Determining the Electromagnetic Environment on Board Ships for Risk-based Approach EMC Analysis

Nancy Omollo
RH Marine
Rotterdam, The Netherlands
University of Twente
Enschede, The Netherlands
nancy.omollo@utwente.nl

Jan-Kees van der Ven
RH Marine
Rotterdam, The Netherlands
Jan-Kees.vanderVen@rhmarine.com

Robert Vogt-Ardatjew
University of Twente
Enschede, The Netherlands
r.a.vogtardatjew@utwente.nl

Frank Leferink
Thales Nederland
Hengelo, The Netherlands
University of Twente
Enschede, The Netherlands
frank.leferink@utwente.nl

***Abstract*— The increased implementation of new electronic systems in a small physical space has resulted in complex electromagnetic environments. A ship is an example of such a system with a complex electromagnetic environment. In order to prevent electromagnetic interference in such complex systems, one needs to understand the composition of the environment and the interaction between the different elements. This paper determines the electromagnetic environment on-board ships, with the intention of achieving electromagnetic compatibility using a risk-based approach.**

Keywords*— *Electromagnetic environment, risk-based approach, maritime, ships

I. Introduction

Electromagnetic interference (EMI) is one of the biggest problems in complex systems and often a major cost-driver [1]. Several installation measures have been and are taken to achieve electromagnetic compatibility (EMC) in such systems. The most common approach is the rule-based approach. In this approach, tests, test conditions and limits are defined in standards to ensure that equipment that comply with these standards are suited for their intended environment. Standards for equipment are however not always matching the intended environment also because setting the limits is more often based on adopted practices than on solid physics. Furthermore, since the standards cannot keep up with the new development in technology, e.g. the use of some frequencies not covered in the standards, such as radars operating at the GHz ranges, and since different equipment are also used in all environment sometimes for which they were not intended, the rule-based approach is thus insufficient to achieve EMC. The change in the environment could be as a result of aging, repair, or introduction of other equipment that were not there when the EMC evaluation was done during installation, such as portable Bluetooth devices, mobile radios, Wi-Fi devices, or any other modern wireless devices and/or systems etc. With standards followed for installations in ships, interference cases have still been observed in many instances, e.g. interference of a satellite TV reception on a modern marine vessel, as reported in [2]. Therefore, a risk-based approach is proposed to deal with these limitations and problems. The risk-based approach has recently been approved and adopted by the certification authority for maritime vessels, Lloyds [3]. It has been applied in the shipbuilding process of naval vessels. The risk-based approach can ensure that generally available commercial off-the-shelf (COTS) equipment can be safely integrated on board ships, resulting in lower costs of the overall installation cost of marine vessels. In [4], [5], and [6], the need of possible implementation of a risk-based approach to solve EMC problems on complex systems have been described. Recently the guide for the EMC directives [7] was published and the word “risk” is mentioned over 20 times, while in the earlier version of the guide it was mentioned only once. The guide thus acknowledges the disadvantages of a purely rule-based approach and requires a risk assessment. New standards are under development to promote the use of risk-based approach in achieving EMC, e.g. IEEE 1848 [8].

This paper describes the risk-based process and steps to apply this approach. One needs to understand the electromagnetic (EM) environment of the complex system first in order to successfully follow this approach. This paper thus evaluates the EM environment on board modern ships as part of the risk-based approach towards EMC. To investigate the difference and to prepare recommendations, the paper also focusses on the determination of the EM environment on ships, citing cases of EMI, pointing limitations of the rule-based approach based on the standards and proposing a risk-based approach for EMC.

II. Electromagnetic Environment On board Ships

The EM environment of a ship is complex, with different sub-systems such as radio communication and navigation system, power generation, propulsion and conversion system; pulsed power intentional radar system; machinery control and switchgear system; interior comms and digital system; hull, mechanical and electrical systems etc. [9]. All these sub-systems have electrical and electronic equipment that generate signals that can potentially interfere with the normal function of other systems, degrade performance, introduce errors or operational faults, and cause total component failure. Therefore, the correct placement and testing of equipment on board a ship is vital to the successful daily operation of the ship and optimization of the performance of the on-board equipment.

