NOVEL LEAD STRUCTURES AND FEED-THROUGH COMPUTATION OF MULTIPLE MR/SINGLE-POLE HEADS FOR PERPENDICULAR RECORDING

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Abstract—We introduce a novel vertically stacked lead structure for multiple head/track systems which can reduce inductive coupling between lead pairs by several orders of magnitude. We develop an analytical expression for the coupling of both vertically stacked and conventional side-by-side lead pairs, and compute the inductive couplings. The sign as well as the magnitude of the mutual inductance between lead pairs depends on their relative displacement. This dependence provides opportunities for cancellation. Also, because of the balance between positive and negative contributions to the mutual induction, the coupling between lead pairs does not necessarily decrease monotonically with distance. The results presented here provide design information for the tradeoffs between crosstalk, spacing, and fabrication costs.

I. INTRODUCTION

Multiple head structures may be used to increase areal density and reduce access time as perpendicular recording systems strive to achieve higher storage density. Conventional thin film magnetic recording head leads use an in-plane side-by-side configuration. When this configuration is used in multi-element (as with a magnetoresistive read after a single pole write) or multi-track head structures, inductively coupled crosstalk between leads (in-plane or down track) degrades system performance. We proposed a novel stacked lead pair structure that can reduce these couplings by several orders of magnitude [1]. We showed that the combination of a conventional lead pair structure and a vertically stacked pair structure placed either vertically (down track) or horizontally (in plane, as shown in Figure 1) can eliminate lead pair couplings entirely. In this paper, we develop a general expression for inductances of two lead pairs that includes permutations of lead pair types, lead dimensions, lead separation, and displacement between two lead pairs. We compare the two lead structures in the general case by computing the couplings (including loading terminations) in the general case using three-dimensional boundary element methods.

II. METHODS

A. Analytical Expression for Inductances of two lead pairs

The inductance of a conducting structure \( j \) as a result of the current in a structure \( i \) may be expressed as

\[
L_{ij} = \frac{\mu_0}{4\pi} \int_{S_i} \int_{S_j} \int_{C_i} \int_{C_j} \frac{1}{R_{ij}} \, dl_i \cdot dl_j \, dS_i \, dS_j ,
\]

where \( C_i \), \( C_j \) are loops enclosing \( i \), \( j \), respectively; \( S_i \), \( S_j \) are the cross section area perpendicular to the \( C_i \), \( C_j \) loops, respectively; and \( R_{ij} \) is \( |r_i - r_j| \), the distance between \( dl_i \) and \( dl_j \). The direction of \( dl_i \) and \( dl_j \) is defined by the right hand rule. The resulting integrated function has the form:

\[
g(x, y, x', y') = \frac{\mu_0}{4\pi} \left( \frac{1}{48} \left( x-x' \right)^4 \left( y-y' \right)^4 \right) - \frac{25}{24} \left( x-x' \right)^2 \left( y-y' \right)^2 \frac{\pi}{6} \left( x-x' \right)^2 \left( y-y' \right)^2
+ \frac{1}{3} \left( x-x' \right)^3 \left( y-y' \right)^3
- \left( x-x' \right)^2 \left( y-y' \right)^2 \arctan \left( \frac{x-y'}{x-x'} \right)
- \frac{1}{3} \left( x-x' \right)^3 \ln \left( x-y' \right) - \frac{2}{3} \left( x-x' \right)^2 \ln \left( x-x' \right) - \frac{1}{24} \left( x-x' \right)^4 \left( y-y' \right)^4
- 6 \left( x-x' \right)^3 \left( y-y' \right)^3 \ln \left( x-x' \right)^3 \left( y-y' \right)^3
\]

where \((x',y')\), \((x,y)\) are the corner coordinates of the source and the field structure, respectively.

For the two vertically stacked lead pairs shown in Figure 2, the inductance is

\[
- 209 -
\]
\[ L_y(u) = L_y(x,y) = -h\left(\frac{w}{2} - x, \frac{d}{2} - y\right) + h\left(\frac{w}{2} - x, \frac{d}{2} + y\right) \]
\[ + h\left(\frac{w}{2} + x, \frac{d}{2} - y\right) + h\left(\frac{w}{2} + x, \frac{d}{2} + y\right) \]
\[ - h\left(\frac{w}{2} - x, \frac{d}{2} - y\right) - h\left(\frac{w}{2} - x, \frac{d}{2} + y\right) \]
\[ - h\left(\frac{w}{2} + x, \frac{d}{2} - y\right) - h\left(\frac{w}{2} + x, \frac{d}{2} + y\right) \]
\[ + h\left(\frac{w}{2} + x, \frac{d}{2} - y\right) + h\left(\frac{w}{2} + x, \frac{d}{2} + y\right) \]
\[ + h\left(\frac{w}{2} - x, \frac{d}{2} - y\right) + h\left(\frac{w}{2} - x, \frac{d}{2} + y\right) \]
\[ \text{and} \]
\[ h(x,y) = g(x,y,\frac{w}{2},\frac{d}{2}) - g(x,y,\frac{w}{2},\frac{d}{2}) \]
\[ - g(x,y,\frac{w}{2},\frac{d}{2}) + g(x,y,\frac{w}{2},\frac{d}{2}) \]
\[ - g(x,y,\frac{w}{2},\frac{d}{2}) + g(x,y,\frac{w}{2},\frac{d}{2}) \]
\[ + g(x,y,\frac{w}{2},\frac{d}{2}) - g(x,y,\frac{w}{2},\frac{d}{2}) \]

where \( w \) is the lead width, \( \delta \) is the lead thickness, \( d \) is the lead separation edge-to-edge and \( u \) is the center-to-center displacement vector of two lead pairs.

