Works toward closed loop degaussing system on board new MCM vessels

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Abstract — MCM (Mine Countermeasure) vessel needs to meet very strict magnetic signature requirements, according to NATO AMP-14 and national standards, to lower probability of detection by sea mines. Significant part of signature reduction – so called passive reduction - is done through proper upfront design i.e. choice of non- or low-magnetic materials for hull and special low-magnetic versions of equipment to be installed on board. Passive techniques are aimed at elimination of sources of magnetic field. The remaining field is actively cancelled using local and ship degaussing system (DG, active technique) by generation of magnetic field of similar shape and magnitude but with opposite polarity. DG is calibrated using analytical or FEM (Finite Element Method) models, physical scale models (PSM) and by measurements of the vessel by overrun or stationary underwater signature range.

Signature check and recalibration is done frequently according to standards and for ships based in different harbours requires sailing to the range location or deployment of portable range. Necessity of DG parameters update is caused by change of vessels' structure and equipment permanent magnetizations. That change eventually leads to exceeding field limits.

To reduce time and costs of periodical checks, Closed Loop Degaussing system (CLDG) concept was invented and deployed on board different ships' classes, including MCM vessels. Such system allows identification of signature change while at sea and prediction of off-board signature basing on network of magnetic field sensors measurements on board. This allows recalculation of the field and update of DG parameters responsible for permanent magnetization signature. However operation of CLDG is prone to magnetic noise (caused by e.g. introduction of small magnetic field sources, sensor misalignment etc.). Therefore systems' algorithms need to be robust and supplemented by vessel's information and data from simultaneous underwater range measurements.

Paper presents CLDG modelling in Centrum Techniki Morskiej (CTM) proprietary software, works in FEM and experiments on board 1:14 physical scale model (PSM) in the laboratory as well as experimental deployment of the system on board new mine hunter and discussion on obtained results.

1 Introduction

Four main sources of ship's magnetic field signature within dc to several hundred Hertz band are [1–3]:

- Permanent and induced magnetization of hull and on board equipment;
- Eddy currents induced in conducting hull and equipment;
- Corrosion related and cathodic protection processes;
- Electric equipment and ship's power distribution system.

The most important source is magnetization of ferromagnetic objects, which is best known, thoroughly described and successfully modelled and minimized. This source can be split into permanent and induced magnetizations. The first depends on the material, its history and varies slowly with time. The second is linearly (within geomagnetic field range) dependent on external magnetic field. Each can be further divided into magnetizations along main axes: vertical, longitudinal and athwartship. Subsequently magnetic signature components are attributed to e.g. vertical induced magnetization, vertical permanent magnetization and so on, giving in total eighteen components.

Reduction of magnetic signature due to magnetization is done by passive and active means. Passive reduction is achieved by appropriate selection and inspection of materials during ship's design and construction phases. Active reduction is performed by DG.

Currently used degaussing systems can be divided into four categories depending connection type and permanent magnetization monitoring and update mode. In most older ships DG coils were connected in groups and ampereturns in each coil were set using connection boxes by inverting current direction or excluding some loops from the circuit. Modern DGs are based on providing power to each coil from its exclusive power supply. The latter one allows for much more flexibility in signature shaping and for more accurate field reduction.

Monitoring and update of permanent magnetization is done through periodic measurements on underwater signature range. Thus DG currents are updated using range measurements and subsequent calculations which is a base of DG working in open loop mode (OLDG - Fig. 1.). In turn equipping the ship with magnetic field sensors on board allows (of course theoretically at the beginning) to find underwater signature basing on thus measurements, thus removing or reducing the frequency of range measurements. This type of DG runs in closed loop mode (CLDG - Fig. 2.). Block diagrams of OLDG and CLDG are show below.