The aim of evaluating an EM environment of a system is so that proper measures can be taken to modify the environment in order to achieve EMC. EMC is defined as the

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ability of a system to function satisfactorily in its intended environment without causing intolerable disturbance to anything in that environment [10]. To achieve this, EMI shall be prevented by reducing or diverting the signals that could interfere with the operation of other electronic equipment. This would involve identifying and setting up specifications for each type of EM disturbance and/or interference on board. These interferences on the vessel are characterized by voltages, currents, magnetic fields, electric fields and EM fields, continuously transmitted (including modulated) or as transients. The sources of those interferences can either be natural such as static noise, cosmic rays, atmospheric noise, solar noise, lightning, or man-made. The man-made sources can either be intentional or unintentional. The intentional sources being those that are designed to radiate EM fields as part of their functionality, e.g. radars, whereas the unintentional sources are those that are not primarily designed to radiate but do so due to their circuitry, e.g. switched-mode power supplies. Different zones on board of ships are characterized by different signals, depending on the subsystems that are installed in those zones. The boundaries between these zones determine how different those interference levels are and thus different kind of mitigation measures that may be required to attenuate the coupling paths. These zones include for example the outer deck regions, for which the threats coming from lightning and strong EM fields from transmitters may interfere. Other zones include above deck and below deck regions.

III. Interaction and Mitigation Methods

The interaction between an EMI source and a victim is through a coupling path. The coupling path can either be conductive or radiative. In order to achieve EMC, one of the three elements of EMI situation is removed. For the intentional sources, the source cannot be removed and thus the coupling path needs to be interrupted or the victim protected, to maintain EMC and hence the proper operation of the ship [11]. Mitigation can be done through one or more of the following: shielding, zoning, earthing, bonding, use of screened cables, filters etc. The nature of the interference helps in determining what mitigation measures need to be taken to safeguard the victim. It is requisite to fully understand the characteristics of these EM environment in terms of:

- Frequency bands in use
- Maximum noise level in operational frequency bands
- Power levels of the transmitted signals
- Characteristics of the antennas involved, their polarization, directivity and gain
- Choice of power distribution network (insulated, earthed, direct current (DC), etc.)
- Construction materials used
- Cable types

IV. Sources and Their Charactersitics On board Vessels

A ship, due to its structure and equipment installation, can be divided into several EM zones. These zones are physically separated by conductive materials or distance. The material that separates two different zones may determine how different their EM environment can be in terms of disturbance levels. For instance, there is the outer deck (the topside system) and the inner deck. The inner deck zone is further divided into above main deck and below main deck, which contains, among other systems, the bridge system. All of these zones are characterized by different types of interference that couple to their victims through a radiated path, conducted path, or a combination of both. Without the coupling path, an interference condition does not exist, therefore breaking this path is requisite to ensure that EMC is achieved. These phenomena are discussed below.

A. Conducted emissions

Conducted emissions involve coupling of interference through cables and conductors. On a ship, there are the marine frequency converters which produce EM emissions in their power sections by switching on and off high voltage resulting in steep voltage and current edges. This creates emissions which can be conducted to other parts of the system through the connected power cables, other cables within the system if the device has a different potential at its environment. The controller and other electronic components of marine frequency converters also consist of very sensitive electronic devices which must be protected against electromagnetic disturbance. To limit the interference emissions of marine frequency converters, measures such as shielding, filtering, etc. must be taken.

Other examples of the conducted interference on board ships include voltage and current surges as a result of lightning, electric fast transients bursts (EFT-B), generated by switching devices (the propagated EFT-B can corrupt data and disrupt communication links), electrostatic discharge (ESD), which is the transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact. It is key to note that ESD however is not a very big problem on board ships. This is because of the high humidity found on board ships, rendering the ESD levels very low.

