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TRANSACTIONS (TM)

ELECTROMAGNETIC COMPATIBILITY IN SHIPS

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Read at 1730 on Monday 11 February 1985

ISSN 0309-3948
Trans I Mar E (TM)
Vol. 97, Paper 16 (1985)

Electromagnetic Compatibility in Ships

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SYNOPSIS

In Part 1 of this paper the general aspects of EMC are described, together with details of laboratory tests, specification requirements and measures which can be taken prior to installation of equipment to ensure compatibility. It is recognized, however, that in the final installations problems may arise which can only be dealt with by onboard investigation and Part 2 describes the methods and techniques for performing such investigations.

INTRODUCTION

It is not too many years ago that interference problems in ships were confined to impairment of radio reception by radio frequency (RF) noise generated by the ship's electrical equipment. A paper[1] on this subject, published in 1948, describes RF noise measurements made on a number of merchant ships and passenger liners.

Modern ships, even relatively small vessels, may carry a vast array of radio and navigational aids and make extensive use of electronic circuits for control purposes, auto-watch, steering and navigational computers. The 1948 paper makes interesting comparison with a more recent paper[2] which provides details of the much greater range and complexity of compatibility problems which have been encountered in present-day ships.

Thus the concept of electromagnetic compatibility (EMC), which is defined as the ability of all electrical and electronic equipment to co-exist without degradation of performance or the environment, is very much applicable to all marine installations.

Achievement of EMC, i.e. satisfactory operation of all equipment despite noise generation, transients due to switching of electrical power and transmissions from radio communications and radar, is a matter of taking all the relevant factors into account as early as possible in the design process. Where it is possible to control emissions, limits should be imposed to restrict RF voltage, current and radiation, and immunity should be built into all sensitive equipment to enable it to withstand such aspects of the electromagnetic environment which cannot be subject to control. Interaction between equipment, stray inductive and capacitive coupling should be reduced as far as possible by physical separation, cable segregation and electromagnetic screening where necessary.

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F. J. Derham MBE is the Chief Project Engineer in the EMC Division of Aish and Company Limited, Poole, Dorset. He has specialized in electromagnetic compatibility for 23 years and heads a team of engineers whose main activity is the investigation of EMC related problems in HM ships and submarines.

PART 1: GENERAL CONSIDERATIONS

Causes of interference

Radio interference in the conventional sense is caused by rapidly fluctuating voltages and currents creating a wide spectrum of noise which may be conveyed to sensitive equipment by propagation methods, often complex, involving conduction, induction and radiation. The sources of noise include all the electrical machinery on the ship, motors, generators, thyristor phase controls, radar modulators and all switching circuits and devices. Such noise is generally classified as broadband, in that the effects are manifest over a wide range of frequencies and may affect communication and navigational receivers from 10 kHz to several hundred MHz.

Switching circuits, relays, thermostats and similar devices produce discontinuous broadband noise, which may not cause serious disturbance to speech communications because of its intermittent nature but can cause errors in digital systems. Transients generated by electromechanical switching, in addition to disturbing electronic equipment, may be at such a high level as to damage integrated circuits.

Harmonics of power frequencies from local oscillators, switched power supplies and other sources of complex waveforms, including digital circuits, are generally classed as narrow band since the effects are manifest at a series of discrete frequencies. This is in contrast with the broadband noise sources, but in all cases the final effect is determined by the bandwidth of the equipment under consideration that is being disturbed.

Generation of harmonics and intermodulation products resulting from transmitter power incident on non-linear junctions can also cause disturbance, particularly to radio reception.

This is sometimes referred to as the 'rusty bolt' effect, since the non-linearities often occur as a result of corrosion in structural metalwork.

Frequency spectrum and the electromagnetic environment

Marine radio communications and navigational aids are within the frequency bands allocated by the International Telecommunications Union for the particular purpose. Spectral coverage extends from 10 kHz to 10 GHz and some indication of the services in various bands is given in Fig. 1(a). The extent of the spectral coverage illustrates the wide range of services, varying from the long range navigational aid, Omega, in the frequency range 10.2 to 13.6 kHz and sensitive to fractional microvolt signals, through to marine radar systems which, even in relatively small vessels, may have a peak power output greater than 50 kW in the 9 GHz band.

