Degaussing System Design Optimization

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Abstract – Steel ships with a magnetic signature requirement are equipped with a degaussing system to reduce their perceptibility for magnetic influence mines. To be able to reduce the magnetic signature accurately, a proper distribution of coils over the ship is essential. Finding the best distribution of coils is a complex optimisation problem, involving many potential coil locations, many possible positions and headings of the ship in the Earth magnetic field, and the unknown permanent magnetisation. Regression techniques are useful to reduce the complexity of this optimisation problem. In this paper, we discuss the complexity of the optimisation problem and how it can be reduced with the aid of Least Angle Regression (LARS).

1. Introduction

Steel ships disturb the local Earth magnetic field, making them perceptible to magnetic influence mines. To reduce the magnetic perceptibility, naval frigates with a magnetic signature requirement are equipped with a degaussing system. This coil system dynamically reduces the magnetic disturbance. The optimum degaussing currents are determined by a model that reduces the static magnetic signature. At a specific moment in time this signature can be viewed as a composition of two magnetic fields. The first one is the frigate's own magnetic field that it has acquired over time, while the second one is an induced field which is the result of the interaction of the frigate's steel and the geomagnetic field at the location and orientation of the frigate at that moment of time. The own magnetic field of the frigate changes over time due to hysteresis effects that occur due to various sources, such as the earth magnetic field, mechanical stress, the degaussing system, the cathodic protection system, stray fields, and eddy currents induced by the frigate's roll and pitch.

An optimal reduction of the magnetic signature requires an approach to tune the coil currents accurately and a proper distribution and dimensioning of the coils on the frigate. The first aspect can be handled by various approaches. A classical degaussing system utilizes a masthead magnetometer to sense the ambient field in the vicinity of the frigate and a control algorithm to adjust the currents in all degaussing coils [1]. The control algorithm generally utilizes measured data and tunes the coils successively according to expected maxima that follow from the measured data. A much more advanced alternative is "closed loop degaussing", which is one of the current trends in degaussing system development over the last decades [2] - [5]. This approach utilizes an array of on-board magnetometers, strategically located on the frigate, to monitor the frigate's magnetic field distribution. The optimum degaussing currents can then for example be determined by mathematical-physical models that relate the on-board sensor measurements to a prediction of the magnetic field surrounding the frigate [5], [6].

The second aspect, i.e., a proper distribution and dimensioning of the coils on the frigate, is part of the degaussing system design. It is strongly connected to the first aspect, since the degaussing system (composed of a fixed set of coils) needs to reduce the frigate's magnetic field (by tuning the coil currents) for all directions of the earth magnetic field that the frigate will encounter. With the advance of mine technology on one hand and the requirements on cost on the other hand, a proper design of the degaussing coil layout is important. To the best of our knowledge, the design of the degaussing system relies heavily on expert knowledge and few (automated) methodologies are available in the literature. References [7] and [8] propose methods to determine the number of turns of each coil, and additionally to set the coil currents, but do not provide an approach to determine the locations of the coils. In this paper we focus on the development of a methodology that should assist the designer and give insight in aspects such as the importance of specific coils for signature reduction and the gain in signature reduction of adding an additional coil.

2. Concept Description

Optimizing the number of coils, their locations, and their number of turns is a complex task. Firstly the coils can have different lengths, widths, and orientations, which are restricted by the frigate's geometry. Moreover, requirements may prevent the installation of coils at certain locations. Consequently, global optimization over arbitrary lengths, widths, and orientations may not only require a rather complex formulation, but may also turn out to be numerically infeasible or lead to solutions that suffer from implementation problems. Therefore, we formulated the main steps of our approach as follows:

1. Construct a reduced geometrical model of the frigate that can be handled by numerical tooling for field simulation.
2. Determine the locations on the frigate where coils can be installed.
3. Introduce a large number of coils in the model of the frigate. This number should be much larger than the number of coils that will be installed in practice.
4. For each coil, simulate the resulting field for a single current amplitude, i.e., the coil effect, in a grid below the frigate. Simulate also the induced fields in the same grid for at least three independent directions of the external field and associated amplitudes.
5. Apply an automatic model-building method to determine the order of importance of coils for one or more specified external (earth) fields.
6. For each specified external field, calculate the optimal coil currents. This last step should also be executed for other external fields than those specified in step 5.