B. Radiated emissions

This involves the emission and reception of electromagnetic energy through antennas and current loops created by conductive structures and cables which act as antennas. Due to the use of fast switching electronics on board ships, there is an increase in the level of RF energy that adds noise to the EM environment, potentially causing immunity problems or increased noise level in communication systems, such that these unintentional radiated emissions cause poor radio reception. Furthermore, intentional transmitters on the top side of a ship can also be a main cause of radiated interference, as a ship is densely compacted with different sets of antennas and EM sensors for communication, navigation, detection, direction finding and tracking [12], [13]. Basic EMC measures include replacement and sector blanking (spatial diversity), using blanking pulses (temporal diversity), or smart frequency selection, frequency agility like hopping and bandpass filters (frequency diversity).

V. Overview of Maritime Frequencies

A marine ship EMC environment is characterized with receivers in different frequency ranges, using frequencies such as very high frequency (VHF) at 156-165 MHz, high power navigation radars operating in the GHz range, long range communication transmitters in high frequency (HF), and heavy electro-mechanical machinery. Table I gives an overview of some of the equipment and the frequency bands in which they operate. The functions of those different systems and/or equipment is given in [14]. Maritime communication systems and radar systems are mostly affected by EMI problems, due to the sensitivity of the communication receivers. This has sometimes major consequences for the link budget.

TABLE I. Overview of Maritime Communication Systems and Frequencies of Operation

System/Equipment	Frequencies
Digital selective calling (DSC)	MF/HF DSC: 2187.5 kHz, 4207.5 kHz, 6312.0 kHz, 8414.5 kHz, 12577.0 kHz, 16804.5 kHz VHF DSC: VHF marine channel 70 - 156.525 MHz
Voice and data communication	1.6 MHz - 26.5 MHz
Narrowband Direct Printing (NBDP or radio telex)	1.6 MHz - 26.5 MHz
Navigational Telex (NAVTEX)	518 kHz, 490 kHz and 4209.5 kHz
VHF other than DSC	156.025 MHz - 162.025 MHz
Automatic Identification System (AIS)	156 MHz –163 MHz AIS 1 161.975 MHz AIS 2 162.025 MHz
Satellite Voice and Data Communication (UHF)	Satellite comms: 406 MHz Inmarsat C: 1626.5 MHz -1645.5 MHz Inmarsat GX 26.5 GHz - 40 GHz high capacity overlay Iridium (Pilot) Ground users – 1616 MHz – 1626.5 MHz (L-band) Terrestrial gateway 29.1 GHz – 29.3 GHz
Terrestrial communication technologies using the UHF/SHF band	4G – LTE Advanced at 2.6 GHz 5G SHF – at 6 GHz and above
RADAR SART, X-Band RADAR S-band	Radar X band - 2.9 GHz -9.5 GHz Radar S-band - 2.9 GHz -3.1 GHz

VI. Rule-based Approach and its Limitations

The rule-based approach is following standards (rules) with the assumption that if equipment fulfil the requirements of a standard, no interference will occur. With respect to marine ships, the basic standard with respect EMC include IEC 60533 [15] that looks into the electrical installation on ships with metallic hull, and IEC 60945 [16] that outlines EMC regulations for radio communication and navigation systems. In the rule-based approach, any maritime electrical device on board a ship should be compliant with either IEC 60945 or IEC 60533, bridge mounted equipment, radio communication and navigation equipment (main source and victim of radiated emissions on board ships). These standards refer to basic standards describing emission tests and immunity tests.

The EMC standards referenced above have their limitations. These limitations render them insufficient to guarantee EMC on board ships at all time and in all situations and circumstances. For instance, due to the threats posed by the densely populate topside (outer deck) of radar and communication antennas, the levels in the standards are often not covering all EM sources. As observed by these two standards, and other generic standards upon which measurement procedures and limits are stated e.g. IEC 61000-4-3, for radiated immunity tests [17], there is provisions for measuring radiated interference only up to a frequency of 2 GHz. However, as has been shown in table I, there are equipment installed on board ships that operate beyond these limits, e.g. radars and satellite communication equipment.