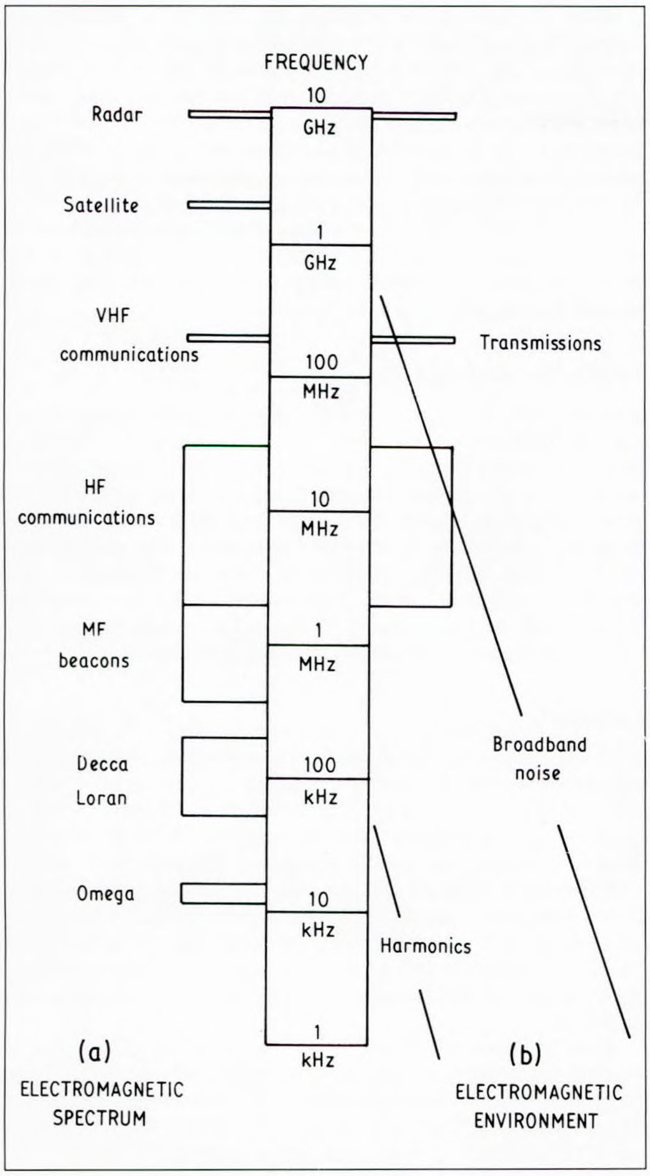

FIG. 1 (a) Electromagnetic spectrum; (b) electromagnetic environment

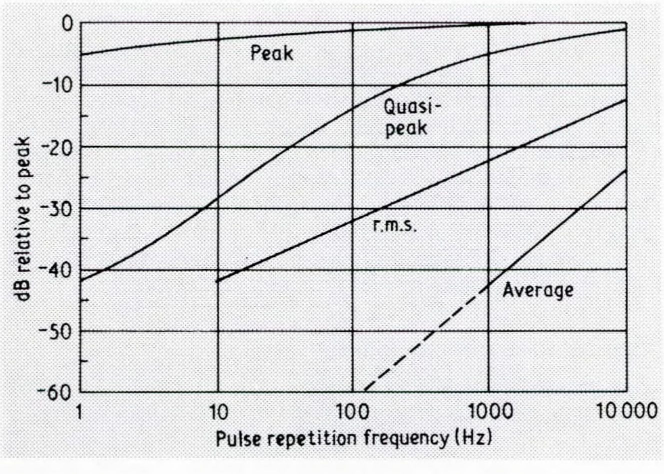

FIG. 2 Measuring receiver detector response

The main radio communications are provided in the MF and HF bands particularly for long range, with extensive and increasing use of the VHF band 156–162 MHz. Certain frequencies designated for distress and rescue purposes require special protection from disturbance. These are 0.5, 2.182 and 156.8 MHz and also the aeronautical search and rescue frequencies of 121.5 and 243 MHz. Satellite navigation and communication systems using 1.53 GHz will come into increasing use as the facilities become available.

