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Experimental modeling of Magnetic Hysteresis Power Loss of Terfenol-D at Different Values of Frequency and Mechanical Pre-stress

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KEYWORDS

Terfenol-D,
Magnetic Hysteresis Loss,
Magnetic Hysteresis Loops.

ABSTRACT

One of the major limitations of using Terfenol-D in actuators and sensors is its magnetic hysteresis power loss which leads to reduction of mechanical power loss, precision and linear measuring range in actuators and sensors, respectively. In this paper, magnetic hysteresis power loss of Terfenol-D and its affecting parameters are studied and modeled experimentally. To this end a fabricated experimental setup is used to obtain magnetic behavior of Terfenol-D consisting of major and minor hysteresis loops at different values of frequency, magnetic field intensity and mechanical pre-stress. Data of these loops are used as an input to analytical equation of magnetic hysteresis loss. Then, an explicit model based on power relations for frequency, peak value of magnetic field intensity and mechanical pre-stress is presented to predict magnetic hysteresis power loss. This model is validated under new different conditions and the results show very good agreement with analytical model

1. Introduction

Magnetostriction is defined as a change of dimensions in ferromagnetic materials when exposed to external magnetic field. Terfenol-D as a magnetostrictive alloy is widely used in actuators such as vibration dampers [1], servo valves [2] and fuel injectors [3] due to its high force and strain, high curie temperature and applicability in high frequencies of magnetic field. It should be noted that during conversion of electrical energy to mechanical energy in these actuators, some magnetic energy losses occur which should be considered in the design phase to achieve optimum operational outputs. Like other ferromagnetic materials, the energy losses of Terfenol-D hysteresis loss (especially at low frequencies) and eddy currents and excess losses (especially at high frequencies). When Terfenol-D goes through magnetic hysteresis loops, hysteresis power loss happens because of the motion of microscopic magnetic domains. At each frequency, the hysteresis power loss is the sum of static (frequency independent) and dynamic (frequency dependant) hysteresis power losses.

Several investigations have addressed the affecting parameters such as magnetic field frequency and peak of magnetic flux intensity on the hysteresis power loss of ferromagnetic materials. The investigations show that the static hysteresis loss is linearly dependant to magnetic field frequency but the dynamic hysteresis loss is not and the degree of frequency dependency varies from one material to the other one. For instance, the experimental studies show that the dynamic hysteresis loss of Fe/Au [4], Co/Cu [5] and Fe/W [6] films are proportional to frequency by power degrees of 1.31, 1.66 and 1.03, respectively. On the other hand, the hysteresis loss is also dependant to peak values of magnetic field intensity and magnetic flux density of the hysteresis loop and this dependency is generally nonlinear. The studies show that the hysteresis power loss of Fe [7], Fe/Au [4], Co/Cu [5] and Fe/W [6] films are proportional to the peak of magnetic flux intensity by power degrees of 1.6, 0.59, 0.67 and 0.25, respectively.

Few investigations have studied the affecting parameters on hysteresis power loss of Terfenol-D and presented a model to predict the loss values [8-10]. These studies are experimental so they need all data of magnetic hysteresis loops; also they have not proposed any model to calculate the loss and not considered the mechanical pre-stress. In the present paper, magnetic hysteresis power loss of Terfenol-D and its affecting parameters are studied and modeled experimentally. To this end a fabricated experimental setup is used to obtain magnetic behavior of Terfenol-D consisting of major and minor hysteresis loops at different values of frequency, magnetic field intensity and mechanical pre-stress. Data of these loops are used as an input to analytical equation of magnetic hysteresis loss. Then, an explicit model based on power relations for frequency, peak value of magnetic field intensity and mechanical pre-stress is presented to predict magnetic hysteresis power loss.

2. Experimental study

To obtain magnetic hysteresis loops of Terfenol-D at different condition, an experimental setup as shown in figure 1 is used. A magnetic circuit is fabricated using Permalloy parts to achieve maximum magnetic permeability and minimum magnetic loss. The components of the experimental setup are as follows:

1- Reference load cell: an US Universal Impex load cell with sensitivity of 33.298 mV, linearity of 0.02% of full range and range of 100 kgf is used.

2- AC power supply: a Gwinstek APA-9201 power supply is used which is capable of generating AC voltage up to frequency 0f 500 Hz and power of 1 kW.

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3- Actuation coil: to generate axial magnetic field, an actuation coil composed of 600 turns of 1 mm thickness wire is used.

4- Hall effect sensor: to measure magnetic field intensity, a CYSJ119 Hall effect sensor is applied. The sensor has the linear range of 0-300 mT and sensitivity of 1.33 V/T.