The fourth step assumes that both coil and induced fields are linear in amplitude. If the induced field is also assumed linear in direction of the external (earth) field, simulations are only required for the directions of the three principal axes. Measurements of these fields on the ship "CFAV Quest" in the frame of RIMPASSE 2011 have demonstrated that these assumptions are reasonable. If field norms at a specified depth need to be maintained, the preferred choice for the grid will be a planar one at that depth.

The automatic model-building method in step 5 should produce a "good" linear model for predicting a response y on the basis of some covariates $\boldsymbol{x}_1$, $\boldsymbol{x}_2$, ..., $\boldsymbol{x}_n$. Here, "good" relates to prediction accuracy and parsimony (simplicity). In the context of the degaussing coil-layout design, the covariates can consist for example of the values of the coil fields obtained in step 4 and the response consists of the values of the induced field(s) for the specified external fields, as approximated by linear regression from the induced fields obtained in step 4.

The model-building method should also provide a much more efficient mean for optimization of the degaussing system than simply checking all possible cases. To sketch the complexity, we consider a set of 117 coils specified in step 3 and a fixed number of 10 coils to be installed on the frigate. In that case there are $\binom{117}{10} \approx 8.9 \cdot 10^{13}$ combinations of coils for which we need to calculate the signature reduction for various external fields. If we also vary the number of coils to be installed on the frigate we get a number of combinations that is even many orders larger.

The purpose of the final step 6 is not only to verify the obtained signature reduction for several external fields, but also to get insight in the required coil currents. Both reduction and currents depend of course on the number of coils from the initial set in step 3 that are taken into account. For the calculation of the frigate's magnetic field from the simulated field constituents, we restrict ourselves to the case that the frigate's magnetic field is composed of induced and coil fields. Taking into account the permanent magnetization in the degaussing coil-layout optimization will be topic of further research. In this respect, we note that, in the frame of RIMPASSE 2011 , we developed and analysed a phenomenological model for the prediction of the magnetic signature and the optimization of the coil currents based on field measurements in an earth-field simulator. This model utilizes a geomagnetic field prediction algorithm for the external field, can optimize the coil currents by various norms, and can approximate the magnetic field at other locations than those of the measurement grid. Moreover, we demonstrated that a few on-board sensors are sufficient to account for the variation in the permanent field of the frigate. The next step is to integrate the compensation for the variation in the permanent field and the mentioned model in one simulation tool.

3. The Model-Building Algorithm and its Application in Degaussing Coil-Layout Design

Various model-building algorithms can be found in the literature. In this paper we restrict ourselves to Least Angle Regression (LARS) [9], [10]. The mathematical framework of LARS can briefly be described as follows. If linear regression is applied to the response $\boldsymbol{y}$ and the covariates $\boldsymbol{\xi}_1$, $\boldsymbol{\xi}_2$, ..., $\boldsymbol{\xi}_K$, the regression coefficients $\boldsymbol{\beta} = (\beta_1, \beta_2, \ldots, \beta_K)^T$ provide the prediction

$$\hat{\boldsymbol{y}} = \sum_{k=1}^{K} \beta_k \, \boldsymbol{\xi}_k = \boldsymbol{\Xi\beta} \tag{1}$$

where the columns of the matrix $\boldsymbol{\Xi}$ are the covariate vectors. The norm of the residual of the prediction (1) is given by

$$\|\boldsymbol{y} - \hat{\boldsymbol{y}}\|_2 = \left\| \boldsymbol{y} - \sum_{k=1}^{K} \beta_k \, \boldsymbol{\xi}_k \right\|_{\mathbf{2}} . \tag{2}$$

where the subscript $_2$ indicates the Euclidean norm. The basic idea of LARS is to select the covariates in a stepwise manner based on their correlation to the response. This correlation is mathematically defined by

$$\boldsymbol{c}(\hat{\boldsymbol{y}}) = \boldsymbol{\Xi}^H(\boldsymbol{y} - \hat{\boldsymbol{y}}), \tag{3}$$

where the components of the vector $\boldsymbol{c}$ are the correlations of each of the covariates and the residual of the prediction $\hat{\boldsymbol{y}}$. At the start of the iterative process the prediction $\hat{\boldsymbol{y}}$ is zero and $\boldsymbol{c}$ gives the correlation between the covariates and the measurements $\boldsymbol{y}$. During the process the

prediction $\hat{\boldsymbol{y}}$ is updated and new covariates are chosen such that their corresponding component in $\boldsymbol{c}$ is at least as large as the components of already selected covariates.
In the context of degaussing coil-layout design, LARS thus provides successively the most important coils in the degaussing system using the Euclidean norm.

