The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 33, Pages 28-35

IConTech 2025: International Conference on Technology

The Novelties by Using R Programming Language for Simulate Magnetic Hysteresis Loop

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Abstract: Magnetic materials can be classified as hard and soft, depending on the shape of the hysteresis loop. The hysteresis loop describes the magnetic behaviour of the magnetic materials to which an external magnetic field is applied. The shape of the hysteresis loop can be obtained by drawing point by point the B-H dependency by measuring the induced magnetic flux density (B) and the magnetizing force (H), or by visualization with specific laboratory equipment (usually the oscilloscope). Because of the labouring process of these experiments and due to the little research in the computational methods in this direction, nowadays it is impossible to find data sets with a hysteresis loop that can be further used for automatic classification of the magnetic materials and automatic detection of the magnetic materials application field. This paper aims to create and generate the magnetic hysteresis loop in the R programming language with two different approaches. One model was created with a hysteresis package, and one was created by using a synthetic function cloned with an existing mathematical model for magnetic hysteresis.

Keywords: Magnetic materials, Hysteresis loop, R programming language

Introduction

Although the primary property of magnetic materials—the ability to generate a magnetic field and interact with other external fields—was discovered many centuries ago, William Gilbert was the first to analyze and observe modern magnetism in the latter part of the 1600s, and his experiments were published nearly three centuries later (Gilbert & Wright, 1893).

Researchers have discovered it over the years and have advocated for various uses of magnetic materials as well as alternative chemistry to produce materials with magnetic properties. Warburg's creation of the first iron hysteresis loop in 1880 was one of the most significant breakthroughs (Schmool, 2018). The figure below (Figure 1) shows the phases of permanent magnetic material development and improvement based on capabilities per unit volume of material.

Years of study and experimentation have led to observations on the dependence between B (magnetic induction) and H (magnetic field strength). This dependence is known as the hysteresis loop for magnetic materials, and it simply indicates that a remanent induction (Br) is present in the material following the annulment of the external magnetic field (H=0). The applied field must be reversed and then cancelled once more to end the hysteresis loop. The hysteresis loop for ferromagnetic materials is in Figure 2.