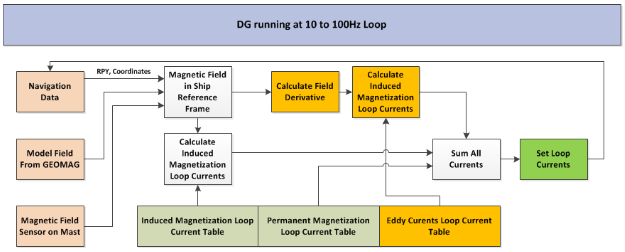

Fig. 1. OLDG block diagram

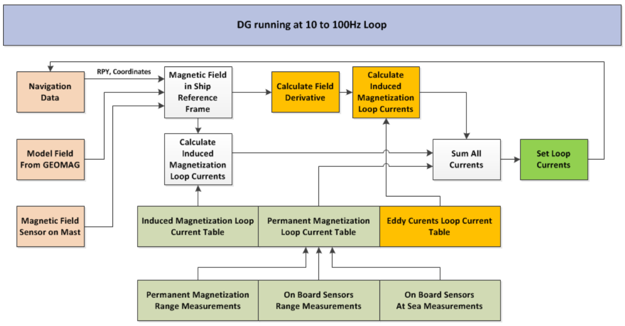

Fig. 2. CLDG block diagram

The differences between the two modes are additional blocks/modules and more importantly software/algorithms that provide information from the sensors and work out useful results.

Reported successful deployment of CLDG on board ferromagnetic and non-ferromagnetic hull ships including mine hunters confirms the concept feasibility and possibility to effectively use it for magnetic signature monitoring and reduction. Moreover earlier multinational RIMPASSE [4] trials and current MASTERCODE [5; 6] and COSIMAR [7; 8] projects being realized by Centre for Ship Signature Management (CSSM) and other publications [9; 10; 3; 11] show importance of the subject.

Among other systems CTM has deployed signature monitoring and reduction system on board recently commissioned Polish Navy Mine Hunter (MH) and is working on two more ships of the Kormoran Class MHs and rescue and salvage vessel.

Therefore in CTM work on further development of DG is underway and selected information about approach and achieved results will be presented in this paper.

We will briefly describe other sources of magnetic field signature to give a complete picture.

Second most important source of magnetic field are eddy currents induced in conducting hull and equipment on board. There is limited literature available on the topic, with main publications being those of J. J. Holmes [1–3], which are references in many articles about sources of ship's magnetic field signature. More detailed description of the topic is available from the same author in Electromagnetic Silencing Symposium 2012 (EMSS) article [12]. There are also several interesting publications about eddy currents in conducting objects that are not directly related to ship's signature. Recently (in 2016) another article with summary of RIMPASSE trials was published (measurements of physical fields of the vessel and their variation due to different conditions in several location in Europe and Canada) – this time concentrating on eddy current magnetic field [13; 4].

Theoretical introduction into eddy current magnetic field and related issues are presented thoroughly in [14; 15].

Due to roll, pitch and yaw of the ship in external magnetic field, eddy currents are induced in conducting materials on board, including hull. Flow of those currents is a source of magnetic field around ship. Dominating component is related to roll frequency, which is usually the highest from three motions mentioned above. This frequency falls in 0,01Hz to about 0,3Hz (much less than 1Hz) band. It differs depending on the vessel, however an average value can be assumed at about 0,1Hz. Roll angle can be estimated to be between $\pm 15°$. Eddy currents will have components in phase and quadrature with respect to roll. It is assumed that magnetic field levels required of the national and NATO standards cannot be met without taking care of eddy current magnetic signature.

Lesser known is corrosion related magnetic field (CRM), considered as a third most important source, and with passive and active ways of its reduction. Also its fall off rate is different than that of coils or magnetized sources (fall off is r^{-2} compared to r^{-3}) [1–3]. CRM arises from currents flowing through the ship's hull (and to lower degree through water) which are caused by voltage difference (due to different electrochemical potentials of the steel hull and typically a nickel-aluminium-bronze propeller) between hull and propeller. Large underwater area of the hull gives rise to significant corrosion currents and to static and alternating (mainly at shaft rotation frequency and its harmonics) magnetic fields. Static field can be treated as originating from longitudinal electric dipole. However ships are equipped with some form of cathodic protection (CP) to reduce the hull's corrosion that adds the complexity to the CRM. CP is realized as sacrificial anode CP (SACP) with zinc bars with lower electrochemical potential that act as anodes (thus turning hull into cathode and slowing/preventing corrosion). More advanced system consists of set of active anodes with their own power supplies that regulate current flow between them according to reference electrodes to achieve set potential with respect to the hull. The latter system is called impressed current cathode protection (ICCP) and can also act as electric field reduction system.

Fourth of the sources – stray field – is also well known and described and minimization methods, such as screens, appropriate cable routing or using special coils are commonly used. This field is generated by current carrying circuits and its largest sources are high power electric devices such as electric generators, electric engines etc. and power distribution cables. Resulting alternating field has mainly base power system frequency and its harmonics and subharmonics. This field is shielded by conducting hull (with larger attenuation by ferromagnetic hull) and to lesser extent by conducting environment – sea water – thus giving the smallest magnetic field from all four main sources.