LARS can be applied in various ways to degaussing coil-layout design. For applying LARS to a single external field, we define the covariates in this paper such that the columns of $\boldsymbol{\Xi}$ represent the components of the magnetic field vectors $\boldsymbol{B}_{\mathrm{coil}(k)}(\boldsymbol{x}_n)$ in the specified grid points $\boldsymbol{x}_n$, where $\boldsymbol{B}_{\mathrm{coil}(k)}$ is the simulated magnetic field of the coil. Moreover, the response $\boldsymbol{y}$ is a column vector that consists of the components of the induced-field vectors $\boldsymbol{B}_{\mathrm{ind}}(\boldsymbol{x}_n)$ in the grid points. Here, $\boldsymbol{B}_{\mathrm{ind}}$ is the magnetic field induced by the specified external field and is calculated from the simulated constituents in step 4 of our approach. With these definitions, the regression coefficients $\boldsymbol{\beta} = (\beta_1, \beta_2, \ldots, \beta_K)^T$ in (1) are the (normalized) coil currents that minimize (2), i.e., they minimize in least-square sense the residual field (coil field minus induced field) over the selected grid points. For applying LARS to more external fields simultaneously, we compose the response $\boldsymbol{y}$ of the response vectors corresponding to each of the external fields and we update the matrix $\boldsymbol{\Xi}$ correspondingly. Consequently, the regression coefficients $\boldsymbol{\beta} = (\beta_1, \beta_2, \ldots, \beta_K)^T$ are not anymore the (normalized) coil currents for a single external field, but they minimize, in least-square sense, the residual field over the selected grid points and all external fields. For the actual degaussing, these coefficients will not be used, since the coil currents will be set for each specified external field separately.

4. Test Set

For testing our approach, we implemented 117 coils on a reduced model of a frigate, each with its own centre, orientation and size, and located both lower and upper decks. For each of the coils, we simulated the magnetic field by an in-house code [11] in a grid at 11 m below the water surface for current amplitudes of 100 A turns. Moreover, for three external fields we simulated the induced fields in the same grid. The field has an amplitude of 50 µT and is directed along the three principal directions, i.e., longitudinal (positive x-axis), athwart ships (positive y-axis), and vertical (positive z-axis). We note that the positive x-axis is pointing to the front of the frigate, the positive z-axis is pointing downwards, and the positive y-axis is oriented athwart ships such that the three axes constitute a right-handed coordinate system.

Figure 1 shows an example of a coil in our test set, which is horizontally oriented and whose normal to its enclosed surface area is pointing in vertical direction. This coil is particularly aimed at reducing the vertical or z-directed component of the frigate's magnetic field. In the rest of our paper we will refer to the coils in terms of the normal of their enclosed surface (x, y, and z) instead of employing the classical nomenclature of M, A, L, F, and Q coils.

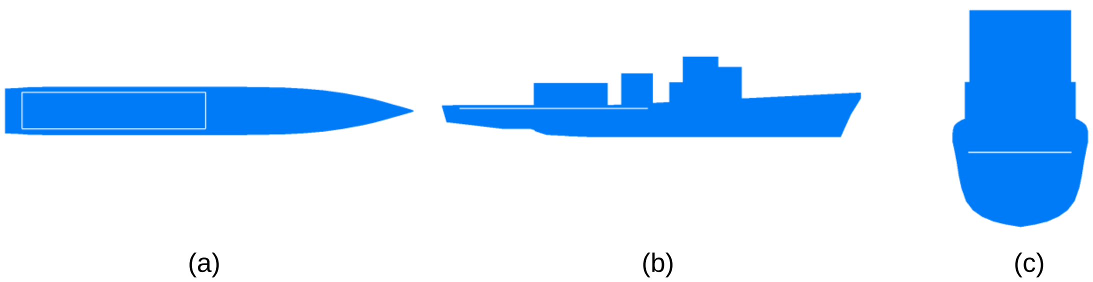


Figure 1: Projected views of the location of one of the coils in our test set. (a) Top view. (b) Side view. (c) Front view.

