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Investigation of Magnetic Circuit Permanent Magnet – Terfenol-D – Air

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Introduction

The progress of nanotechnologies is the mean feature of the last ten years. The nanomeasurements are necessary for nanotechnologies. One of actual parameters is distance. Well-known device for distance measurement - micrometer - is inaccurate in this case. A device for smaller distance measurement –nanometer - is required. It is serious problem to obtain accurate and repeatable displacement by mechanical means. The phenomena when non-mechanical action causes variation of linear dimension must be used. One of theirs is magnetostriction – elongation of magnetic material in magnetic field. The preeminent material which has giant magnetostriction is terfenol-D [1]. It is sufficient to use the magnetic field created by permanent magnet for nanodisplacements of the terfenol-D strip.

The different realisation ways of magnetic circuit composed of permanent magnet, terfenol-D and air are investigated in this paper.

Magnetic field of permanent magnet and magnetic circuit possible realisations

The oblong permanent magnet is the best for magnetostrictive nanometer. Its magnetic field distribution is showed in fig. 1, a. The magnetic flux density inside terfenol-D increases and magnetic field distorts when the terfenol-D strip gets in magnet surroundings (see fig. 1, b).

We can consider that magnetic flux is uniform inside strip if the mean part of magnetic flux is directed along the terfenol-D strip. It is convenient to use the equivalent electric schema of magnetic circuit in this case (see fig. 2). In fig. 2 the permanent magnet is presented as source of magnetic flux Φ_{Σ} like current source in electric circuit. The magnetic flux Φ_{terf} circulates inside terfenol-D strip. The Φ_{r} is remaining magnetic flux. The values of Φ_{terf} and Φ_{r} depend on the magnetic resistance R_{mr} (in which circulate flux Φ_{r}), the magnetic resistance of terfenol-D strip R_{mterf} and serial to it magnetic resistance R_{mn}. The most part of magnetic circuit is air, therefore the magnetic circuit is linear.

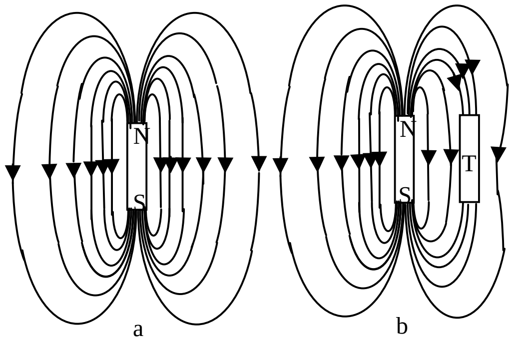

Fig. 1. The distribution of permanent magnet field without disturbance (a)and near terfenol-D strip (b)

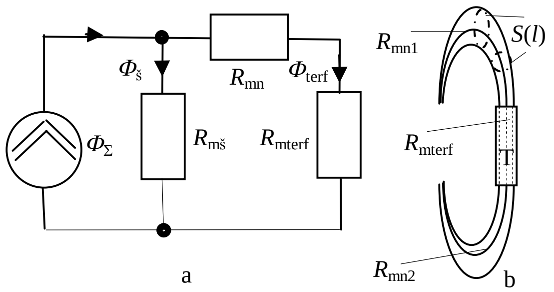

Fig. 2. Equivalent electric schema of magnetic circuit (a) and distribution of magnetic flux Φ_{terf} (b)

The magnetic resistance of terfenol-D strip can be expressed this way:

$$R_m = \frac{l_m}{S_m \mu_r \mu_0}, \tag{1}$$

where S_{m} and l_{m} are, accordingly, area of cross-section and length of terfenol-D strip, $\mu_0=4\pi\cdot10^{-7}$ H/m – permeability of a vacuum, μ_{r} – relative permeability of terfenol-D (its values interval is [3, 10]). The R_{mn} is magnetic resistance of air to magnetic flux Φ_{terf}. It is composed of two magnetic resistances R_{mn1} and R_{mn2}. Let the length of magnetic lines

l_v inside the resistances R_{mn1} and R_{mn2} be even and equal to length of magnetic flux line, which connects magnet surface with geometrical centre of terfenol-D surface. Magnetic resistances R_{mn1} and R_{mn2} can be expressed:

$$R_{mn1(2)} = \frac{1}{\mu_0} \int_{l_{v1(2)}} \frac{dl_v}{S(l_v)} . \tag{2}$$

The mean value of magnetic flux area $S_{v1(2)}$ is equal

$$S_{v1(2)} = \frac{l_{v1(2)}}{\int_{l_v} \frac{dl_{v1(2)}}{S_{1(2)}(l_{v1(2)})}} . \tag{3}$$