Each source's influence on total magnetic signature depends mostly on hull material. So for MCM vessels with hulls built from non-ferromagnetic and sometimes non-conducting materials there will be no hull component in static magnetic field and eddy current magnetic signature can be greatly reduced or eliminated. However it is very difficult and costly to remove all magnetic materials from the ship's machinery and equipment. Therefore we can expect several local extrema in magnetic signature on test depth, whereas with ferromagnetic hull all is smoothed but at much higher level. Due to that effect sometimes local degaussing system with coils around main machinery and equipment on board the ship is used to complement ship's DG or equipment in special low magnetic versions is requested. Non-ferromagnetic and non-conducting hulls provide respectively less and no shielding to alternating field form electrical equipment on board. There is also power supply requirement closely connected with the hull type and field level that means an order of magnitude increase in power needed for degaussing of ferromagnetic hull ship with respect to non-ferromagnetic one. Of course combatants have much higher field limits and are measured at different depths than MCM vessels.

2 Approach

Requirements put forward for signature management system list among others necessity to monitor magnetic field on board the MH. To this purpose special magnetic field sensors together with necessary electronics and communication were developed and integrated into DG network. Sensors were positioned in carefully chosen locations on board with special emphasis on main magnetic field sources in main and auxiliary ship's power plants. Each sensor is equipped with 3D offset coils that allow cancellation of arbitrary field levels. Of course number of sensors on board is a compromise between scientific willingness to deploy as sensors as possible along the ship and practical feasibility. Data from the sensors is transferred in real time to DG main processing unit. Magnetic field measurements are then complemented by navigational data and current DG parameters and can be stored in file for future use.

Works on the ship were preceded by development of physical scale model (PSM) of the ship with full DG arrangement and multiple sensors placed in rescaled positions inside the PSM (Fig. 3.).

Fig. 3. PSM with test stand and sensors on board

Another work performed was development of CTM's proprietary software environment for simulation of magnetic and electric fields of the arbitrarily chosen set of coils, dipoles, ellipsoids or anodes accompanied by detailed mathematical model of the ship's DG and PSM's DG with sensors in LabVIEW. Ship and PSM were also put into third party FEM modelling environment (Fig. 4.).

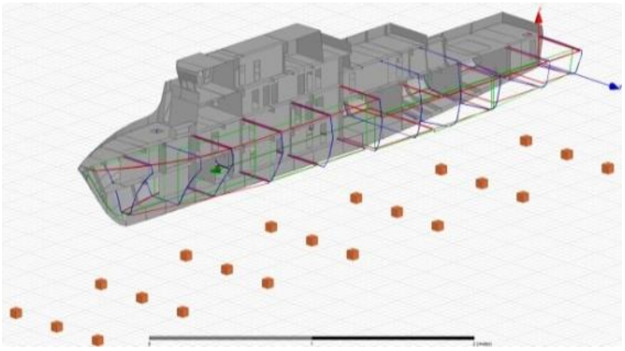

Fig. 4. PSM FEM model

These PSM and software were subsequently integrated with test stand constructed under the PSM, power supply for DG and algorithms relating measurements with models, optimization and so on. PSM test stand system consists of three PCs responsible for data acquisition from sensors under the PSM and on board; second for controlling power supply of the PSM's DG and third with all logic for simulation and control of whole system (Fig. 5.). All components are linked via Ethernet and exchange data in real time.

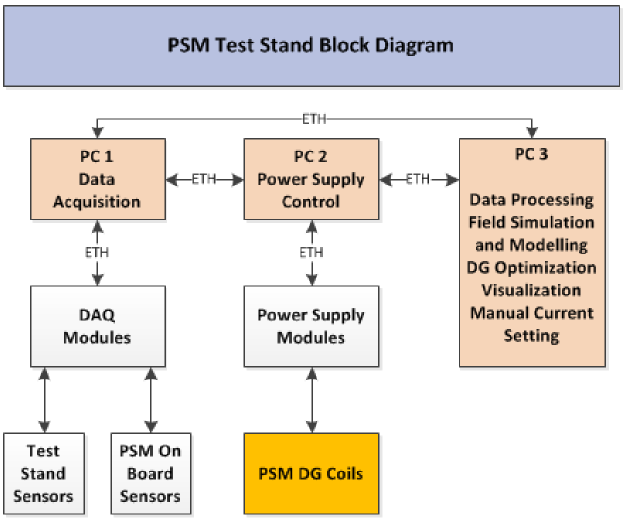

Fig. 5. PSM test stand block diagram

Main PC also processes data from the actual ship and measurements from sensors on board and has mathematical models of both PSM and full scale vessel.