An indication of the electromagnetic environment which may be encountered aboard ship is given in Fig. 1(b). At low frequencies, i.e. below 10 kHz, the dominant source is likely to be harmonic generation by the ship's power supply equipment and will include generation by thyristor phase control and similar circuits. Broadband noise generated by the electrical equipment may cover a wide range of frequencies from d.c. possibly extending to several hundred MHz. In this frequency range a significant contribution may be due to switched power supplies, pulse modulators of radar equipment and, increasingly, digital equipment using fast-rise pulses at high frequencies which may produce signals in the VHF band.

For the immunity or susceptibility of sensitive equipment, the dominant factor is the level of field strength generated by transmitters. Their power output has increased considerably over the years and field strengths in excess of 100 V/m may be encountered on the upper decks, owing to the operation of HF transmitters. The extent of penetration of such field levels below deck depends very much on the extent of screening provided but with the increasing use of non-conducting materials in ship construction it is unwise to rely on significant attenuation. The VHF transmitters tend to be somewhat lower in power but strong fields will be encountered locally near the transmitting aerials. In the radar bands the peak field strength may be several hundred volts per metre within the radar beam and, although highly directional narrow beams are employed, the contribution to the environment from the ship's own radar and from nearby vessels cannot be ignored.

Instrumentation and measuring techniques

Instrumentation, frequency domain

The characteristics of radio interference measuring receivers are given in detail in BS 727:1983[3] and in the international standard CISPR No. 16. The design parameters of the receivers, such as bandwidth, overload characteristics, dynamic range etc., were selected on the basis of providing repeatable, consistent results with vastly differing input signals and noise.

Originally designed to provide pulse response related to the subjective annoyance encountered in broadcast reception, the quasi-peak receiver is in extensive use for determinations of compliance with national and international standards, and legal regulations. The characteristics of quasi-peak receivers have been extended to provide coverage of frequencies from 10 kHz to 1 GHz. It is, however, frequently necessary to obtain further information about the characteristics of noise sources, since many problems of interference occur with communications other than speech.

Thus measuring receivers are now available with peak and average detectors as well as multiple bandwidth. A comparison of the response characteristics of the detectors used in VHF measuring receivers is shown in Fig. 2. Many such receivers are reasonably portable, capable of battery operation and, in addition to laboratory and test house applications, are fully capable of use on board ship in the detection, measurement and location of sources of noise and unwanted signals.

Spectrum analysers, giving a swept frequency display of signals over a wide frequency range, are extensively used for measurement of harmonics from local oscillators and other RF generators, including digital circuits. Here again, instruments with multiple bandwidth provision and storage facilities can be used for signal analysis where the characteristics of the disturbing source are required.

Time domain

Transients and similar disturbances in power supply systems cannot be reduced to negligible proportions and sensitive equipment must have some inherent immunity to them. Investigation of immunity requires information on transient characteristics, e.g. probability and frequency of occurrence, amplitude and duration. Transient and surge recorders capable of unattended operation are readily available, as are storage oscilloscopes of wide bandwidth and having the ability to display waveforms for transients of high amplitude, lasting much less than one microsecond.

Laboratory measuring techniques

Laboratory measurements are generally involved in investigation of noise and unwanted signals and their propagation characteristics. Several standards and specifications exist for the control of potential interference. Laboratory tests are made to determine compliance with these requirements and also to assess the extent to which installation of filters, suppressors and screening is necessary.

The important feature in laboratory measurements is to define the conditions under which they are made, in order to achieve repeatability between laboratories; and also to make the conditions as representative as possible of the practical installation. Measurements may be divided broadly into two categories. First, assessment of signals and noise propagated by conduction, and hence measurement of RF voltage and current; and, second, assessment of the electromagnetic fields radiated from equipment by measurement of the magnetic and electric components.

Propagation is a complex mechanism in a ship's wiring and cabling system but in general the conduction mechanism is dominant below 30 MHz, whereas at higher frequencies, where attenuation in power cables increases quite rapidly, direct radiation is more important.