Figure 2. Cross sectional geometry of two vertically stacked pairs.

The inductance between two conventional pairs can be obtained from the above expression with the interchange of thickness and width and then switching the \( x, y \) coordinates (or rotating 90 degrees). Setting \( u \) equal zero for two identical vertically stacked pairs or two identical conventional pairs gives the self inductance of a stacked or a conventional structure.

**B. Three-Dimensional Boundary Element Method for Load Inductance and Feed-Through Computations**

We use Amperes\textsuperscript{©} by IES for three-dimensional boundary element analysis. The model used for the computation contains a two by four array: four single-pole type heads in the first row and four MR read heads in the second row. The single-pole type head includes a four-turn coil. The MR read head is approximated by a U-loop. The location of each head is indexed by \((m,n)\), where \( m \) is the row (cross track) and \( n \) is the column (down track). The separation between two write heads (or two neighbor elements in the row) is 500 microns and between the write head and the read head down track (or two neighbor elements in the column) is 200 microns. The source is element \((1,1)\) for computing in-plane write head couplings and adjacent plane write and read head couplings, and is element \((2,1)\) for computing read head in-plane couplings. Because the system is linear and reciprocal, the mutual inductance of other combinations is equivalent to one of these couplings. In feed-through computation, each lead is modeled as being 200 microns wide, 3 microns thick and 10 mm long. The separation of two leads of a pair is 10 microns edge to edge for both conventional and vertically stacked leads. The load (SPT or MR element) is always concentric with the lead pair.

**III. RESULTS AND DISCUSSION**

In a multiple track/head system, write heads, read heads and servo heads may be in an array aligned in crosstrack and down track positions. In such a system combinations of conventional and vertically stacked lead pairs can be versatile. For a linear and reciprocal system, all possible permutations can be evaluated using three combinations of two lead pairs: two conventional pairs, two stacked pairs and one conventional and one stacked pair. Since the problem is linear, we may decompose the total coupling of a multiple head system into conducting lead couplings and lead end couplings (i.e. coils with magnetic poles, and U-loop leads and magnetoresistive elements).

**A. Mutual Inductance of Lead Pairs**

Figures 3 and 4 show the mutual inductance of the three lead pair combinations as functions of the in-plane and the down track components of the displacement \( u \). In both down track or in-plane displacement, the coupling between two conventional pairs or two vertically stacked pairs decays roughly inversely with distance squared. However, with our representative conductor dimensions, we find that the inductive coupling between two vertically stacked lead pairs separated down track by a lead width, is equal to that of two conventional pairs about twenty times further apart. Similarly, the coupling of two vertically stacked pairs separated by two lead widths in the across track direction is equal to the coupling of two conventional pairs fifteen times further apart. These large differences point to a clear advantage in favor of using stacked structure leads for high density storage system. Moreover, along down track displacements two conventional pairs are positively coupled and two stacked pairs are negatively coupled; while along
Figure 3. In-plane mutual inductance of conventional-conventional (dotted line), stacked-stacked (solid line) and conventional-stacked (dashed line) as function of displacement.

Figure 4. Down track mutual inductance of conventional-conventional (dotted line), stacked-stacked (solid line) and conventional-stacked (dashed line) as function of displacement.

in-plane displacements, two conventional pairs are negatively coupled and two stacked pairs are positively coupled. We shall see below that because of this sign difference the mutual coupling of two such structures is affected in opposite directions when they are connected to the same loading terminations.

For a conventional and a vertically stacked pair in either exact crosstrack or down track displacement, the symmetry of the field ensures that the flux linkage integrates to zero. With this combination in such a position, the lead pairs are decoupled, independently of distance.

Figure 5 shows the cross coupling between two pairs when they are displaced laterally with constant down track spacing. In the exact down track position, the coupling between two vertically stacked or two conventional pairs exhibits a maximum, while the conventional-stacked pair coupling is zero, as stated before. In this configuration, as the lateral displacement increases, the flux linkage between two stacked or two conventional pairs exhibits a sign reversal at a displacement of a little more than a lead width. This behavior arises from a sign reversal of the flux generated by the leads at this lateral displacement. The conventional-stacked pair combination has a coupling maximum in the vicinity of a lateral displacement of a lead width.

Figure 5. Adjacent plane mutual inductance of conventional-conventional (dotted line), stacked-stacked (solid line) and conventional-stacked (dashed line) as function of displacement.