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

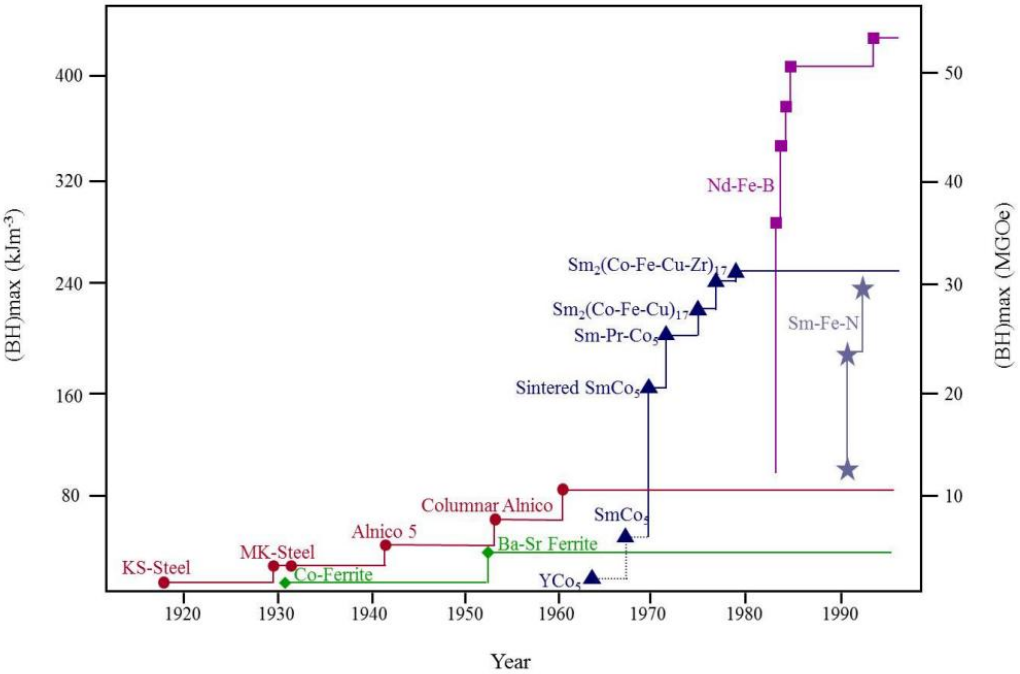


Figure 1. The stages of development and improvement of the permanent magnetic materials between 1920 and 1990 (Coey, 2011)

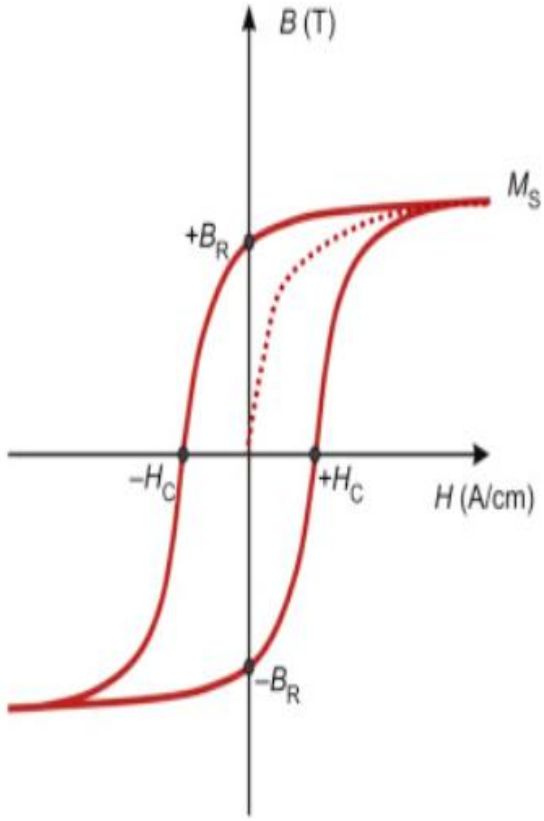
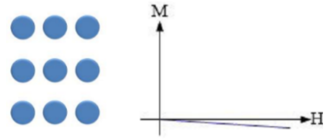
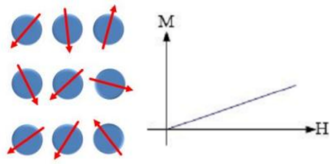
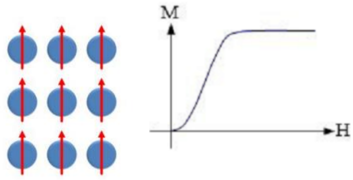
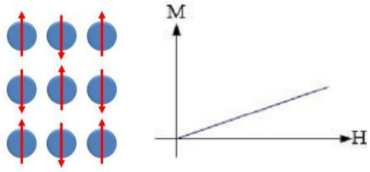
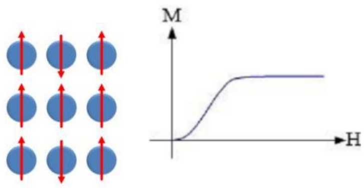


Figure 2. (B, H) dependency for ferromagnetic materials. Histerezis loop (Sieniutycz, 2016)

These three magnetic parameters—saturation magnetisation (Ms), induction remanence (Br), and coercivity (Hc)—are essential for practically characterising a ferromagnetic material. The magnetic materials were classified into five groups due to their distinct behaviours when exposed to an external magnetic field (different dependencies between M and H). The table below provides a brief description of these groups (Table 1) (Scepka, 2016).