The techniques of measurement tend to reflect this situation; up to 30 MHz limits of noise and unwanted signals are quoted in terms of RF voltage and current, measured with the instrumentation described above, in conjunction with appropriate current and voltage probes. The conditions of measurement are defined as far as possible by supplying the equipment under test through line impedance stabilizing networks (LISN). These units provide filtering and isolation from the mains power supply and thus enable the impedance in the measuring circuit to be defined for the full frequency range of measurement. A typical measurement arrangement is shown in Figure 3.

However, it is not always possible to define the conditions of measurement, for example in the case of very large generators which may have to be tested *in situ*. In this case, RF current can be measured by clamp-on, ferrite-cored current transformers. These devices also have useful application in measurements aboard ship since RF current flow can be determined with minimal disturbance to the circuit. High-impedance (e.g. 1500 ohms) voltage probes can also be used, in which case access to terminals or conductors is required, but again the disturbance to the circuit under test can be almost negligible.

The distinction between the two categories is not necessarily well defined but, in general, the propagation mechanism dominant above 30 MHz is radiated field. In certain specifications radiated field measurements and limits are recommended over the entire frequency range and these may require determination of the magnetic and/or electric components of the field. In laboratory measurements on individual items of equipment, the measurements are invariably made inside a screened enclosure with the experimental arrangement well defined in terms of separation distance and layout of the equipment under test.

All radiated field measurements are subject to difficulties caused by reflection, secondary radiation, presence of the operator etc, and it is only by defining the arrangement as closely as possible that a reasonable degree of consistency can be obtained.

Field strength is measured using the radio interference receivers specified in BS 727, together with appropriate aerials: loop aerials for the magnetic component and rod or dipole aerials for the electric component. It is usual to confine magnetic field measurements to the range below 30 MHz although the loop aerial also provides a convenient means of detecting and locating sources of noise and propagation paths and may be used for this purpose at much higher frequencies.

For the VHF and UHF bands broadband aerials, such as the biconical, log periodic and log conical, are convenient to use both in the laboratory and on ships, since continual adjustment at each test frequency is not required.

Interaction and coupling

Achievement of overall electromagnetic compatibility in any complex installation is a matter of ensuring that all equipment functions correctly. In a typical marine installation, devices sensitive to fractional microvolt signals must co-exist with plant generating many kilowatts. The interaction between them must therefore be kept to a minimum. The mechanisms of interaction include coupling via common impedance, for example common earth impedance, inductive coupling through the mutual inductance between adjacent wires and cables, and coupling through cable-to-cable capacitance.

Immunity

Certain aspects of the marine electromagnetic environment may be subject to control: for example, limits are imposed on RF voltage, current and field strength of noise-generating equipment. These limits may be complied with by installing filters, screening and similar measures. Despite these actions and the application of the principles described in the various codes of practice, there are certain aspects of the EM environment which cannot be subject to control. These aspects of the environment are transient disturbances caused by switching operations and RF transmissions from communications and radar.

It is therefore necessary to subject sensitive equipment to various tests to ensure an adequate degree of immunity. Tests to assess immunity to transients are injection of a disturbance of specified amplitude, duration and risetime into the power supplies (and also into interconnecting cables).

Both current and voltage injection are used via appropriate probes or transformers and coupling networks. Subjection of equipment to radiated fields is considerably more involved and several methods are in use. Direct radiation from suitable transmitting aerials can be applied throughout the frequency range and is the only method practicable at UHF frequencies. Difficulties arise from the non-uniformity of the field and the problems of reflection and field distortion, since tests are generally performed in screened enclosures.

At lower frequencies and possibly extending up into the VHF band, the test fields can be developed in parallel plate transmission lines with sufficient separation between the plates to permit installation of the equipment under test. These transmission lines provide somewhat better uniformity of field and, in general, an E/H ratio close to that of free space fields. All tests for immunity to radiated fields are difficult and investigations are in progress which have led to extensive development of current injection methods, such as now specified for avionic and other military equipment.