The frigate is geometrically centred with respect to the grid. If we denote the length and width of the grid by $2L$ and $2W$, the frigate's length and width are approximately 1.5 L and 1.2 W. Moreover, the grid is uniform with 81 grid points along the x-direction and 21 grid points along the y-direction. In total we have thus 1701 grid points.

In our simulations we apply LARS to three different subsets of the 117 coils:

1. all the coils that are located lower decks (67 coils),
2. the 83 coils with the largest estimated field strengths at 11 m depth,
3. all 117 coils.

5. Optimization with respect to a Single External Field

As a first test case we consider the case of degaussing coil-layout optimization with respect to a single external field. First we apply a downward directed external field of 50 µT. Figure 2 shows the maximum and mean amplitudes of the (degaussed) magnetic field in the grid points at 11 m depth as a function of the LARS step. Since LARS adds one coil in each step, the horizontal axis can also be viewed as the number of coils in the degaussing system. We observe that the first two coils provide the most significant reduction in the magnetic signature. One of these coils is the one depicted in Figure 1 and the other one is a similar coil extending over the front half of the frigate. We also observe that after adding approximately 15 coils to the degaussing system, the maximum signature stabilizes around 1 µT up to the 46th coil, while the mean signature slowly but steadily decreases with the number of coils. The reason for this stabilization is a particular maximum in the residual field near the front of the vessel as illustrated by Figure 3 (a) for the first 20 coils obtained by applying LARS to the set of 67 coils. Our test set does not incorporate a separate coil that can reduce this particular maximum. Instead of exciting a single coil, the signature reduction is achieved by an assembly of about 30 coils (coils 15 to 45).

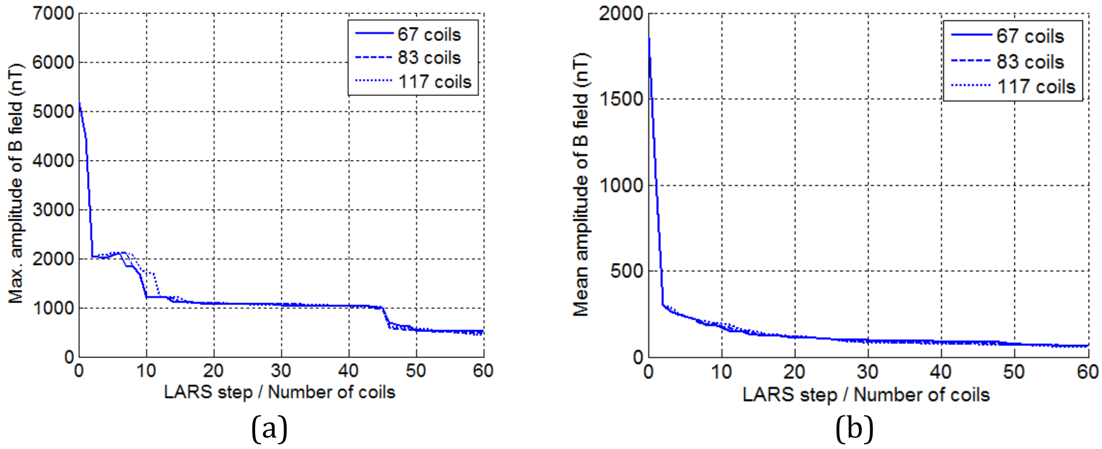
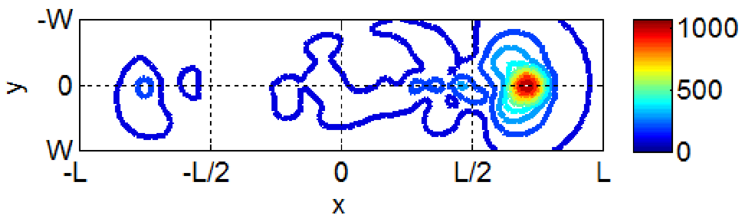


