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MODELING OF THE NORMAL MAGNETIZATION CURVE OF FERROMAGNETIC

Abstract. The normal magnetization curve is used in technical calculations of magnetic circuits when it is required to investigate (to model) nonlinear inductive elements. Modeling of the normal magnetization curve by the use of an analytical function allows describing with a high precision a real magnetization curve along all characteristic sections and defining the magnetization curve by the continuous function. This procedure allows avoiding breaks and discontinuities of the extreme dependences obtained as a result of differentiation. There are a lot of ways of approximating the table function by the analytical function which with a particular degree of accuracy models an initial function at the given points. Modeling of the normal magnetization curve of the ferromagnetic is done by using the *arctangent* function for approximation of the curve and the Matlab software. The *arctangent* function is chosen because this function and its derivative are easily calculated and also because this function describes the normal magnetization curve with an adequate accuracy. There are also the experimental data of magnetic field induction dependence on magnetizing field intensity and the approximating magnetization curve. The obtained diagrams show that the table function is approximated by the analytical function of *arctangent* which with a sufficient accuracy models the table function at the given points.
Key words: ferromagnetic, magnetization curve, experimental data, approximation, arctangent function.

Introduction. Modeling of the normal magnetization curve of the ferromagnetic is done by using the Matlab software [1-7]. The Matlab software is based not only on the best practices of development and computer realization of numerical methods build up for the last three decades but also on all experience of formation of mathematics throughout all history of mankind. About one million legally registered users already apply this software. The top universities and scientific centers of the world willingly use it in their scientific projects. It is important that the Matlab software can be integrated with such popular software as Mathcad, Maple and Mathematica. Thus, the Matlab system can become the excellent assistant in scientific research.

Unfortunately, the numerical calculations which are carried out by students often are done by means of the calculator that is almost manually. Modern computers are frequently used only for presentation of the work. Actually students should be able not only to solve these or other engineering problems, but also do them by using modern methods, that is, using personal computers.

The use of the computer simulation allows: to individualize and differentiate tutoring process; to exercise control with diagnostics of mistakes and with a feed-back; to carry out self-testing and self-correction of educational activity; to avoid during indoor classes the laborious routine calculations due to performing them by computers; to visualize an educational information; to simulate and imitate the studied processes or phenomena; to carry out the virtual version of the real laboratory works and experiments by simulating them on the computer; to develop imaginary and theoretical thinking; to enhance learning motivation; to form the culture of cognitive activity, etc.

In M.Auezov South Kazakhstan State University computers are used on Physics classes for the following activities: statistical processing of results of a laboratory experiment and plotting the diagrams of the studied relationship; demonstration and study of processes which for various reasons can't be observed in reality.

Application of Matlab software on Physics classes allows simulating and researching various physical processes, saves time for practical classes, promotes deeper understanding the phenomena, increases interest in studying physics; develops creativity of students.

In our early works [8-28] we have shown the potentials of the Matlab software for modeling and visualization of physical processes in mechanics, molecular physics, electromagnetism and quantum physics.

The normal magnetization curve is used in technical calculations of magnetic circuits when it is required to investigate (to model) nonlinear inductive elements. The normal magnetization curve is presented by the diagram of the magnetic field induction versus magnetic field intensity or reverse functional dependence H(B). The normal magnetization curve has three segments: the initial segment corresponding to lower part of the curve, the second segment corresponding to the swift increase of the induction and the third segment corresponding to the saturation of the steel core of the inductor.

As an example in the table we have given the data for the magnetization curve of the **steel 2312.**

Source: © simenergy.ru

№	1	2	3	4	5	6	7	8	
H, A/m	**0**	**68**	**76**	**86**	**96**	**140**	**190**	**240**	
B, T	**0**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	
№	9	10	11	12	13	14	15	16	17
H, A/m	**300**	**400**	**550**	**1000**	**1600**	**3400**	**7700**	**13400**	**19400**
B, T	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**

There are many ways of approximation of table function by analytical function which with a particular degree of accuracy models the initial function at the given points. These mathematical ways of description of the table function are based on application of various mathematical functions. Modeling of the normal magnetization curve by using analytic function allows with a high precision describing a real magnetization curve along all characteristic segments, defining the magnetization curve by the continuous function. This procedure allows avoiding breaks and discontinuities of the extreme dependences obtained as a result of differentiation. In general, power functions are widely used since they allow carrying out calculations of magnetic circuits with alternating magnetic fields. The accuracy of approximation of a real curve by power polynomial is proportional to the determination number of its coefficients. Hyperbolic sine and tangent at their expansion in a series turn into power polynomial. The results of approximation by a hyperbolic sine and tangent are close to approximation by a power polynomial, and in many cases they almost exactly coincide with data of natural experiments.