Table 1. Materials clasification according to their magnetic susceptibility and atoms magnetic moments

Type	Characteristics for magnetic behavior	Graphics
Diamagnetic materials	Atoms have no magnetic moment. Susceptibility - small and negative	
Paramagnetic materials	Atoms have randomly oriented magnetic moments. Susceptibility- small and positive.	
Ferromagnetic materials	Atoms have parallel aligned magnetic moments. Susceptibility- bigger.	
Antiferromagnetic materials	Atoms have antiparallel aligned magnetic moments. Susceptibility - small and positive.	
Ferrimagnetic materials	Atoms have mixed parallel and antiparallel aligned magnetic moments. Susceptibility -bigger	

The magnetic susceptibility (χ) value and sign indicates the strength of attraction (or not being attracted) of the materials into an external magnetic field. According to their internal magnetism, magnetic materials can be divided in two main categories:

- Hard magnetic materials: magnetism is permanent and are difficult to magnetize and demagnetize into external magnetic field
- Soft magnetic materials: magnetism is temporally and can be easily magnetized and demagnetized into external magnetic field (Prathik, 2024)

The figure below illustrates the (B, H) dependency of the two kinds of magnetic materials (hysteresis loop) as reported by Prathik et al. (2024).

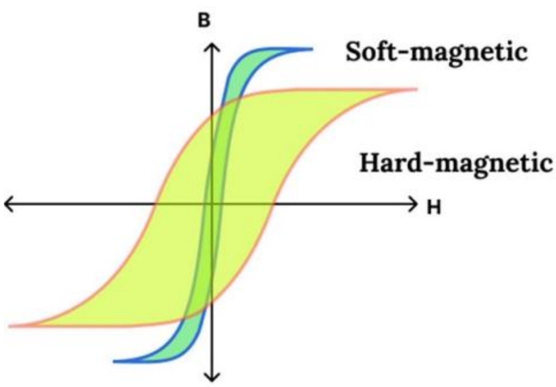


Figure 3. Histerezis loop for hard and soft magnetic materials (Prathik, 2024)

Figure 3 shows that the magnetic hysteresis for hard magnetic materials has a higher coercivity, a smaller saturation of magnetization, and a larger angle of inclination. The inclination angle is smaller for soft magnetic materials, but the saturation and coercivity are larger and smaller, respectively.

Method

The B-H dependency of the magnetic materials that are exposed to an external magnetic field, and several mathematical models have been created over time to simulate behavior. Few models can produce good results when compared to experimental data, but not all of them have been able to accurately simulate the behavior of the complete phenomenon that happens every time a material is exposed to external fields. A brief list of some of the numerous mathematical models is shown here (Morée Gustav, 2023):

- Duhem model
- Coleman-Hodgdon model
- Jiles-Artherton model
- Talukdar-Bailey model
- Flatley-Henretty model, so on.

With the new modern technologies and AI (Artificial Intelligence), the concept included nowadays everywhere, AI algorithms have been implemented to develop new magnetic materials with characteristics requested by advanced applications and equipment. Liccardi et al. (2024) has been developing neural network architecture to model magnetic hysteresis (Licciardi, 2024). According to Liccardi et al. (2024) neural networks are suitable for use to modelling magnetic hysteresis. Liccardi et al. (2024) shown that RNN (Recurrent Neural Network) and CNN (Convolutional Neural Network) models have the capability to predict hysteresis dynamics even in the absence of material information. But, even with this cutting-edge studies, it is impossible to find a data base with hysteresis loops that furthen can be used for faster classification of magnetics materials. The moste used open acces datasets as Kaggle, open ML, Sigma AI and Github, are not given datasets with hysteresis loop. In this scope, this paper aim to tackle the programming part that can be used after in genereting more hysteresis loops. Two methods are presented for modelling the magnetic hysteresis loop, as follow:

- Using hysteresis package in R programming language
- Creating functions in R programming language that simulate the mathematical model of hysteresis.