B. Feed-Through Analysis

Couplings between two in-plane terminating loads are tabulated in Table 1. Two SPT write-heads generally exhibit negative mutual inductances across track, and positive down track. When these loads are connected to two vertically stacked lead pairs with couplings that are positive across track and negative down track, the total coupling can be further reduced. Two MR U-loop ends normally show positive across track coupling which depend on the dimensional ratio of the magnetostrictive end element and the two loop arms. Unlike vertically stacked lead pairs, the conventional lead pairs have mutual inductances much larger than the terminating loads. Cancellation due to sign differences here is not a major factor.

Table 2 shows the mutual inductances between a write-head structure located in one plane and four read head structures located in another plane with a constant down-track displacement of one lead width. Lead pairs and terminating loads are listed separately. To obtain the feed-through of a given system, the appropriate combinations of results may be superimposed. It may be noticed that the coupling to terminating loads at the (2,2) position is smaller than at (2,3). This occurs because the coupling between the loop-arm pair and the write-head coil exhibits a sign reversal from positive to negative with lateral displacement (similar to what we have described in conventional pairs), while the coupling between the loop front end and the write head coil remains positive and falls off slowly.
Table 1. In-plane mutual inductances (Henrys) of write head and read head systems.

<table>
<thead>
<tr>
<th>location</th>
<th>(1,2)</th>
<th>(1,3)</th>
<th>(1,4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>write heads</td>
<td>-0.217e-10</td>
<td>-0.185e-11</td>
<td>-0.114e-12</td>
</tr>
<tr>
<td></td>
<td>+0.374e-11</td>
<td>+0.252e-11</td>
<td>+0.218e-11</td>
</tr>
<tr>
<td>read heads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stacked leads</td>
<td>+0.147e-11</td>
<td>+0.345e-12</td>
<td>+0.151e-12</td>
</tr>
<tr>
<td>conv. leads</td>
<td>-0.921e-10</td>
<td>-0.223e-10</td>
<td>-0.985e-11</td>
</tr>
<tr>
<td>overall in w. h. plane:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/ stacked leads</td>
<td>-0.202e-10</td>
<td>-0.151e-11</td>
<td>+0.370e-13</td>
</tr>
<tr>
<td>w/ conv. leads</td>
<td>-0.114e-09</td>
<td>-0.241e-10</td>
<td>-0.996e-11</td>
</tr>
<tr>
<td>overall in r. h. plane:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/ stacked leads</td>
<td>+0.521e-11</td>
<td>+0.287e-11</td>
<td>+0.233e-11</td>
</tr>
<tr>
<td>w/ conv. leads</td>
<td>-0.884e-10</td>
<td>-0.248e-10</td>
<td>-0.767e-11</td>
</tr>
</tbody>
</table>

Table 2. Mutual inductances (Henrys) between a write head at (1,1) and four read heads in row 2 of four locations.

<table>
<thead>
<tr>
<th>location</th>
<th>(2,1)</th>
<th>(2,2)</th>
<th>(2,3)</th>
<th>(2,4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>loading ends</td>
<td>+0.386e-10</td>
<td>+0.272e-11</td>
<td>+0.367e-11</td>
<td>+0.289e-11</td>
</tr>
<tr>
<td>lead pairs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stacked-stacked</td>
<td>-0.586e-11</td>
<td>+0.842e-12</td>
<td>+0.304e-12</td>
<td>+0.143e-12</td>
</tr>
<tr>
<td>conv.-conv.</td>
<td>+0.121e-08</td>
<td>-0.213e-09</td>
<td>-0.808e-10</td>
<td>-0.378e-10</td>
</tr>
<tr>
<td>stacked-conv.</td>
<td>0</td>
<td>-0.152e-10</td>
<td>-0.214e-11</td>
<td>-0.642e-12</td>
</tr>
</tbody>
</table>

Quite generally, with conventional leads it is the leads that dominate the coupling, and the terminating loads make only a small contribution to the feed-through; with vertically stacked lead pairs, the terminations are the major source of feed-through. The worst combination would be a system with a write head and a read head connected to conventional leads in the (2,1) configuration, since in such a system one can never adjust the dimensions of the structures for cancellation.

C. Self-inductance and Input Impedance

The vertically stacked lead pair has self-inductance about ten times smaller than the conventional lead pair, and its capacitance is about ten times larger than that of the conventional pair. Because the characteristic impedance is roughly proportional to the square root of the inductance-capacitance ratio, the characteristic impedance of a vertically stacked structure would generally be lower than that of a conventional structure. For signals below several megahertz, the major factor in power dissipation is still the resistance. There is no difference in this respect between two structures with the same conducting lead size; however since the vertically stacked structure occupies only half the width, its width can be doubled without requiring additional planar area, reducing the resistance and hence the power dissipation by a factor of two.

IV. Conclusions

We have presented an analysis of the inductive coupling of multiple write and read head structures fed both by conventional side-by-side lead pairs and by a novel vertically stacked lead pair structure. We find that the vertically stacked lead pair structure offers dramatic reductions in feed-through, as well as potential advantages from the view point of power dissipation. We tabulate results of coupling computations for representative element dimensions and for typical multiple head configurations and spacings. The results are intended to serve as general design tools for such systems.

REFERENCES