Specifications and standards

Specifications for the achievement of EMC in marine installations are available. BS 1597[4] has been in existence for a considerable time but had not, until the 1975 revision (BS 5260[5]), contained direct requirements for the control of noise generated by marine equipment prior to installation on the ship. This standard is under further revision and will contain

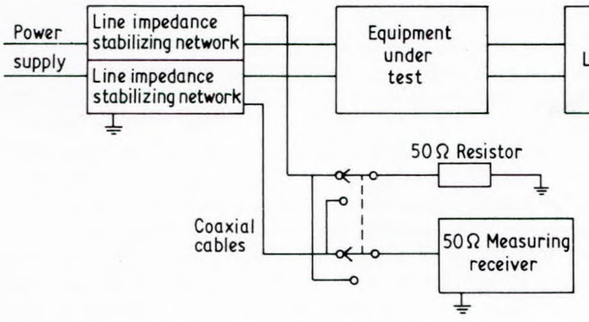

FIG. 3 Test circuit block diagram

requirements for limitation of RF current and voltage in the range from 10 kHz to 50 MHz, in addition to limitation of the radiated field between 30–300 MHz. It was recognized in 1975 that immunity of electronic equipment should be taken into account and a code of practice was published at the same time, giving general guidance on all aspects of the subject without specifying limits and methods of measurement.

The most comprehensive document on EMC in ships is the internationally agreed IEC No. 533 of 1977.[6] This specifies limits for the control of broad and narrowband noise in the range from 10 kHz to 30 MHz and also for achievement of immunity but only to injected current and voltage. The IEC publication is probably unique in that it specifies a measuring method and limit for the coupling between disturbances on the main ship's power supply and a nominal 1 m reference aerial. There is also considerable guidance on achieving compatibility, together with requirements for the environmental performance of suppressors. The extent to which it is implemented is not known.

A code of practice similar to BS 5260 is included as Appendix 7 of the IEE Ship's Regulations[7] and in this document considerable emphasis is placed on screening and segregation of wiring and cables.

PART 2: SHIPBOARD INVESTIGATIONS

Introduction

The need to exercise control over a ship's electromagnetic environment is of increasing importance owing to the dense packaging of electrical, electronic and communication systems. The introduction of non-metallic vessels, where the screening afforded by metal bulkheads is absent, raises additional problems. EMC specifications must be rigidly enforced and installations strictly controlled if equipment is to function without degradation of performance.

Specifications and measurement methods have been discussed in Part 1 and equipment meeting these specifications will, in general, perform satisfactorily in the environment, provided care is taken in the installation.

Laboratory testing is largely concerned with the evaluation of individual items and difficulties arise when attempting to assess complete scale systems. Important elements are not always available and simulation equipment has to be incorporated which may not be fully representative. Assessments carried out under these conditions can, however, be valuable since potential EMC problems can be identified and corrected. Laboratory tests alone cannot guarantee successful performance in the ship environment, unless the shipboard environment can be similarly controlled.

Many of the problems investigated have been due to incorrect application of the basic EMC concepts of equipment and cable separation, screening and bonding.

An increasing number of marine equipments, although meeting specified emission requirements, have not been subjected to adequate immunity tests and consequently fail in service. Particularly vulnerable are electronic control and monitoring equipments which can be susceptible to common mode interference appearing at amplifier inputs as differential mode signals.

To verify that a ship is free of the EMC related problems, it is desirable to carry out a full ship trial. This entails running all equipment and systems in a controlled programme and monitoring for undesirable interactions with communication systems, navigational aids, intercommunication and electronic control systems.

Investigation and measurement

The initial task in investigating a complaint of interference with a specific system is to determine whether excessive interference from external sources is responsible or whether the victim equipment is unduly susceptible.

Levels of interference at equipment terminals and current flow in the associated cable system can be measured using receivers similar to those employed in laboratory tests. Current measurement by clamp-on probes is preferred, since it does not disturb the system. Should interference levels be unacceptably high, a progressive shutdown of the ship's equipment may be necessary to identify the offending source.

Spatial emissions can be measured with calibrated aerials and measuring receivers, but the majority of problems below decks are due to conducted emissions.