Using (3) we obtain of (2):

$$R_{mn1(2)} = \frac{l_{v1(2)}}{S_{v1(2)}\mu_0} . \tag{4}$$

The magnetic flux density inside terfenol-D strip must be changed to change the magnetostrictive displacement of this strip. The change of magnetic flux density we can obtain changing the reciprocal disposition of terfenol-D and magnet. The investigating variants are showed in fig. 3: In this fig. N and S are north and south permanent magnet poles, accordingly, T – terfenol-D strip.

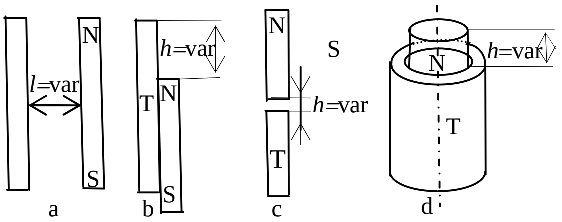

Fig. 3. The variants of magnetostriction change: a) changing distance between parallel magnet and terfenol-D strips; b) changing magnet position along terfenol-D axis; c) changing distance between coaxial magnet and terfenol-D; d) changing magnet position inside hollow terfenol-D cylinder

The regularities of magnetostriction change for variants showed in Fig. 3, a, b and d, can be investigated using equivalent schema Fig.2. This schema is not suitable for variant shown in Fig. 3, c, only, because the magnetic field in distance variation zone is very uneven.

The exact quantitative results we obtain by modeling.

Modelling technique

The finite element method was chosen and program package COSMOSM was used. The spatial 3D distribution of static magnetic field was investigated. The dimensions of modelled space were 4-5 times more then terfenol-D strip dimensions. The permanent magnet field was set by axis component of coercive strength H_{cy}. We suppose that permanent magnet parameters are not changed with changing reciprocal postion of terfenol-D and magnet. In the all investigating variants the coercive strength and the relative permeabilities of magnet and terfenol-D was the same H_{cy}=1885A/m, $\mu_{rmag}=\mu_{rterf}$=5. There are the typical values [1,2]. The scalar magnetic potential of magnet south pole was accepted V_m=0. The terfenol-D strip was situated along axis y and the axial component of magnetic flux density B_y was investigated.

Cylindrical magnet inside hollow terfenol-D cylinder

This variant is showed in Fig. 3, d. The model of this variant is presented in Fig. 4.

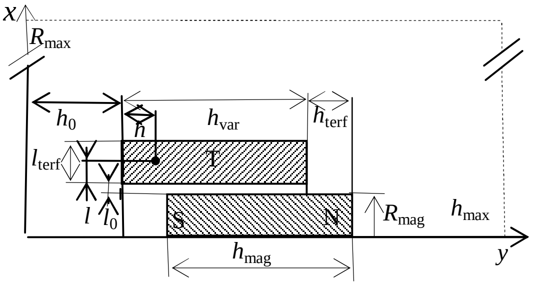

Fig. 4. The cross-section of model, when magnet is situated in hollow terfenol-D cylinder

The modelling was performed by the values: $h_{terf}=h_{mag}=h_0$=30mm, R_{mag}=8mm, h_{terf}=5mm, l_0=1mm. The modelling space was limited by planes y=0, $y=h_{max}$=180mm and 6^o spacing angle of cylinder R_{max}=60mm. The distance h_{var} between terfenol-D strip and magnet upper surfaces was changed in interval 0-35 mm. The processed modelling results are presented in the Table 1.