Although the R language has been selected for this study, both of these approaches can be effectively implemented in the phyton programming language as well. A strong tool for statistical programming is the R language. Complex probability issues, linear and logistic regression, ANOVA, time series analysis, multilevel linear and non-linear models, etc., can all be effectively resolved with the R programming language (Long J. D, 2019). Many fields, including economics, physics, engineering, medicine, and more, use the R programming language to solve complex problems. (Field, 2012).

Results and Discussion

1. Hysteresis package in R programming language

Magnetic hysteresis loop occurs because the output variable (magnetization M and inductance B of the material) can have more possible values at the same input value (external magnetic field with the strength H) and depends on the material history (has already being magnetized or not) and on the strength and sign of the applied magnetic field. R programming language has been published in their repository and inserted the new package "Hysteresis" (Maynes, 2021).

The hysteresis packedge does help to fit, summarize and plot sinusoidal hysteretic processes using two step harmonic least squares. The pachadge fits input and output variables x and y that form a hysteresis loop based on the generalized transcendental equation (Maynes, 2021).

$$x_t = b.x * \cos\left(2\pi \frac{t}{T} + phase.angle\right) + cx + e_{x,t} \tag{1}$$

$$y_t = b.y * \cos\left(2\pi\frac{t}{T} + phase.angle\right)^n + retention * \sin\left(2\pi\frac{t}{T} + phase.angle\right)^m + cy + e_{y,t} \quad (2)$$

$$t = 0, \ldots, n.points - 1 if times = 'equal' \quad (3)$$

The functions used and their functionality in the programm cand be found in the table here below (Table 2).

Table 2 Functions used in hysteresis packhadge (S. Maynes, 2021)

Name	Characteristics	Example
mloop	Simulate a hysteresis loop with a variety of possible parameters	`mloop(cx = 0, cy = 0, retention = 0.2, b.x = 0.6, b.y = 0.8,n = 1, m = 1, sd.x = 0, sd.y = 0, phase.angle = 0, n.points = 24, period = 24,extended.classical=FALSE,seed=NULL)` `mloop2r(cx=0,cy=0,retention.above=0.2,retention.below=0.15,b.x=0.6,b.y=0.8,n=1, m=1,sd.x=0,sd.y=0,phase.angle=0,n.points=24,period=24, extended.classical=FALSE,seed=NULL)`
floop	Fits a hysteresis loop given values of n and m chosen by the user. floop2r fits an asymetric loop with different values for retention above and below the split line.	`floop(x,y=NULL,n=1,m=1,times="equal",period=NULL, subjects=NULL, subset=NULL,na.action=getOption("na.action"), extended.classical=FALSE,boot=FALSE,method="harmonic2", ...)` `floop2r(x,y=NULL,n=1,m=1,times="equal",period=NULL, subjects=NULL, subset=NULL,na.action=getOption("na.action"), extended.classical=FALSE,boot=FALSE,method="harmonic2", ...)`
mel	Produces an ellipse based on 1 of 4 possible formulations: 1-Eigenvalues, 2-Hysteresis Coefs, 3-Amplitudes and 4-Algebraic Coefs.	`mel(method=1,seed=NULL,...)` `mel1(cx=32,cy=39,rote.deg=2,semi.major=7,semi.minor=0.23, phase.angle=0,n.points=24,period=24,sd.x=0,sd.y=0)` `mel2(cx=32,cy=39,b.x=6.99,b.y=0.244,retention=0.23, phase.angle=0,n.points=24,period=24,sd.x=0,sd.y=0)` `mel3(cx=32,cy=39,ampx=6.99,ampy=0.335,lag=2.888,phase.angle=0, n.points=24,period=24,sd.x=0,sd.y=0)` `mel4(x2=0.002293,xy=-.06960,y2=0.9976,x=2.567,y=-75.58,int=1432.7, phase.angle=0,n.points=24,period=24,sd.x=0,sd.y=0)`
fel	Fit a sinusoidal hysteretic (elliptical) process between an input and an output.	`fel(x, y=NULL, method = "harmonic2", period = NULL, subjects = NULL, times="unknown",subset = NULL,na.action= getOption("na.action"), control=nls.control(), boot=FALSE,...)`
summary.fittedloop	Summary methods for classes ellipsefit and fittedloop created by the functions fel and floop. Can bootstrap results to produce parameter estimates with reduced bias and standard errors.	`## S3 method for class 'ellipsefit'` `summary(object,boot=TRUE, N = 1000, studentize=TRUE, center=FALSE, cbb=NULL, joint=FALSE,seed=NULL,...)` `## S3 method for class 'fittedloop'` `summary(object,boot=TRUE,N=1000, cbb=NULL,joint=FALSE,seed=NULL,...)` `## S3 method for class 'loop2r'` `summary(object,boot=TRUE,N=1000, cbb=NULL,joint=FALSE,seed=NULL,...)`