On upper decks, however, direct radiation from the ship's transmitting aerials can cause interference with wheelhouse equipment. Aluminium foil wrapped around the victim can help to determine whether the interference is conducted via cables or by direct penetration due to imperfections in the cabinet structure. Interference can be conducted into a susceptible equipment via power lines, or any cable penetration.

To identify the coupling path, a current probe can be used with associated signal source and amplifier to inject controlled levels of signal into each cable. Once the couplng path is located, it is relatively simple to identify the susceptible circuitry and apply corrective measures, these being progressed with the equipment manufacturer or supplier.

It should always be remembered that 'eyes were made before meters' and a thorough visual examination of the installation is desirable, since excessive susceptibility is frequently caused by incorrect installation.

Installation

Interference is generated by sudden transitions in current or voltage demands, the interference energy appearing between conductors (symmetric) or between each conductor and earth (asymmetric). Asymmetrically generated interference is the net unbalanced current flowing in conductor systems returning to the source via earth and this usually represents the worst case. The currents can flow in large loops, creating radiated emission problems in addition to inducing interference into adjacent cable systems. Conversely, loops associated with susceptible systems can inadvertently couple with interfering sources.

Installations must be carefully planned in respect of equipment siting and cable layouts in order to achieve compatibility.

Interference generating equipments

Power and other cables carrying interference should be run together and be sited close to metal bulkheads to reduce the area of radiating loops. They should also be well separated from cables associated with susceptible equipment. A distance of 150 mm is recommended in BS 5260.

Cables running on upper decks in the vicinity of transmitting aerials should be enclosed in earthed metal trunking or conduit to avoid interference current being carried below decks and, conversely, to prevent coupling to receiving aerials of power from below-deck sources. Cable screens should be bonded at both ends.

In metal ships, some degree of screening is provided by metal bulkheads and decks and equipment can be sited advantageously. In non-metallic ships, tapes are used as bonding points for equipment, the tapes being connected to metal plates in the hull.

Cables should be installed as closely as possible to the tapes to avoid loops and each major system should have its own tape directly connected to a hull plate. It should be noted that the tapes can act as radiating aerials and this fact should be considered when siting sensitive cables or equipment near to tapes associated with interference-causing systems.

Transmitter feeder cables should be as short as possible and sited at least 200 mm from all other cables.

Susceptible equipment

Equipment susceptible to interference includes radio receivers, data acquisition systems, sonar, intercommunication systems, monitoring devices, navigational aids and the control gear for many items of electrical machinery. If EMC aspects are considered at the design stage, significant reductions in susceptibility can be achieved at low cost.

The following recommendations are general and apply to many potentially susceptible equipments:

(a) The minimum bandwidth necessary to fulfil functional requirements should be used. Audio-amplifiers can respond to signals into the VHF range, demodulation of the RF occurring due to non-linearity in the input circuits. Intelligible speech requires a bandwidth of 300 Hz–3.5 kHz and designs should incorporate filtering to reject signals outside this range.

(b) Low-level signal transmission should be avoided in equipment employing remote transducers or sensors. If system requirements preclude this, pre-amplifiers adjacent to the sensors should be used. Alternatively, it may be necessary to run cables carrying low-level signals in conduit.

(c) Zero-volt lines running betweeen equipments should be earthed at one point only, to avoid loops.

(d) Equipment designed for the upper deck use can be susceptible to radiated emissions from the ship's transmitting systems and it may be necessary to use shielded enclosures with appropriate RF gasketting.

(e) Signal pairs carrying low-level signals at low frequencies should be tightly twisted and enclosed in a continuous overall screen, protected with an insulated outer sheath. The screen should be bonded at one end only and never used as a signal path.

(f) The screens of coaxial cables carrying RF should be bonded at both ends.

(g) Signal cables should be well separated from power cables and other interference-carrying cables, and parallel runs avoided.

(h) In cases where adequate separation cannot be achieved, cables should be run in earthed metal trunking or conduit.

Suppression

Suppression components are invariably necessary to control conducted interference. Adequate space should be provided, together with screened compartments where necessary. Low-pass filters to attenuate both asymmetric and symmetric components are generally required to be installed in each line.