Standards applied do not entirely take into consideration every single detail and changes in the given environment, such as aging, repairs etc. They also do not take into account the evolution in technology. For instance, the new VHF Data Exchange System (VDES) technology that is yet to be adopted for improved and more efficient VHF communication, may not have all the required limits and tests laid down already, in the standards. VDES is developed to meet the increasing need for data communication between maritime users and due to the significant rise in VHF data link load with the increasing use of AIS, would provide faster data transfer rates with greater integrity than current VHF data link systems.

VII. Practical Cases of EMI in Complex Systems

In this section, a few examples are given of interference cases on complex systems, and reasons indicated why standards are insufficient to prevent such interference cases.

A. *Interference of AIS reception*

On a modern ferryboat it was not possible to acquire AIS targets which were farther away than 8 NM [2]. Because of the disturbed frequency band the whole lightning on board has been switched off. To solve the problem the distributor was requested to recommit other types of energy saving lamps with other types of power supply units.

B. *Influence on a DGPS receiver*

At a new built vessel, the reception of the DGPS signal has not been possible due to emissions from an air conditioner and some components within the switching, which were not properly grounded [2]. After the grounding was corrected and also when the air conditioner was switched off, the DGPS receiver was not interfered with anymore.

C. *Interference of a satellite TV reception on a modern marine vessel*

A distortion of the satellite-TV reception by navigation radar has been reported in [18]. The satellite reception band was at 3.4 GHz to 4.2 GHz, whereas the radars installed were operating at frequencies around 3 GHz and 9 GHz, the two basic navigation radar bands. This interference is of course caused by a lack of frequency selectivity of the satellite communication equipment.

D. *Malfunction of medical equipment*

The medical care industry has also been affected by EMI. A 93-year-old heart attack victim died when the attached monitor and defibrillator shut down every time the radio transmitter was used in an ambulance. This was due to the metal fiberglass ambulance roof that allowed high levels of radiated radio fields inside the patient area of the ambulance [18].

E. Accidental firing of ammunition from an aircraft

In 1967, a military aircraft was exposed to a ships radar that caused it to accidentally fire its ammunitions, hitting another armed aircraft sitting on the outer deck of the same ship. This accident was a result of an EMI case, as investigations revealed that a degraded cable shield termination on the first aircraft, caused emissions that interfered with the radar and hence operation of the aircraft causing it to misfire. Other sources reported that one of the pilots activated the ships radar and then a Zumi rocket was fired prematurely. Several deaths resulted from the accident [18].

F. Effect of emissions from LED lights on VHF reception

Cases have also been reported of poor VHF receptions on board ships due to the emission from LED lights on board, installed within the vicinity of such receptors [19]. For example, the maritime rescue coordination center in one port was unable to contact a ship involved in a traffic separation scheme incident by VHF radio. That ship also experienced very poor AIS reception. Other ships in different ports have experienced degradation of the VHF receivers, including AIS, caused by their LED navigation lights. LED lighting installed near VHF antennas has also shown to compound the reception. Another case, was also reported where ships disappeared from the radar, an occurrence caused by interference from emissions by LED lights [19]. This creates unsafe situations as communication is key, between ships, and between ships and shores.

G. Walkie-talkie interferes with ship steering, causes minor collision

An incident occurred outside United Kingdom (UK) waters where there was a minor collision between a supply vessel servicing a semi-submersible offshore oil and gas installation. The vessel experienced a sudden power increase brought on because of interaction between radio signals from a portable VHF radio and the joystick control. This caused the joystick to execute commands not requested by the operator and resulted in contact between the vessel and the installation. The interaction caused minor damages [20].

H. Interference issues on a research and recovery vessel

EMI generated by the switching power supplies in the COTS equipment slightly degrades the LORAN-C signal-to-noise ratio through radiated coupling. COTS computing equipment generates sufficient radiated interference on the HF bands to render HF communications impractical. Broadband interference and harmonics from COTS computing equipment interfere with communications reception on selected VHF channels, in some cases enough to prevent useful communications [21] .