The results of plotting the hysteresis loop with the help of “hysteresis” packadge from the R, can be found in the figure here below (Figure 4)

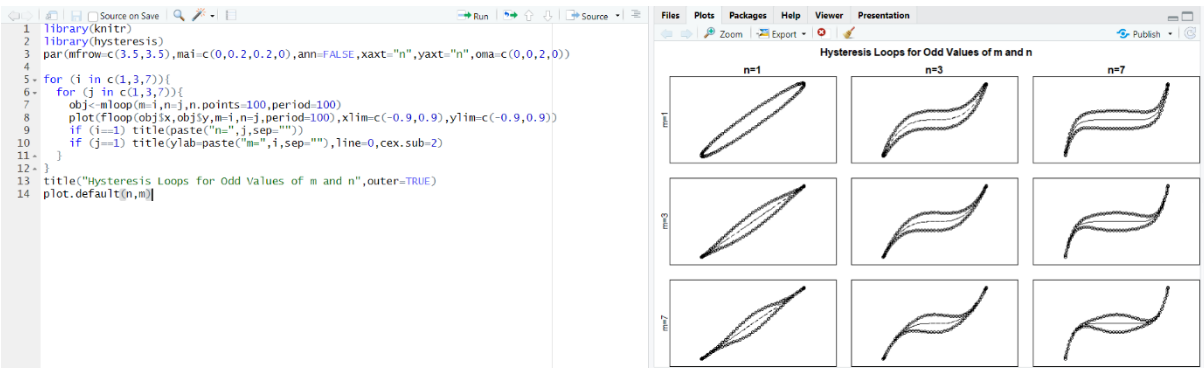


Figure 4. Hysteresis loop for odd values for n and m

For fitting the hysteresis loop it will be used the next sequence of the code:

15 loop <- mloop(n=3, m=5,sd.x=0.05,sd.y=0.1)

16 fitloop <- floop(loop$x,loop$y,n=3, m=5,period=25,times="equal")

17 plot(fitloop,main="Fitted Hysteresis Loop")’’

The results cand be seen in the figure here below (Figure 5):

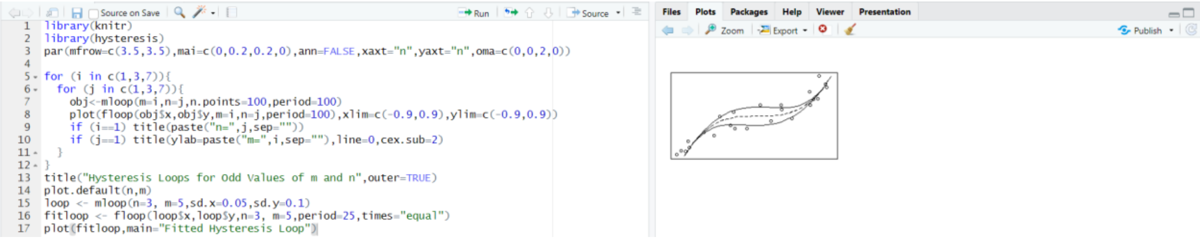


Figure 5. Fitted hysteresis loop

2. Mathematical model of hysteresis implemented in R programming languages

As mentioned previously in Method chapter, many mathematical models were developed to simulate hysteresis loops. For this study it was used as a mathematical model proposed by Pop (2019) in the scientific paper “A model for magnetic hysteresis” (Pop, 2019). In the mathematical models for magnetic histeresis proposed in this paper, it was succesfully prove that equation (4) for the cobalt ferite sample simulate with high accuracy the magnetic histeresis for this material

$$CoFe_2O_4$$

(Pop, 2019).