3 Modelling, algorithms, measurements and results

As discussed above, ship's magnetic signature due to magnetization is divided into two main parts: field from permanent and field from induced magnetizations. The first one is considered constant or rather very slowly varying with time and does not directly depend on external magnetic field. The second one is in direct relationship with applied external magnetic field and that dependence in whole geomagnetic field range can be treated as linear. It changes with every pitch, roll or heading change where field components along main axes of the ship change. So in traditional DGs we divide currents into parts responsible for permanent (constant) and induced components and recalculate the latter with regard to the external field before summing up both and sending to power supplies. We briefly noted that permanent magnetization can slowly vary with time thus leading to necessity to recalculate permanent currents. Permanent magnetization change happens due to several factors: long exposure to external field, shock, temperature, mechanical stress. This change estimation and corresponding current recalculation is done using underwater signature ranges and periodical measurements of the ship (every say three, six months or other time). However limited number of ranges or portable ranges and distance between home base and range means necessity to sail for each signature check. Between checks change of permanent magnetization cannot be traced and resulting signature may differ from last measured and in case of MCM vessels and very low field requirements this could mean exceeding the limit. Checks could be done with magnetic field sensors on board, algorithms and appropriate data from sensor-signature calibration process.

To try to write relationship between underwater signature and measured by ship sensors we divide magnetic field into originating from induced and permanent magnetization:

$$B_j = B_{jp} + B_{ji} \qquad (1)$$

Where indexes j, p, i denote field component (i.e. B_x, B_y, B_z) and components from permanent and induced magnetization respectively. Each component is dependent on permanent and induced fields related to magnetization along each of three main axes (usually longitudinal, perpendicular and vertical with respect to the hull) and can be rewritten as:

$$B_j = B_{jpx} + B_{jpy} + B_{jpz} + B_{jix} + B_{jiy} + B_{jiz} \qquad (2)$$

$$B_j = \sum_{k=x,y,z}\left(B_{jpk} + B_{jik}\right) \qquad (3)$$

Each induced magnetization component can be linearly related to external magnetic field value (standard procedure when looking for coils' currents settings). Every coefficient in form of $X_{jk}\frac{\mu T \text{ or } nT}{1\mu T}$ can be established to relate field measured at arbitrary chosen point to external field value (e.g. per $1\mu T$. Note that units in coefficient were left on purpose to emphasize relationship). Those can be used to create equations with permanent components and induced in close connection to current external field. FEM calculated example variation of induced magnetization field with course for four cardinal courses and hull ca. 60m long with $\mu_r = 200$ with vertical field $B_v = 47{,}2\mu T$ and horizontal $B_h = 17{,}2\mu T$ is shown in Fig. 6. Sum with permanent magnetization component is shown in Fig. 7. Only cardinal courses are plotted, but ideally measurements should be taken as densely as possible to yield large number of magnetization states.

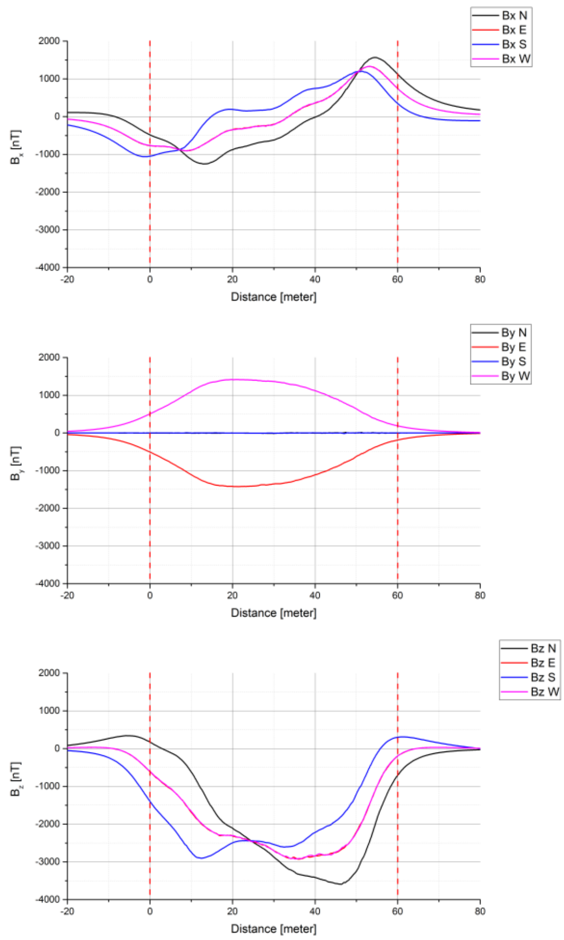

Fig. 6. Change of induced magnetization field with external field values (from top to bottom: longitudinal, athwartship and vertical components)

