), pp.2353-2360.
18. Mallick, K.K., Shepherd, P. and Green, R.J., 2007. Dielectric properties of M-type barium hexaferrite prepared by co-precipitation. *Journal of the European Ceramic Society*, *27*(4), pp.2045-2052.
19. Gutiérrez, J., Lasheras, A., Barandiarán, J.M., Gonçalves, R., Martins, P. and Lanceros-Méndez, S., 2015. Induced magnetoelectric effect driven by magnetization in BaFe 12 O 19-P (VDF-TrFE) composites. *IEEE Transactions on Magnetics*, *51*(11), pp.1-4.
20. Dairy, A.R.A., Al-Hmoud, L.A. and Khatatbeh, H.A., 2019. Magnetic and structural properties of barium hexaferrite nanoparticles doped with titanium. *Symmetry*, *11*(6), p.732.
21. Evans, P.G. and Dapino, M.J., 2010. Efficient magnetic hysteresis model for field and stress application in magnetostrictive Galfenol. *Journal of applied physics*, *107*(6), p.063906.
22. Soong, W.L., 2008. Bh curve and iron loss measurements for magnetic materials. *Power Engineering Briefing Note Series*, *12*.