5- Search coil: to measure magnetic flux density passing through Terfenol-D sample, a search coil composed of 5 turns of 0.15 mm thickness wire is used.

The experiments to obtain hysteresis loops of the material, have been performed at 5 values of frequency (7, 45, 75, 150 and 200 Hz), 3 values of magnetic field intensity (20, 50 and 93 kA/m) and 4 values of mechanical pre-stress (0, 3.12, 6.24 and 9.36 MPa).

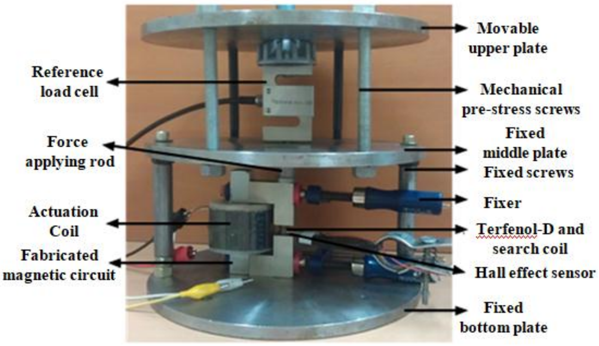

Fig 1. The experimental setup

Figure 2 shows major hysteresis loops (h=93.3 kA/m) for all frequencies at zero pre-stress. It can be seen that area of each loop increases by increasing frequency. Figure 3 shows major Hysteresis loops at frequency of 150 Hz for all values of mechanical pre-stress and figure 4 indicates major and minor hysteresis loops at frequency 0f 75 Hz and mechanical pre-stress of 6.24 MPa. Applying mechanical pre-stress leads to reduction of magnetic flux density and area of loop at each frequency.

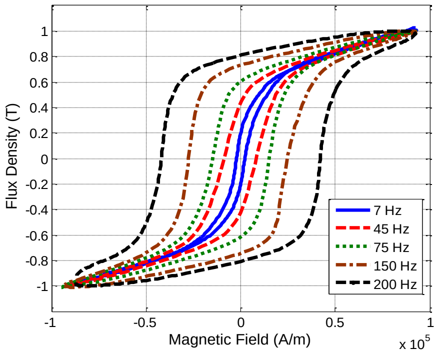

Fig 2. Major Hysteresis loops of Terfenol-D at zero mechanical pre-stress

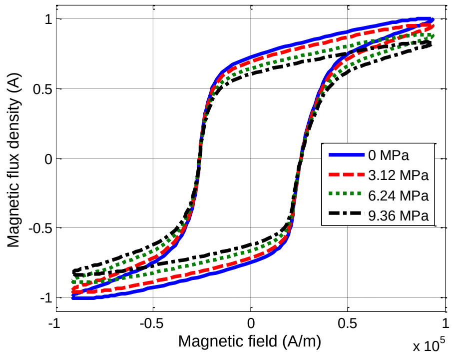

Fig 3. Major Hysteresis loops of Terfenol-D at frequency of 150 Hz

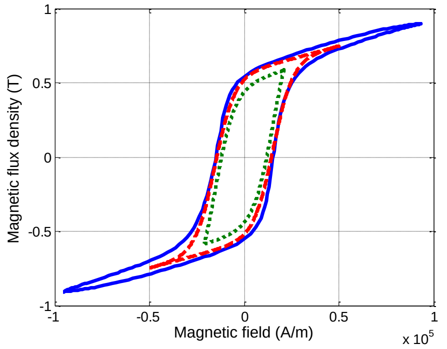

Fig 4. major and minor Hysteresis loops of Terfenol-D at frequency of 75 Hz and mechanical pre-stress of 6.24 MPa

3. Results

Area enclosed by a hysteresis loop is equal to hysteresis energy loss in unit volume of Terfenol-D. Hence, the hysteresis power loss of the sample can be written as follows:

$$P_{hys} = Vf\int H.dB \tag{1}$$

V is the volume of the Terfenol-D sample and f is the magnetic field frequency. Using Eq. 1 hysteresis power loss density of Terfenol-D is calculated for all hysteresis curves obtained before. The results are shown in Figures 5 to 6. At specific frequency, increasing the mechanical pre-stress leads to reduction of hysteresis power loss density. Also, at specific mechanical pre-stress, increasing the frequency or magnetic flux density increase the hysteresis power loss density.