Variation of each component with external field can be clearly seen. Influence of induced component on total field can be seen in Fig. 7., however due to dominant vertical magnetization, permanent magnetization set on the similar level and the fact that vertical external field is constant for all four courses, its effect is limited.

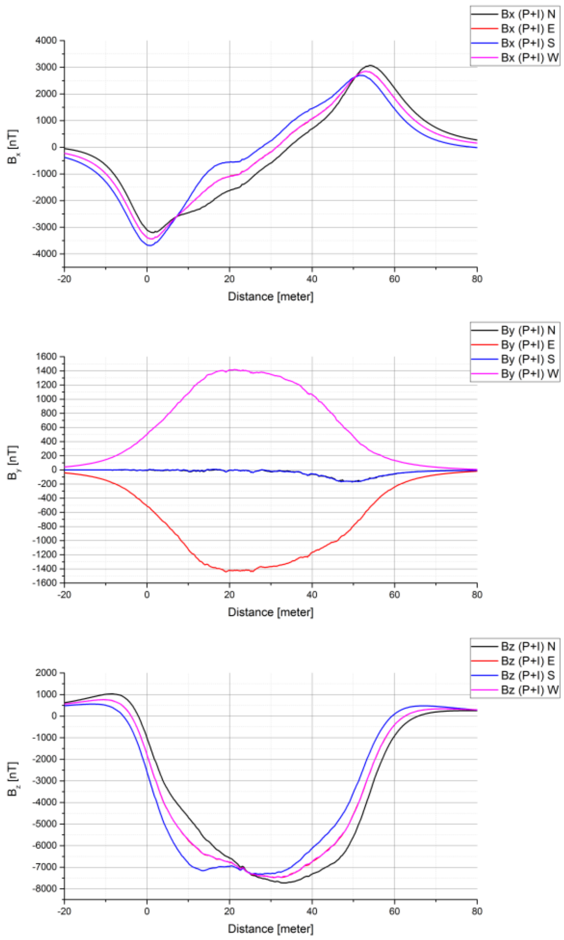

Fig. 7. Variation of sum of permanent and iduced field with course (from top to bottom: longitudinal, athwartship and vertical components)

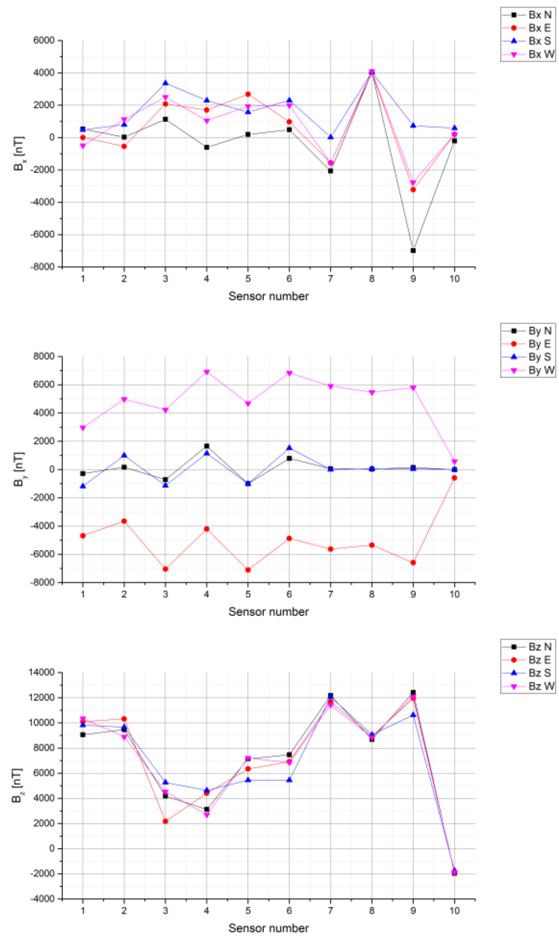

Fig. 8. Magnetic field components calculated at sensor positions (from top to bottom: longitudinal, athwartship and vertical components)

Based on these samples already a relation between external field and underwater signature can be established and in fact as mentioned earlier this is base of finding coils' currents. Adding sensors on board and performing similar operation can lead to extracting induced component on board. However as most overrun ranges have one or two lines of sensors this will have some limitations. And relation to vertical field cannot be calculated that way. Fixed ranges adds much more data and field simulators with range such as EFS in Lehmbek [16] are the best options as change of external field along each and every axis can be applied individually and across whole geomagnetic field range.