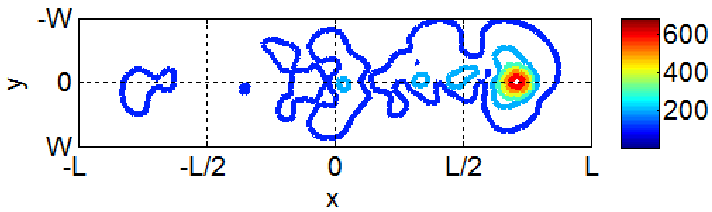
Figure 2: Maximum (a) and mean (b) amplitude of the (degaussed) magnetic field in the grid points at 11 m depth versus the number of coils in the degaussing system, for a downward directed external field of 50 µT. The system optimization is carried out by LARS applied to three sets of coils and the same external field.

This rather simple case illustrates the role that automated model-building algorithms can play in the design process. Based on the results provided by LARS, one can decide to add an additional coil. Since the simulation times with LARS are only of the order of seconds, new simulations for an additional field can be rapidly carried out.

The results in Figure 2 also demonstrate that similar reductions can be achieved with LARS applied to the three sets of coils. The extra coils in the sets of 83 and 117 coils do thus not automatically lead to a lower signature. In Figure 2 (a) we observe that the maximum amplitude of the reduced field is higher if the 7 to 12 most important coils are selected from the set of 117 coils than if they are selected from the sets of 67 or 83 coils. This behaviour can hardly be observed for the mean in Figure 2 (b). In this respect we note that LARS minimizes the residual field in least-squares sense in the measured grid. Thus, LARS minimizes the mean instead of the maximum. As noted in for example [7] and [8] minimization of the mean does not necessarily imply that the maximum is reduced. This can be an issue for determining the optimal coil currents at sea for a specific external field, but is less an issue for the coil-layout design, since we aim at a set of coils that can reduce the magnetic signature for a multitude of external fields. Secondly, Figure 2 demonstrates that the differences in qualitative behaviour between the maximum and the mean are relatively small. Thirdly, as emphasized before, performing a global optimization with a genetic or evolutionary algorithm and the maximum field intensity as objective function may be computationally too expensive for various design iterations.



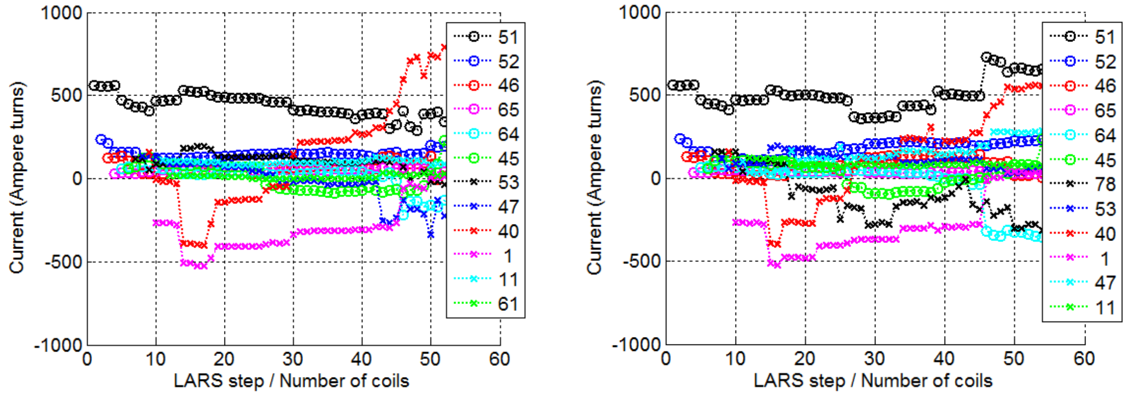
(a)



(b)

Figure 3: Residual field magnitudes in the grid at 11 m depth as obtained with the first 20 coils (a) and the first 46 coils (b) for a downward directed external field of 50 μT. The system optimization is carried out by LARS applied to set of 67 coils and the same external field.