Table 1. The processed modelling results, when magnet is inside cylinder of terfenol-D

h_{var}, mm	0	5	10	15	20	25	30	35
$h_{var}/\ h_{terf}$,%	0	16,6	33,3	50	66,6	83,3	100	116,6
$\left\|\overline{B}_y\right\|$,,10^{-6} T	1344	1198	948	720	500	372	334	302
$\Delta B_{y,}10^{-6}$ T	0	-146	-250	-228	-220	-128	-38	-32
δB,%	0	-10,8	-18,6	-16,9	-16,4	-9,5	-2,8	-2,4
δB_s,%/mm	0	-2,4	-3,9	-3,2	-3,2	-1,9	-0,6	-0,5

In this table $\left|\overline{B}_y\right|$ is the mean value of magnetic flux density y components absolute values in all volume of terfenol-D strip for $h=h_{var}$. ΔB_y, δB ir δB_s are calculated this way:

$$\Delta B_y = \left|\overline{B}_y\right| - \left|\overline{B}_{y0}\right| , \tag{5}$$

$$\delta B = \frac{\Delta B_y}{\left|\overline{B}_{y0}\right|} \cdot 100\% , \tag{6}$$

$$\delta B_s = \frac{\delta B}{\Delta h_{var}} \cdot 100\%, \tag{7}$$

where the $\left|\overline{B}_{y0}\right|$ is value of $\left|\overline{B}_y\right|$, when h_{var}=0.

The maximal ratio of relative magnetic flux deviation δB_s to h_{var} deviation equal to 3,7 %/mm is between h_{var}=5mm and h_{var}=10mm. This ratio is less for h_{var} interval [0, 5mm] because the direction of magnetic flux alternates in the lower part of terfenol-D cylinder. The full variation of magnetic flux density is big, but the difference between absolute values is considerably lesser. There is serious defect of investigating case. The mean relative deviation is δB_{sm}=2,5%/mm, when the magnet position variation is equal to magnet height Δh_{var}=30mm.

Magnetic flux density is distributed non-uniformly in axial and in radial direction. The magnetic flux density distribution $B=B(h,l)$ is presented for two cases h_{var}=0mm and h_{var}=15mm in Table 2.

Table 2. Magnetic flux density values in particular points of terfenol-D cylinder $B=B(h,l)$

h, mm		0	3	6	9	12	15	18	21	24	27	30
h/h_{terf}·,%		0	10	20	30	40	50	60	70	80	90	100
h_{var} =0	l=1mm	483	1551	1805	1891	1919	1924	1919	1885	1806	1553	486
	l=2mm	272	1201	1641	1795	1846	1861	1845	1798	1643	1206	273
	l=3mm	157	1048	1505	1704	1766	1806	1772	1707	1503	1045	159
	l=4mm	60	905	1416	1647	1710	1759	1709	1643	1415	902	63
h_{var} =15	l=1mm	022	1506	1624	1571	1191	39	-676	-568	-441	-314	-148
	l=2mm	911	1378	1501	1408	992	105	-454	-484	-406	-301	-153
	l=3mm	844	1297	1409	1291	880	183	-309	-415	-376	-294	-163
	l=4mm	811	1260	1346	1213	819	224	-222	-365	-353	-292	-181

In axial direction magnetic flux is biggest in the median layers of terfenol-D cylinder and it is diminished approaching to top and bottom of cylinder. In radial direction magnetic flux diminishes receding at magnet.

The obtained results are suited for design shown in Fig. 3, b, too.

Terfenol-D strip over magnet

The modelling area is shown in Fig. 5. The modelling was performed by the values: $h_{terf}=h_{mag}$ =30mm, $R_{mag}=R_{terf}$=8mm. The modelling space was limited by planes y=0, $y=h_{max}$=180mm and 6° spacing angle of cylinder R_{max}=40mm.. Distance between terfenol-D strip and magnet h_{var} was varied. The processed results are presented in Table 3.

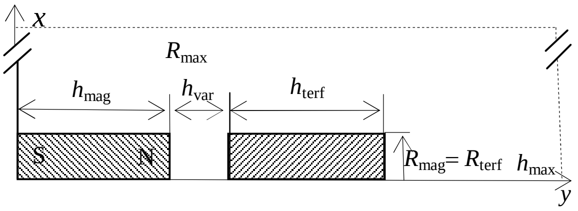

Fig. 5. The cross-section of model, when terfenol-D strip is over magnet and its axes coincides

Table 3. Processed modelling results, when terfenol-D strip is over magnet

h_{var}, mm	0	1	2	4	7	10	15
$\left\|\bar{B}_y\right\|$,μT	1150	855	701	508	331	227	126
$\Delta B_{y,}$μT	0	-295	-154	-193	-177	-104	-101
δB,%/1mm	0	-25,6	-13,4	-8,4	-5,1	-3,0	-1,8

Comparing results, presented in Tables 1 and 3, we can see, that the mean value of y component of magnetic flux density $\left|\bar{B}_y\right|$ in terfenol-D cylinder is more by 14,4% than in the case, when terfenol-D strip is over magnet (for h_{var}=0). Varying distance h_{var} the most ratio of relative magnetic flux density deviation δB with distance variation is considerably more in the last case: 25,6 %/mm comparing with 3,7 %/mm. This deviation quickly decreases with h_{var} increase. When h_{var}=10mm, it is δB=3%/mm. In interval [0, 10mm] the mean deviation is δB=8 %/mm, therefore, considerably more than in the case of terfenol-D cylinder.