Putting sensors on board we obtain results shown in Fig. 8. The sensors have to be placed carefully not to measure large quickly decaying fields or too close to the hull to minimize error. From that point we can try to build a set of equations that have to satisfy conditions (values) both underwater and on board. Of course in ideal FEM or analytic model case there is no noise, sensors are perfectly aligned with ship's axes and positioned at exact spot. Equations at the beginning can abstract from the mathematical model (i.e. do not have to include dipole, ellipsoid or coils sources) and can start with data from sensors on board and in subsequent steps include underwater measurements.

Number of equations for each point needs to be as large as possible with each one providing data taken for different magnetization condition (i.e. for different external field, so on various courses) to allow obtaining overestimated set of equations to solve. We can then build equations in the form of linear combination of parameters (with *n* being measurement point index):

$$B_{jn} = B_{jpn} + B_{jixn} + B_{jiyn} + B_{jizn} \quad (4)$$

Where each induced component can be related to external field using appropriate coefficient:

$$B_{jn} = B_{jpn} + X_{jxn} * B_x + X_{jyn} * B_y + X_{jzn} * B_z \quad (5)$$

Where B_x, B_y and B_z are known external field components. This way using large number of measurements (not indexed above) we find components resulting from permanent magnetization and coefficients for induced magnetization. So far we obtained numbers that connect plots shown in Fig. 8. with external field and this might be enough to detect change in permanent component (with good quality data), however without ability to project this onto underwater signature. Simultaneously it is straightforward to build accurate source model basing on range measurements exclusively. Including data from Fig. 7. we can build mathematical model that allows to make such projection. Of course usually it will be possible to get data from limited number of courses, like from two (N, S or mixed) or four cardinal. Number of sources (meaning also number of parameters in equations to solve) and their optimization bounds determine accuracy of the model. Therefore variation in bounds can attribute for expected source magnitude.

PSM with mathematical models can be also employed for the purpose of DG and CLDG development. Currently non-ferromagnetic hull PSM of MCM vessel fitted with DG is available. Assembly of ferromagnetic model is almost done and will be followed by installation of DG coils inside (Fig. 9.).

Fig. 9. Ferromagnetic PSM under construction

First works are carried out using PSM shown in Fig. 3. which mathematical model together with sensors below and on board is shown in Fig. 10.

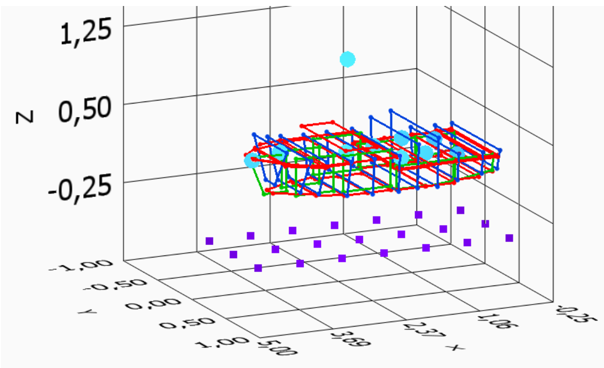

Fig. 10. PSM model in software environemt

PSM and sensors have to be carefully aligned and synchronized with mathematical model. Using small number of sensors to reconstruct good looking signature (Fig. 11. right) by interpolation and extrapolation the result is very susceptible to measurement points' misallocations that introduce larger errors. Still for the tests raw data is taken (Fig. 11. left). Calculations have to be done the same way – first on limited number of points and then interpolated/extrapolated to finer resolution plot to avoid fine vs coarse mesh error.