The *arctangent* function is widely used nowadays for approximation of the magnetization curve because this function and its derivative are easily calculated and also because this function with an adequate accuracy describes the normal magnetization curve.

Formulation of the problem. Let us consider the approximation of the normal magnetization curve by the function containing *arctangent* and three adjustable coefficients

$$B(H) = p1 \cdot arctg(p2 \cdot H) + p3 \cdot H$$

The unknown coefficients (*p1, p2, p3*) may be determined by using least square technique. According to this technique the approximating function is determined as the minimum of the sum of squares of the calculated approximating function deviation from experimental points. This criterion of the least square technique is written as the following expression:

$$\sum_{i=1}^{N} \delta^2 = \sum_{i=1}^{N} \left(p1 \cdot arctg(p2 \cdot H_i) + p3 \cdot H_i - B_i\right)^2 \to \min$$

The necessary condition for existence of the function minimum is the equality to zero of its partial derivatives with respect to unknown variables *p1, p2* and *p3*. As a result we obtain the following system of equations:

$$\frac{\partial}{\partial p_1}\sum_{i=1}^{N}\delta^2=0;\sum_{i=1}^{N}2\cdot\left(p1\cdot arctg\left(p2\cdot H_i\right)+p3\cdot H_i-B_i\right)\cdot arctg\left(p2\cdot H_i\right)=0$$

$$\frac{\partial}{\partial p_2}\sum_{i=1}^{N}\delta^2=0;\sum_{i=1}^{N}2\cdot\left(p1\cdot arctg\left(p2\cdot H_i\right)+p3\cdot H_i-B_i\right)\cdot\frac{p1\cdot H_i}{1+p_2^2\cdot H_i^2}=0$$

$$\frac{\partial}{\partial p_3}\sum_{i=1}^{N}\delta^2=0;\sum_{i=1}^{N}2\cdot\left(p1\cdot arctg\left(p2\cdot H_i\right)+p3\cdot H_i-B_i\right)\cdot H_i=0$$

The solution of this system of nonlinear equations allows determining the coefficients of the approximating function.

There is the listing of the program for approximation at small magnitudes of the magnetizing field:

```
>> H=[0 68 76 86 96 140 190 240]; % in A/m
>>  B=[0 0.4 0.5 0.6 0.7 0.8 0.9 1]; % in T
>> plot(H,B,'o')
>>grid on
>> p1=0.984;
>>p2=7.273*10.^-3;
>>p3=1.935*10.^-5;
>>hold on
>>B=p1*atan(p2*H)+p3*H;
>>plot(H,B,'-');
```

The result is presented in the fig.1

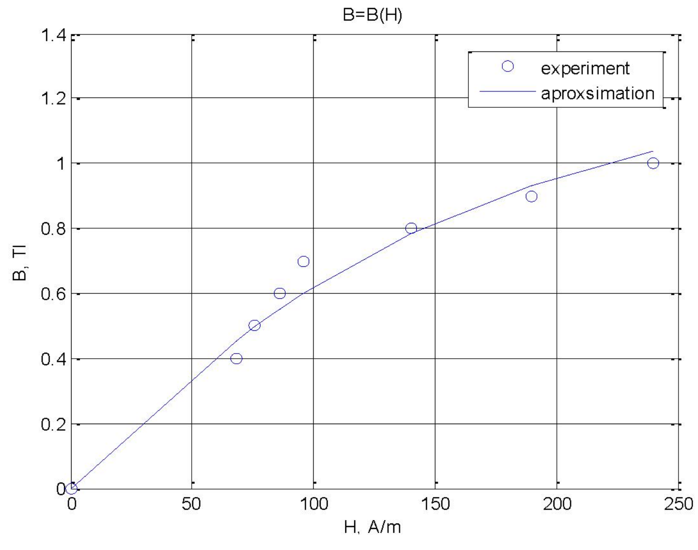

Figure 1 - Approximation of the magnetization curve by *arctangent* function at small magnitudes of the magnetizing field