The distribution of magnetic flux density inside terfenol-D strip is presented in Table 4. The magnetic flux is distributed very unevenly in axial direction.

Table 4 Magnetic flux density values in particular points of terfenol-D strip $B=B(h)$, when terfenol-D strip is over magnet

h, mm	0	3	6	9	12	15	18	21	24	27	30
h/h_{terf}·100%	0	10	20	30	40	50	60	70	80	90	100
h_{var}=0mm	3316	2964	1660	205	963	742	574	444	330	291	161
h_{var}=4mm	1318	1000	813	633	502	395	313	240	172	128	71

Terfenol-D strip is parallel to magnet

In Fig. 6 the cross-section of model is shown in xy plane. The terfenol-D strip and permanent magnet shapes was simulated as rectangular parallelepipeds with dimensions 30×1,5×1,5. The longest side was directed along y axis. The modelling volume was rectangular parallelepiped, too, with length along y axis h_{max}=120 mm. Along x and z axes the side lengths were $x_{max}=z_{max}$=60 mm. The obtained results are generalised in Table 5.

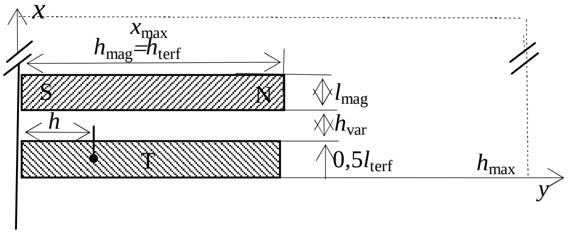

Fig. 6. The cross-section of model, when the terfenol-D strip is parallel to magnet

The relative variation δB is less than in two previous cases. But the magnetic flux is distributed very even in the most part of terfenol-D strip (see table 6).

Table 5. Processed modelling results, when terfenol-D strip is parallel to permanent magnet

h_{var}, mm	0	1	2	3	6	9	12	15
$\left\|\bar{B}_y\right\|$,10^{-6} T	2165	1775	1694	1636	1548	1488	1434	1391
$\Delta B_{y,}10^{-6}$ T	0	-390	-81	-48	-88	-60	-54	-43
δB_s, %/mm	0	-18	-3,7	-2,2	-1,4	-0,9	-0,8	-0,66

Table 6. Magnetic flux density values in particular points of terfenol-D strip $B=B(h)$, when terfenol-D strip is parallel to magnet

H, mm	0	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25	27,5	30
h/h_{terf}%	0	8.3	16,6	25	33,3	41,6	50	58,3	66,6	75	83,3	91,6	100
h_{var}=0	1964	1964	1964	1965	1968	1976	1998	2060	2239	2788	4064	12182	
h_{var}=9	1785	1785	1785	1785	1786	1787	1790	1794	1798	1750	1412	112	1

The δB dependences of h_{var} for all three investigated cases are presented in fig 7. Delta B1, delta B2, delta B3 are the relative variations of magnetic flux densities in the cases when magnet is inside terfenol-D, over terfenol-D and parallel to terfenol-D.