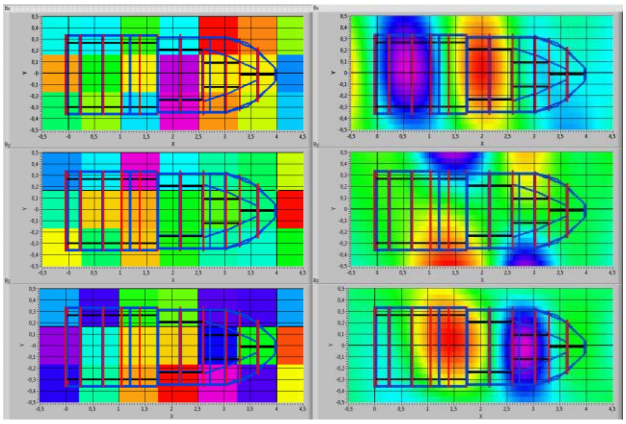

Fig. 11. Measured (left) and interpolated (right) signatures (from top to bottom: longitudinal, athwartship and vertical components)

Simulation of induced magnetization variation with course and slow changes of permanent magnetization, in absence of ferromagnetic PSM, can be simulated using DG coils of actual non-ferromagnetic hull PSM. Some constant current offset to selected coils is applied and additional variable current component responsible for rotations in external field is changer every measurement. Permanent component is provided by a combination of longitudinal (L) and main (M) coils and shown in Fig. 12.

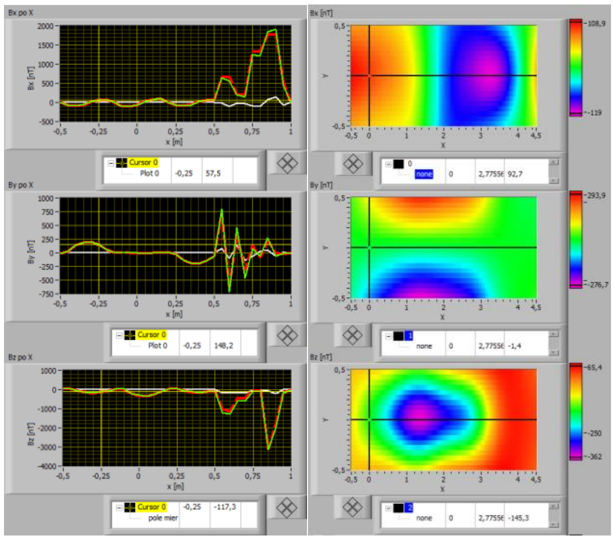

Fig. 12. Measured raw (left) and measured interpolated (right) signatures (from top to bottom: longitudinal, athwartship and vertical components)

In the following example induced magnetization is varied from -0,6*P to +0,6*P with 0,1*P steps giving total 12 sets of equations (plus one for only permanent longitudinal magnetization). Vertical magnetization is constant. Optimization algorithms for finding best fit parameters of dipole or coil model from measurements under the model or also from sensors on board PSM are already in place and working. Therefore forward/inverse modelling is feasible and will be used later. Solving equations yields four parameters for every component at each measurement point. Those allow subtraction of induced component for each magnetization conditions leaving only permanent one at the sensor. Accuracy of the reconstruction is shown in Fig. 13. with components at sensors combined for the purpose of calculations.

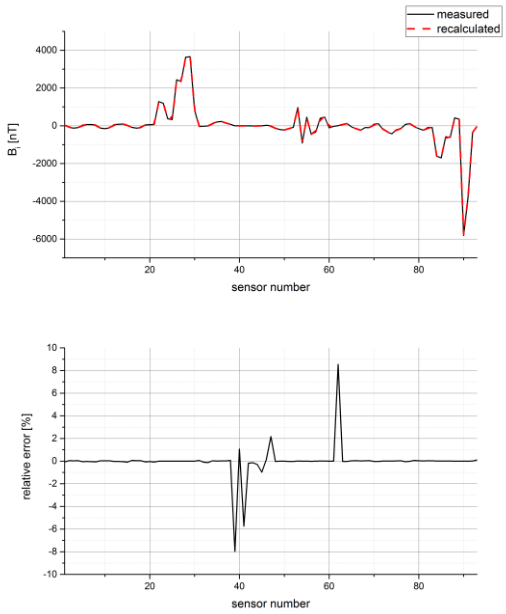

Fig. 13. Comparison (top) of measured (black) and recalculated (red) fields at sensors and relative error in percent (bottom)

Reconstruction of the field under the ship using coil model with parameters outside previously measured range leads to the following results shown in Fig. 14.