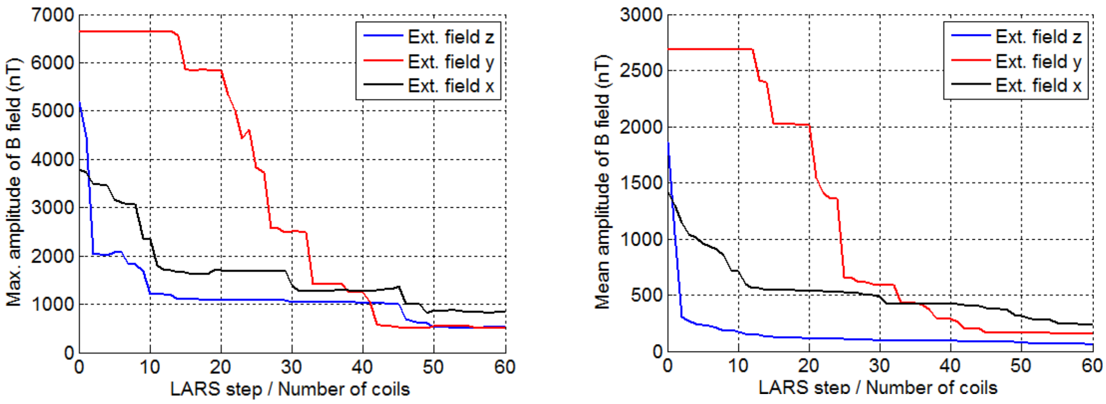
Next we consider the coil currents as obtained by LARS. Figure 4 shows the coil currents of the first 12 coils as determined by LARS applied to the sets with 67 and 83 coils, and the same single external field as before. The indices in the legends are the coil indices as originally assigned to the coils in the test set. The second coil in both lists, i.e., coil 52, is the coil depicted in Figure 1. Most of the coils in both lists are similarly oriented as this coil and are thus z-coils in our terminology. Only coils 1 and 11 are x-coils. The first 12 coils obtained by applying LARS to the set of 67 coils include by definition only coils lower decks, while the first 12 coils obtained by applying LARS to the set of 83 coils include also one coil of the super structure. The index of this coil is 78, which turns up as 7^{th} coil as shown in Figure 4. The magnitude of the coil currents is in the order of hundreds of Ampère turns, which can be handled by power amplifiers providing currents of the order of 10 A in combination with a few tens of turns per coil.



(a) (b)

Figure 4: The degaussing coil currents (in A turns) of the first 12 coils for a downward directed external field of 50 µT. The system optimization is carried out by LARS applied to the sets with 67 coils (a) and 83 coils (b) and the same external field. The indices in the legend are the coil indices as originally assigned to the coils in the test set.

Finally we verify to what extent the successive sets of coils obtained by LARS applied to the single external field can reduce the magnetic signature for other external fields. Figure 5 shows the maximum and mean amplitudes of the (degaussed) magnetic field as a function of the number of coils for three external fields. The order of the coils is determined by LARS applied to the set of 67 coils and a downward directed external field of 50 µT as before. The results for the z-directed external field are the same as in Figure 2. For the x-directed external field the reduction of the signature is still reasonable, since this field induces a magnetic field with relatively strong z-components that can be cancelled by the z-coils. Moreover, we know that the first 12 coils also contain 2 x-coils. For the y-directed external field, the reduction becomes only substantial for more than 30 coils. This observation is not surprising since the LARS optimization of the degaussing system was focused on a single downward directed field. Therefore, we will investigate the simultaneous optimization for multiple external fields.



(a) (b)

Figure 5: Maximum (a) and mean (b) amplitude of the (degaussed) magnetic field in the grid points at 11 m below the water surface versus the number of coils in the degaussing system, for external fields of 50 µT in the three principal directions. The system optimization is carried out by LARS applied to the set of 67 coils and a downward or z-directed external field of 50 µT.