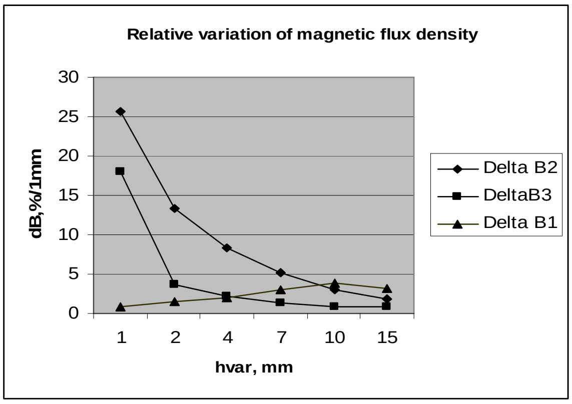

Fig. 7. Dependance $\delta B_s(h_{var})$ for modeled variants

Conclusions

1. Three different modes of variation reciprocal position of magnet and terfenol-D was investigated.
2. The most value of magnetic flux can be obtained, when magnet is inside hollow terfenol-D cylinder.
3. The most ratio of relative magnetic flux density and distance between magnet and terfenol-D variations is obtained, when terfenol-D strip is over magnet, but the magnetic flux is distributed very unevenly in this case.
4. The magnetic flux is distributed evenly, when magnet and terfenol-D strip are parallel one to other, but the ratio of relative magnetic flux density and distance between magnet and terfenol-D variations is smaller then in the case when terfenol-D strip is over magnet.

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Magnetostrictive properties of Terefenol-D can be used for a nanometer creation. There was investigated the magnetic field created by permanent magnet distribution in terfenol-D strip and its variation when reciprocal position between permanent magnet and terfenol-D is varied. The finite element method was used. The reciprocal position was varied by three different modes. The greatest absolute value of magnetic flux density can be obtained when the permanent magnet is situated inside cylinder manufactured of terfenol-D. The greatest ratio of magnetic flux density relative variation to distance between permanent magnet and terfenol-D deviation is obtained, when the terfenol-D strip in situated over the permanent magnet. The magnetic flux is distributed very unevenly inside terfenol-D in this case. Magnetic flux is distributed evenly in terfenol-D when the magnet and terfenol-D are situated parallel one to other, but ratio of magnetic flux density relative deviation to distance deviation is the smallest in this case. Ill. 7, bibl. 3. (in English; summaries in English, Russian and Lithuanian).

Р. Бансевичюс, Д. Григалюнас, Ю. А. Вирбалис. Исследование магнитной цепи, состоящей из постоянного магнита, терфенола-Д и воздуха // Электроника и электротехника. – Каунас: Технология, 2008. – № 6(86). – С. 3–6.

Магнитострикционные свойства терфенола-Д могут быть использованы для создания нанометра. Методом конечных элементов было исследовано распределение плотности магнитного потока, созданного постоянным магнитом в образце из терфенола-Д, и его изменение, когда тремя различными способами меняется взаимное расположение магнита и терфенола-Д. Наибольшее значение плотности магнитного потока было получено, когда магнит движется внутри цилиндра из тефенола-Д. Наибольшее отношение изменений плотности магнитного потока и расстояния между магнитом и терфенолом-Д получается, когда терфенол-Д расположен над магнитом и соосен с ним. Однако, магнитный поток в терфеноле-Д в этом случае распределен очень неравномерно. Магнитный поток в терфеноле-Д распределен достаточно равномерно, если магнит и терфенол-Д расположены параллельно, но в этом случае отношение изменений плотности магнитного потока и расстояния между магнитом и терфенолом-Д будет наименьшим из исследованных случаев. Ил. 7, библ. 3. (на английском языке; рефераты на английском, русском и литовском яз.)

R. Bansevičius, D. Grigaliūnas, J. A. Virbalis. Magnetinės grandinės, sudarytos iš nuolatinio magneto, terfenolo-D ir oro, tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 6(86). – P. 3–6.

Terefenolas-D magnetostrikcinės savybės gali būti panaudotos nanometrui sukurti. Baigtinių elementų metodu buvo ištirtas nuolatinio magneto sukurto magnetinio lauko srauto tankio pasiskirstymas terfenolo mėginyje ir jo pokytis, keičiant nuolatinio magneto ir terfenolo mėginio abipusę padėtį trimis skirtingais būdais. Didžiausią absoliučiąją srauto tankio vertę, esant tam pačiam magnetui, galima gauti, kai magnetas juda iš terfenolo pagaminto cilindro viduje. Didžiausias santykinis magnetinio srauto tankio pokytis vienam milimetrui atstumo tarp magneto ir terfenolo pokyčio gaunamas, kai terfenolo mėginys yra virš magneto, tačiau šiuo atveju magnetinis srautas pasiskirsto labai netolygiai. Magnetinis srautas pasiskirsto pakankamai tolygiai tuo atveju, kai magnetas ir terfenolo mėginys yra lygiagretūs, tačiau tada santykinis srauto tankio pokytis vienam milimetrui atstumo pokyčio yra mažiausias. Il. 7, bibl. 3. (anglų kalba; santraukos anglų, rusų ir lietuvių k.)