$$M_i = \frac{M_s}{2}\left(\frac{H_e + H_c}{\sqrt{H_e^2 + H_a^2 + 2H_eH_c}} + \frac{H_e - H_c}{\sqrt{H_e^2 + H_a^2 - 2H_eH_c}}\right)$$
$$H_e = H + \alpha_0' M \tag{4}$$

The data used for this simulation are given in the next table (Table 3)

Table 3. Data used in the R language simulation for magnetic hysteresis for the cobalt ferite materials (Pop, 2019)

Parameter	Meaning	Value
Ms(A/m)	Saturation magnetization	420000
Mr(A/m)	Remanent magnetization	201700
Hc(A/m)	Coercivity	20200
Ha(A/m)	Fictional magnetic field	188700
α_0'	Fitting coeficient	0.478

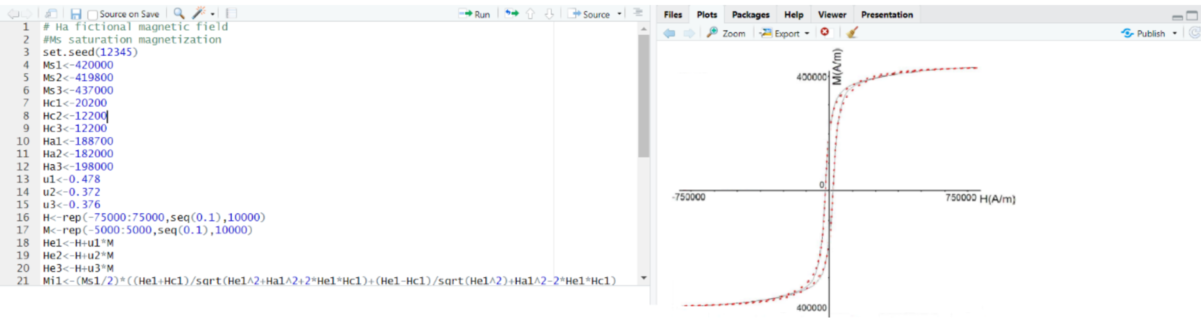


Figure 6. Magnetic hysteresis for cobalt ferite materials by using syntetic function as per eq. (4) and the values from Table 3 in R programming language

Conclusion

Because of the complexity of the physical phenomenon that occurs every time when a magnetic material is supposed to be an external magnetic field, the research to find the best solution to simulate this behavior is still of high interest for the researchers in this domain. Also, the high competences in programming language does not guarantee the disclosure of a general of a model for magnetic hysteresis general valid for all types of materials. With the use of the R programming language, it was accomplished in generation magnetic hysteresis loops from two different approaches. Firs one by using the R package "hysteresis" and the second by using the mathematical model developed with synthetic physical functions for cobalt ferrite materials. Further research aims to develop a generative R programming language for the two types of magnetic materials (hard and soft) for better and faster classification. For this a large amount of laboratory measurement data will be needed.

Scientific Ethics Declaration

The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

The authors declare that they have no conflicts of interest

Funding

This study received no external funding.

Acknowledgements or Notes

This article was presented as a poster presentation at the International Conference on Technology (www.icontechno.net) held in Trabzon/Türkiye on May 01-04, 2025.

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To cite this article:

Raducan, E., Moldovanu, S., & Vlad, C. (2025). The novelties by using R programming language for simulate magnetic hysteresis loop. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 33,* 28-35.