6. Optimization with respect to External Fields Directed Along the Three Principal Directions

As a first step towards optimization with respect to multiple external fields, we consider the optimization of the degaussing system by LARS, simultaneously applied to three external fields and the set of 67 coils. The three external fields are directed along the three principal directions. Figure 6 shows the maximum and mean amplitudes of the (degaussed) magnetic field in the grid points at 11 m depth as a function of the LARS step, or number of coils, for the external fields in the three principal directions. The optimal degaussing currents are of course determined per external field, while the order of the successive coils is determined by LARS over the three external fields simultaneously. We observe that the first coil introduced by LARS is a y-coil, because the y-directed external field generates the induced field with the largest mean amplitude. The next coils are z-coils, because, after the reduction by the first coil, the z-directed external field generates the induced field with the largest mean amplitude. As previously observed for a single external field, the greatest reductions are achieved by adding the first few coils. After adding those coils, the reduction of the maximum amplitude is in all three directions gradually decreasing as a function of the number of coils, except for some little jumps. In contrast, LARS applied to the single downward directed external field showed a stabilization of the maximum amplitude around 1 μT over a range of about 30 coils. This difference is explained by the fact that simultaneous optimization with respect to three external fields leads to x, y, and z-coils being alternatingly added.

Figure 7 shows the currents of the first 12 coils, as determined by LARS, for each of the three external fields. The indices in the legend correspond again to the originally assigned coil indices. The first coil with index 39 is a y-coil that extends over the complete length of the frigate. The next 6 coils are z-coils, followed by a y-coil, two x-coils, a y coil, and an x-coil. For the z and y-directed external fields, the currents are in the order of tens to hundreds of Ampère turns. For the x-directed external field we observe that three coils get currents of the order of a thousand Ampère turns if more than 30 coils are added to the degaussing system. These coils are relatively small in enclosed surface area. Given that their centres are positioned around the water surface or higher, these coils have a significantly smaller magnetic field at the grid and may thus require larger currents.

We note that the results in this paper are particularly meant for illustration of our approach based on LARS. The test set of coils, the geometrical model of a frigate, and the grid for field evaluation are not optimized for achieving a specific norm at a specific depth.

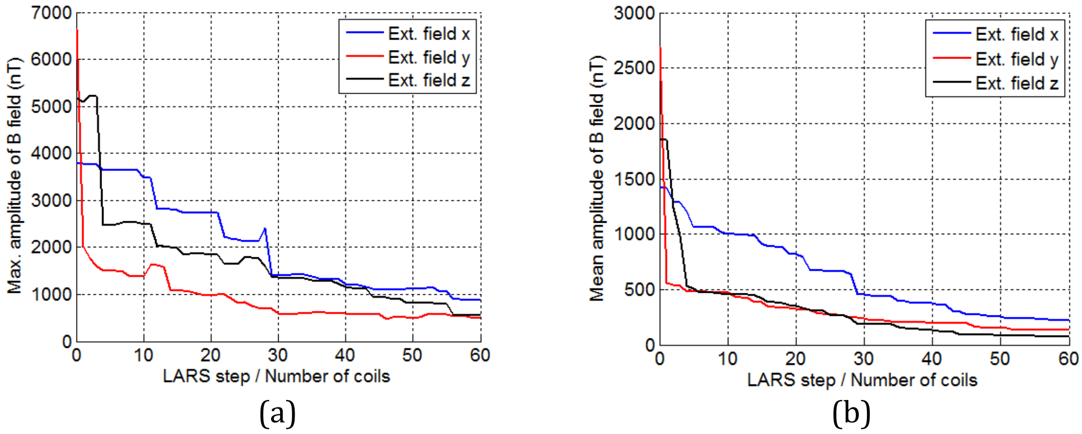


Figure 6: Maximum (a) and mean (b) amplitude of the (degaussed) magnetic field in the grid points at 11 m depth versus the number of coils in the degaussing system, for x, y, and z-directed external fields of 50 μT. The system optimization is carried out by LARS applied to the set of 67 coils and to the external fields in the three principal directions simultaneously.