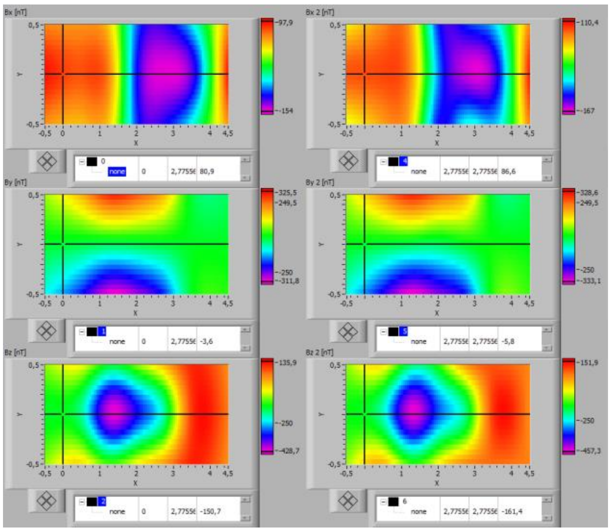

Fig. 14. Comparison of measured (left) and recalculated (right) fields under the PSM

Differences in measured and reconstructed fields are shown in Fig. 15. It can be seen that there is a good fit under the keel and worse with incresing latteral offset. This is the effect of errors and noise on the sensors and of some error especially on the athwartship component measured by the sensors vs modelled (Fig. 12. Left).

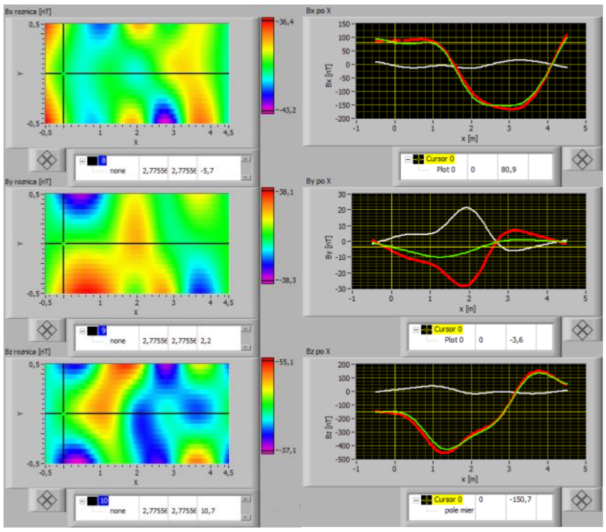

Fig. 15. Error in recalcualtion of the field under the PSM (surface – left, under the keel – right; red – recalculated field, green – measured field, white – difference)

Using similar approach one can reconstruct each component of the field related to three induced magnetizations and permanent magnetization simply by choosing only one part of the parameters. Of course in the example above we had number of sensors which on a ship will be exchanged for larger number of measurements but still mathematical model is created or supplied with data using underwater and on board measurements.

However there is always forward/inverse model complexity matter which determines accuracy of the reconstructed field and magnetizations. The more sensors on board, the more complex and accurate model can be. With limited number of sensors, number of the parameters (dipoles, coils, ellipsoids) has to be reduced to still obtain overestimated equations. In given example we have altogether ten sensors, which means nine effectively as mast sensor is used as a reference one to provide external field values in ship's reference frame.

4 Conclusions and future work

Software tests and simulations were performed and calculations using real data from PSM sensor system were done and first solutions were found that prove the approach. Simultaneously data gathered on board the ship was processed and shows promising results. However still much work has to be done before deployment, currently concept and system are in testing phase not operational.

Measurement campaign is underway and will be continued throughout late spring and summer both in lab and at sea. Works are part of extensive project around underwater signatures management whose previous results (regarding DG and eddy currents) were presented as a poster on UDT 2018 [17] and in detail on NATCON 2016 [18] and 2018 [14] and published in PNAJ [15]. Ferromagnetic PSM is expected soon and works will be continued.

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Paweł Polański, physicist, PM of Signature management system for two MH ships, is involved in modelling, simulating and reduction of ship’s magnetic and electric signatures, influence sweep and DG software and algorithms as well as in magnetic field test stands, underwater ranges, mines’ TDDs and magnetic detection of sea mines, mine warfare.

Franciszek Szarkowski, PM of Signature management system for Rescue and Salvage Vessel, is long time expert in maritime magnetic field area and leads projects or takes part in all works related to magnetic field underwater, including DG systems, underwater magnetic detection, influence sweeps, mine warfare.

Marta Czarnowska, physicist, specializes in magnetic field measurements and works on simulations of the response of materials to short duration loadings from explosions.