The use of rule-based standards does not necessarily guarantee EMC. This is because of the several undefined factors in the standards, as has been depicted in the limitation to standards that may or may not be present in a complex EM environment like a ship. Therefore, it does not prevent all EMI failures. As mentioned in the introduction, more and more organizations like Lloyd’s [3] and in the European Guide for the EMC Directive [7] the risk-based approach is supported, and is considered as a way to take care of most of these different factors. The risk-based approach does not require more hardening and more EMI protection measures! It requires common sense, and as a result, when properly applied, can enable for instance the use of COTS equipment on board of ships without hardening every COTS device.

VIII. Risk-based Approach

The risk-based approach takes care of the actual operation environment such as high EM fields in the topside environment, and protection against indirect lightning, for instance. Sources and victims have to be identified; it defines mitigation measures when necessary; it requires testing the effectivity of the mitigation measures; and requires validation of the proper functioning of equipment. Also, since COTS equipment have been proposed for their availability and cost-effective ship building [9], the risk involved must be evaluated and proper measures put in place for mitigation. Experienced engineers will recognize elements which are being used in military standards [22], [23], **Error! Reference source not found.**. In [4] and [5] four main actions for implementing the risk-based approach are detailed.

EMC management plan: This plan defines the EM environment in which the ship will operate, fixes the requirements both from the legal and customers perspective, defines and agrees on the responsibilities between all parties involved: contractors, sub-contractors, system integrators and equipment suppliers. In general, the EMC management plan defines the EM threats that follow from the requirements of the customer and states who is responsible for what.

EMC control plan: Controlling identified risks and defining measures is a major part of this plan. It defines the best practices to mitigate the risks and translate them into purchase specifications for the parties involved. An input to this plan consists of EM threats and operational requirements from the customer combined with the equipment that will be used on board. To identify the different risks and threats, a source victim matrix can be used. The output of this plan is a number of documents and instructions that will enable the system integrator to properly inform all involved parties which requirements are made with respect to their delivery and the installation work. In general, this plan states what needs to be done in order to prevent interference.

EMC implementation plan: This plan explains in detail how the control plan should be carried out. For instance, details on how to arrange cables, distances to be kept in carrying out specific tests, the right procedures in mounting certain devices and components, etc. The EM topology is the reference defining the EM boundaries [25] and defining EM zones. At every boundary interface the proper EM mitigation measure has to be implemented. This can be filtering or circumferentially bonding a screened cable to the boundary, such as a wall or a deck penetration. Harsh EM environments require screened cables which are routed through solid metal tubes or even prohibit cables in the exposed environment. This can be achieved by designing equipment such that the metal shielding structure is mounted immediately on a deck. Power supply group can be split into several categories, such as mission critical or crew use. The first requires an insulated power supply system with a power insulation monitor while the second requires an earthed power system with residual current device protection, and EMI filters will be different for both power systems.

EMC verification & validation plan: This plan describes the measurement methods to be used, the voltages and currents involved, the field strengths, frequency ranges, measurement distances etc. When everything is verified to have been done the way it was supposed to, it is the expectation of the process that EMC is achieved in that system. Verification includes tests performed during construction phase, while the validation part is performed during harbor acceptance and sea acceptance trials.

The risk-based approach has been implemented by several companies active in the maritime sector. It enabled them to realize a cost-effective installation of a ship by having a defined environment which can be established by specifying engineering requirements and having the tests done, verified, and validated.

IX. CONCLUSION

In order to design a complex system such as a ship, to operate with proper levels of EMC, emissions and immunity, one needs to understand the EM environment, the EM zones, the components and their characteristics, as well as the interactions between those components. In this paper, the EM environment on board ships has been determined, and a risk-based approach is proposed to achieve EMC. This approach, with the knowledge of the EM environment, will enable, for instance, the use of COTS equipment in this environment. Necessary steps as defined by the risk-based approach encompass several steps of understanding the environment, devising a control plan and implementing, validating and verifying it.

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