7. Conclusions and Outlook

The results in this paper indicate that the automated model-building algorithm LARS (least-angle regression) can be of added value to the degaussing coil-layout design. In the proposed approach, the fields of pre-specified coils on a model of a frigate are first simulated in a specific grid. Next, LARS is employed to rank the coils according to their contribution to the achieved magnetic-field reduction in that grid, either for a single external (earth) field or for multiple external fields simultaneously. By specific test cases, we have demonstrated that LARS indeed selects the coils in correspondence with the nature of the specified external field(s) and the associated external field(s). Moreover, the test cases demonstrated that the first few coils determined by LARS account for the major part of signature reduction and that field plots may give insight in locations where coils could be added to improve this reduction. Finally the low computation times make LARS suitable for rapid prototyping in coil-layout optimization. In an actual design process, the definition of a large set of coils and of the geometrical model of the frigate should be based on expert knowledge and during the design process of the coil layout, several iterations of LARS with different subsets (as also shown in this paper) will be necessary. Our next steps will be in the directions of taking into account permanent magnetization, handling constraints on the currents, and applying LARS to a multitude of external fields (with different amplitudes based on geomagnetic conditions).

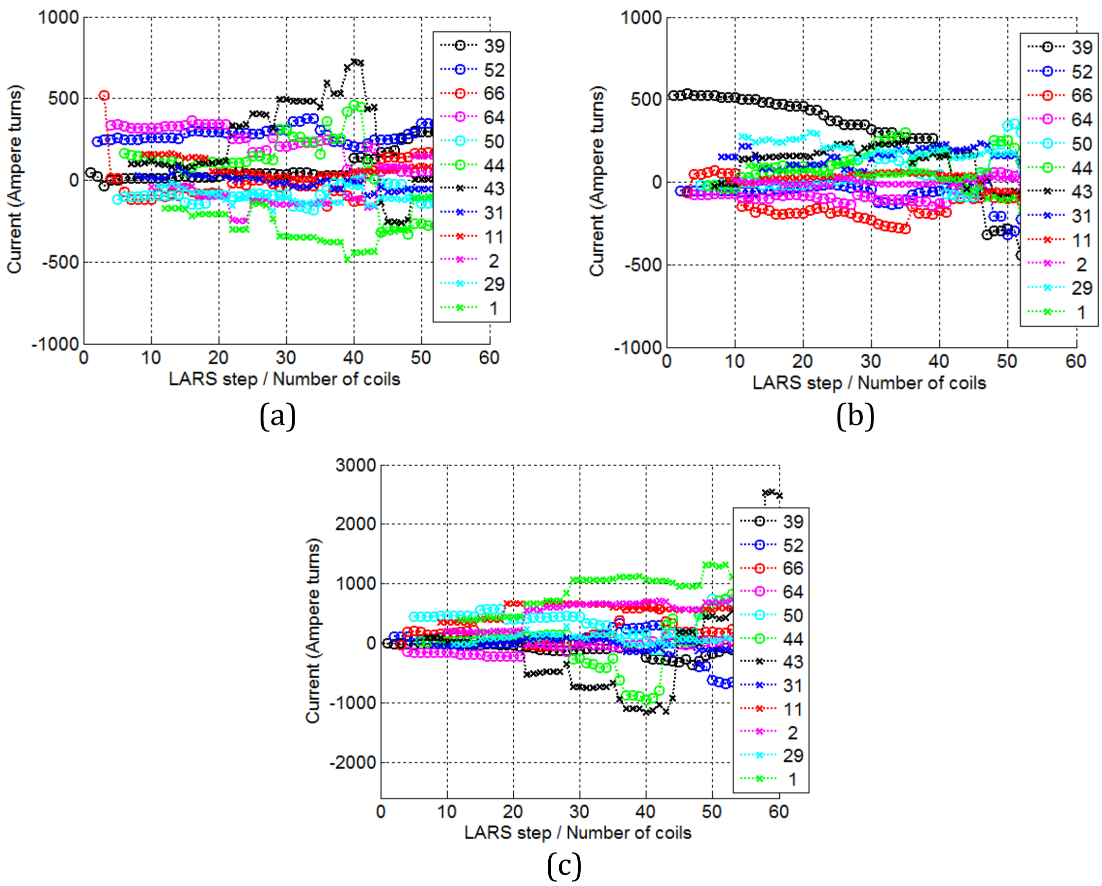


Figure 7: The degaussing coil currents (in A turns) of the first 12 coils for a z-directed (a), y-directed (b), and x-directed (c) external field of 50 μT. The system optimization is carried out by LARS applied to the set with 67 coils and to the external fields in the three principal directions simultaneously. The indices in the legend are the coil indices as originally assigned to the coils in the test set.

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