If the circuit design precludes the use of suppression components as, for example, in the excitation field supply cables from an automatic voltage regulator supplying a power generator, these must be treated as very noisy cables and techniques of separation, twisted pairs and screening applied.

As a general rule, low-pass Pi or Tee networks will provide adequate suppression, the cut-off frequency being chosen to give the required attenuation at the lowest frequency of interest.

The components should be housed in a metal enclosure and capacitor leads kept extremely short (<2 cm). The earthy ends should be connected to the case which, in turn, should make good metal-to-metal contact with the equipment frame.

Lead-through or bushing capacitors can be incorporated in the design if high levels of interference exist at frequencies above 10 MHz but care must be taken to observe manufacturers' recommendations in respect of fitting if improved performance is to be realized.

When installing suppression units, input and output cables must be kept well separated and the suppressed cables separated from any interference-carrying cables within the equipment.

Occasionally, it is necessary to fit additional suppression units as a result of onboard investigations and these must be installed correctly for optimum performance.

The high values of capacitance necessitated by some EMC specifications can present a safety hazard. Great care must be exercised to ensure that suppression unit earth bonds are not removed and suitable warning notices displayed.

CONCLUSION

The published information on radio and similar interference problems in ships shows how the requirements have progressed during the past 30–40 years. The dominant factor in specifications for marine electrical and electronic equipment published around 1940–1950 seems to have been the need to fit suppressors and filters which could withstand the severe conditions of temperature, humidity etc. likely to be encountered in the marine environment; but there was relatively little guidance as to their electrical performance.

More recent publications certainly highlight the increased complexity of marine electronic equipment, particularly for control and navigation purposes, and also the greater possibility of interaction between the systems. Few specifications for electromagnetic compatibility of other than naval marine equipment contain requirements for immunity or susceptibility tests and this is one aspect which will require attention.

Even so, it is evident that completely satisfactory operation of all systems in any vessel depends very much on good installation practice. Although there is considerable basic guidance in several codes of practice, the need for onboard EMC investigations is likely to remain undiminished for some time.

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Discussion

J. K. ROBINSON (Lloyd's Register): The planning of cable layouts by shipyards to achieve both EMC and minimal cost, within the generally restricted space available, requires more detail than is given in BS 5260. Can the authors provide any additional guidance correlating cable separation distances and EMI generation/susceptibility with the length of parallel runs and the use of unscreened or screened cables?

It is noted that the authors recommend a minimum separation distance for radio transmitter feeders, double that contained in 4.2.3 of Appendix 7 of the IEE Ships Regulations. Is this difference to allow for the use of unscreened cable or do they consider the IEE recommendations inadequate?

Recognising the growth in EMI emission levels and increasing use of EMI-sensitive controls, Lloyd's Register now require immunity testing as part of their environment testing for type approval of electronic equipment.

The authors give the dominant source of EMI at low frequencies as harmonic generation by the power supply equipment. Do they consider that equipment meeting the audio frequency susceptibility tests for conducted interference of Naval Weapon Specification No. 3 would operate satisfactorily when fed from a power system with significant thyristor loads, supplied by generators whose waveform (on no-load) is only just within the limits of Clause 8 of BS 2949 or Clause 40.6.1.2 of BS 4999?

Alternatively, as the requirements of BS 1597 and IEC 533 do not extend below 10 kHz, do the authors consider there is no significant problem below this frequency?

R. DOHERTY (Lloyd's Register): Do the authors consider that the peak measuring receiver is better suited than the quasi-peak measuring receiver for the susceptibility testing of electronic control equipment?

And do they consider that testing for emission and susceptibility for radiated interference below 30 MHz is unnecessary, as suggested by BS 1597?

G. E. WOODLIFF (GEC Electrical Projects Ltd): The authors have given a good deal of useful information on what the shipbuilder should do to ensure a satisfactory installation and how the maintainer should set about investigating problems. However, the paper does not give much advice on how to design equipment, other than to say that EMC problems are best solved during the design stage. What advice can the authors give to the designer?