The obtained results are fitted by power relations of frequency and peak magnetic field intensity as follows:

$$P_{hys} = (0.448)f^{2.275}H_p^{1.313}P^{-0.0684} \quad W/m^3 \tag{2}$$

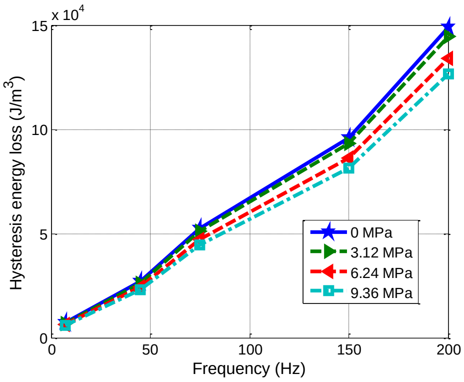

Fig 5. Density of hysteresis energy loss at peak of magnetic field intensity of 93 kA/m

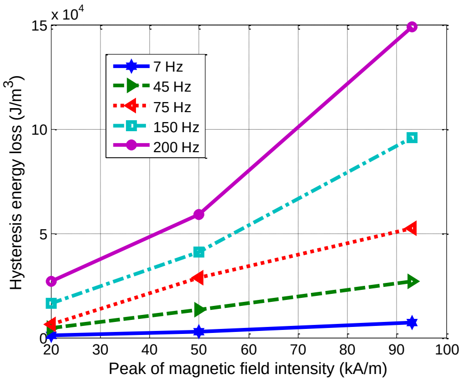

Fig 6. Density of hysteresis energy loss at mechanical pre-stress of 0 MPa

4. Validation

To validate Eq. (2) at new conditions, initially major and minor hysteresis loops at frequency of 100 Hz and zero pre-stress and frequency of 300 Hz and pre-stress of 12.48 MPa are obtained experimentally, shown in Figures 7 and 8. Then, values of hysteresis power losses are calculated by both analytical (Eq. (1)) and empirical (Eq. (2)) equations, shown in table 1. Mean errors for ceases 1 and 2 are 3.9% and 5.1%, respectively.

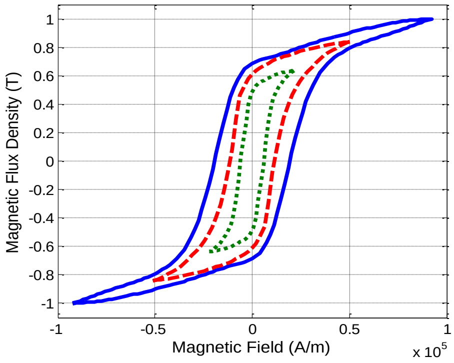

Fig 7. Major and minor hysteresis loops at frequency of 100 Hz and pre-stress of 0 MPa

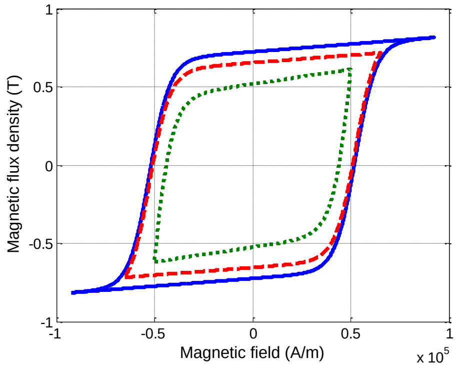

Fig 8. Major and minor hysteresis loops at frequency of 300 Hz and pre-stress of 12.48 MPa

Table 1. Errors between experimental and model results

Hysteresis power loss (W)			Peak of magnetic field	
Error (%)	Empirical equation	Analytical equation		
4.2	1.151	1.202	21	100 Hz , 0 MPa
3.1	3.359	3.361	50	
4.5	6.915	6.614	93	
7.1	31.356	33.761	50	300 Hz, 12.5 MPa
3.2	44.255	42.895	65	
4.8	70.838	67.614	93	

5. Conclusion

In this paper, hysteresis power loss of Terfenol-D and its affecting parameters were studied experimentally and modeled empirically. The novel experimental setup was fabricated and used to obtain magnetic hysteresis loops of Terfenol-D at different values of frequency, peak of magnetic field intensity and mechanical pre-stress and values of hysteresis power loss were calculated using the analytical relation. To determine the effect of each operational parameter, the empirical model based on power relations of the parameters were obtained which was validated by comparing its outputs with the experimental results at new conditions. The results show that the empirical model can precisely predict the hysteresis power loss in frequency range of 0-300 Hz and mechanical pre-stress of 0-12.48 MPa. Also it does not need experimental data of hysteresis loops and works only with three parameter of frequency, peak of magnetic field and mechanical pre-stress.

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