The listing of the program for approximation at large magnitudes of the magnetizing field:

```
>> H=[300 400 550 1000 1600 3400 7700 13400 19400];% in A/m
>> B=[1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9]; % in T
>> plot(H,B,'o')
```

```
>> grid on
>> p1=0.984;
>> p2=7.273*10.^-3;
>> p3=1.935*10.^-5;
>> hold on
>> B=p1*atan(p2*H)+p3*H;
>> plot(H,B,'-');
```

The result is presented in the fig.2

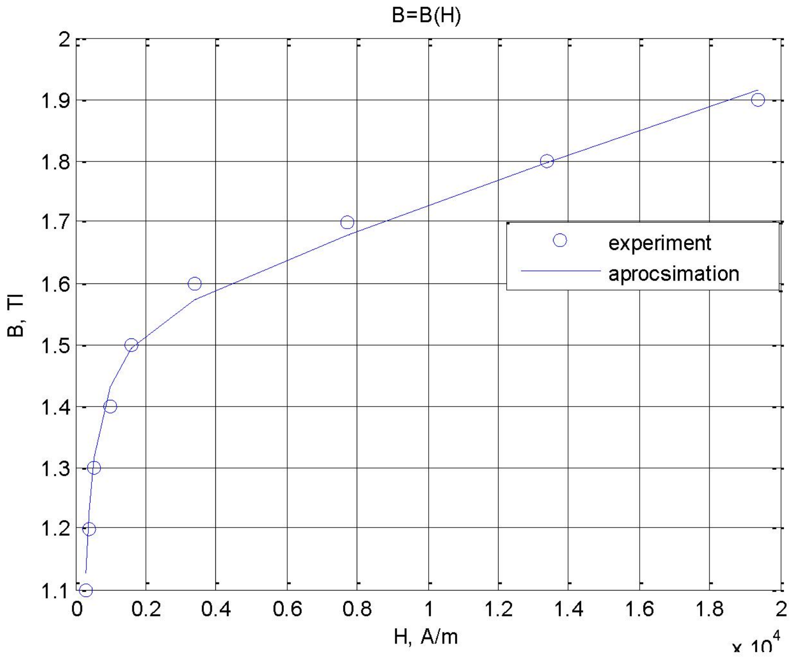

Figure 2 - Approximation of the magnetization curve by *arctangent* function at large magnitudes of the magnetizing field

This approximation is odd and may be applied for calculation of magnetic circuits with stationary as well as with alternating fields.

The listing of the program for approximation at magnitudes of the magnetizing field from zero up to 7700 A/m:

```
>> H=[0 68 76 86 96 140 190 240 300 400 550 1000 1600 3400 7700];
>>  B=[0 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7];
>> plot(H,B,'o');
>> plot(H,B,'o');
>> grid on
>> p1=0.984;
>>p2=7.273*10.^-3;
>>p3=1.935*10.^-5;
>>hold on
>>B=p1*atan(p2*H)+p3*H;
>>plot(H,B,'-');
```

The result is presented in the fig.3

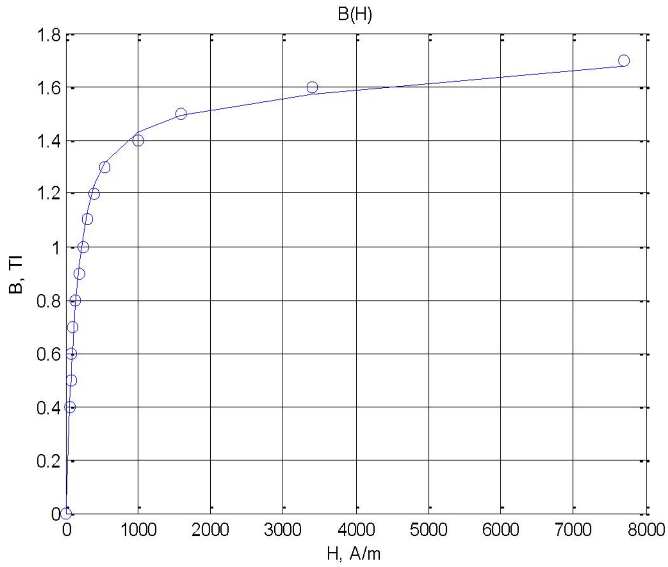

Figure 3 - Approximation of the magnetization curve by *arctangent* function at magnitudes of the magnetizing field from zero up to 7700 A/m