D. St. SEIGNE (Dept of Transport): I note with interest the author's remarks concerning immunity and susceptibility tests. The Department of Transport's Marine Directorate is funding a study in order to obtain and collate details of the electromagnetic environment experienced in typical merchant ships. This information should enable a draft specification to be written proposing equipment immunity requirements. It is intended to submit this draft to British Standards for development.

Any information and comment on this subject which is already available would be of help in this work an should be sent to Department of Transport, Marine Directorate, Room 5/62, Sunley House, 90/93 High Holborn, London WC1V 6LP.

Author's Reply

With reference to planning of cable layouts (Mr Robinson), the current induced in a cable by an adjacent disturbing cable can be calculated in simple cases and the MOD document 'Electromagnetic Compatibility Guide TP 1006' contains much useful information on cable coupling.

In the practical situation where cables are loomed and terminating impedance unknown, meaningful calculation becomes very difficult, if not impossible.

An approach to cable layout planning attributable to Swedish naval sources is interesting and deserves consideration. All cables are graded, four grades being identified and the onus of designating grades put on the equipment supplier:

1 Interfering cables, e.g., power cables, cables supplying non-linear loads etc.
2 Non-interfering, not susceptible.
3 Susceptible and interfering (e.g., digital signal cables).
4 Susceptible (e.g., analogue cables carrying low-level signals).

Multicore cables should be graded taking account of the worst-case cores. All cables of the same grade should be run together and separated from other grades by the following minimum distances.

Grade	*Grade*	*Distance (mm)*
1	4	300
1	2	100
2	3	100
3	4	100

If cable grades have to come together they should do so for a minimal distance and any crossing made at right angles.

If separation distances cannot be achieved, a screen between grades, welded to the hull and at least 20 mm higher than the cable height, will provide screening in addition to acting as a support for the cables. Colour coding of cable grades could also be of great assistance in fault tracing, investigatory work etc.

With regard to separation distance of transmitter feeder cables, the RF current, flowing on the outside surface of the feeder screen, is a function of matching, adequacy of ground plane and direct coupling from the aerial system. In GRP vessels the provision of an adequate ground plane is difficult and, if long feeder runs are unavoidable, coupling to adjacent cable systems will result. The minimum distance of 200 mm was recommended to take into account HF transmitter installations on GRP vessels and cases here long feeder runs are necessary.

Direct comparison between the requirments of the BS2949 and 4999 and the af susceptibility tests in NWS3 requires detailed study to transform the percentage waveform distortion limits into equivalent frequency domain harmonic levels.

The audio frequency susceptibility test in NWS3 relates to dc lines only and is intended to simulate ripple and modulation frequencies present on low-voltage dc supplies derived from rectifier equipment supplied from 440 volt 60 Hz 3-phase sources.

The test procedure would seem satisfactory for a system with significant thyristor loads but injected level would have to be reconsidered.

BS 1597 and IEC 533 are primarily concerned with commercial ships. Tests below 10 kHz are intended to cover miltiary requirements where ship installations include large-scale sonar and intercommunication systems.

In the sub-committee responsible for the current revision of BS1597 the decision was taken to impose limits for the protection of the Omega navigation system i.e., down to 10 kHz, and it was considered unnnecessary to impose limits at lower frequencies for merchant vessels.

In reply to Mr R. Doherty, susceptibility tests on electronic control equipment are generally a matter of injection of CW or modulated signals into power leads and cables, and also of using similar signals to generate radiated fields. The use of either peak or quasi-peak receivers should be acceptable for most monitoring purposes. Differences in the detector response will only be apparent for pulse-modulated signals, in which case the peak receiver is preferred.

The dominant mode of propagation in the frequency range below 30 MHz is conduction in the ship's wiring system and satisfactory control of interference can generally be obtained by limitation of RF voltage and current. Susceptibility tests for marine equipment are consideration in the sub-committee responsible for BS1597. Several EMC standards now specify current-injection methods for susceptibility tests in the frequency range up to 400 MHz and these methods have significant advantages as compared with tests involving radiated fields.

Published for THE INSTITUTE OF MARINE ENGINEERS by Marine Management (Holdings) Ltd
(England Reg. No. 1100685) both of 76 Mark Lane London EC3R 7JN.
Photoset by Paston Press, Norwich. Printed in England