Conclusion: Modeling of the normal magnetization curve of the ferromagnetic is done by using the *arctangent* function for approximation of the curve and the Matlab software. The *arctangent* function is chosen because this function and its derivative are easily calculated and also because this function describes the normal magnetization curve with an adequate accuracy. There are also the experimental data of magnetic field induction dependence on magnetizing field intensity and the approximating magnetization curve. The obtained diagrams show that the table function is approximated by the analytical function of *arctangent* which with a sufficient accuracy models the table function at the given points.

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ФЕРРОМАГНЕТИКТІҢ НЕГІЗГІ МАГНИТТЕЛУ ҚИСЫҒЫН МОДЕЛДЕУ

Аннотация. Магниттік тізбектерді техникалық есептеулерде сызықтық емес индуктивті элементтерді зерттегенде (моделдеуде) негізгі магнттелу қисығы қолданылады. Магниттелудің негізгі қисығын аналитикалық функция көмегімен модельдеу барлық сипаттамалық бөлімдерде нақты магниттелу қисығын жоғары дәлдікпен сипаттауға, дифференциалдау нәтижесінде пайда болатын экстремалды тәуелділіктердегі үзілістерді болдырмайтын үздіксіз функциямен магниттелу қисығын орнатуға мүмкіндік береді. Белгілі бір дәлдікпен берілген нүктелердегі бастапқы функцияны модельдейтін аналитикалық функциямен кестелік функцияны жақындастырудың көптеген әдістері бар. Ферромагнетиктің негізгі магниттелу қисығын модельдеу үшін біз Matlab жүйесін және магниттелу қисық сызығын аппроксимациялау үшін, функцияның өзі мен оның туындысын есептеу қарапайымдылығына, сондай-ақ тәжірибелік магниттелу қисығын жеткілікті дәлдікпен сипаттайтына байланысты, арктангенс функциясын таңдадық. Нақты ферромагнетик үшін магниттік индукцияның магниттеуші өрістен тәуелдігінің эксперименттік мәліметтері мен олардың аппроксимацияланған қисық келтірілген. Келтірілген суреттен (кесте бойынша) нүктелермен берілген функцияны жеткілікті дәлдікпен арктангенс фукциясымен аппроксимацияланған, яғни бастапқы функцияны модельдейтін арктангенс фукциясы арқылы алынған магниттелу қисығы көрсетілген.

Түйін сөздер. Ферроманетик, магниттелу қисығы, тәжірибелік берілгендер, аппроксимация, арктангенс функциясы.

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МОДЕЛИРОВАНИЕ ОСНОВНОЙ КРИВОЙ НАМАГНИЧЕНИЯ ФЕРРОМАГНЕТИКОВ

Аннотация. Основная кривая намагничивания используется при технических расчетах магнитных цепей, когда требуется исследовать (моделировать) нелинейные индуктивные элементы. Моделирование основной кривой намагничивания с помощью аналитической функции позволяет с высокой точностью описать реальную кривую намагничивания на всех характерных участках, задать кривую намагничивания непрерывной функцией, что позволяет избежать изломов и разрывов экстремальных зависимостей, получаемых в результате дифференцирования. Существуют множество способов аппроксимации таблично заданной функции аналитической функцией, которая с определенной степенью точности моделирует исходную функцию в заданных точках. Для моделирования основной кривой намагничивания ферромагнетика нами выбрана система Matlab и арктангенсная функция аппроксимации кривой намагничивания из-за простоты вычислений самой функции и ее производной, а также достаточной точности отображения оригинальной кривой намагничивания. Представлены экспериментальные данные зависимости индукции магнитного поля от напряженности намагничивающего поля с аппроксимационой кривой намагничивания. Из представленной картины видно, что таблично заданная функция аппроксимируется аналитической функцией арктангенса, которая с достаточной степенью точности моделирует исходную функцию в заданных точках.

Ключевые слова. Ферромагнетики, кривая намагничивания, экспериментальные данные, аппроксимация, функция арктангенса.

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