Design of a Helmholtz Coil For Low Frequency Magnetic Field Susceptibility Testing

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Abstract: This paper describes the design of a Helmholtz coil that is a candidate test apparatus for low frequency magnetic field susceptibility testing on military equipment and subsystems. Use of this coil would reduce electromagnetic compatibility (EMC) qualification test time, and subject the equipment under test (EUT) to a relatively uniform field which is representative of the actual electromagnetic environment on some Naval platforms. Specifically, this paper presents practical analytical expressions that may be used to design a Helmholtz coil for this unique application. Experimental test results for a three foot diameter coil are presented, including:

- Maximum magnetic field strength vs. frequency
- Impedance vs. frequency
- Resonant frequency behavior
- Effect of coil separation distances greater than one radius.

INTRODUCTION

Low frequency magnetic field susceptibility testing is an environmental qualification requirement for Navy shipboard equipment and certain other military systems and equipment. MIL-STD-461C test method RS01, or the more recent MIL-STD-461D test method RS101 is normally specified [1, 2]. Experience has shown low frequency magnetic field susceptibility testing during the equipment qualification phase to be a key component for ensuring platform electromagnetic compatibility, particularly for submarine electronics systems. For example, sonar, radio and accelerometer-based monitoring systems are all potentially susceptible to low frequency magnetic fields; the presence of such fields can degrade system performance by causing false targets or reducing signal to noise ratios. To prevent electromagnetic interference (EMI) problems of this nature, it is important to test equipment to the anticipated magnetic field environment prior to platform installation.

The present MIL-STD-461 test method (i.e., RS101) covers the 30 Hz - 100 kHz frequency range and uses a small multi-turn loop antenna (12 cm. diameter) to generate the required magnetic flux densities at a distance of 5 cm.; its physical and electrical characteristics are specified in MIL-STD-462D [3]. The small loop antenna must be repositioned successively over every square foot on each side of the EUT enclosure (5 cm. from the EUT surface) to determine locations and frequencies of susceptibility. With the exception of small equipment, this is a time consuming procedure. By using a relatively large Helmholtz coil, EMC qualification test time and cost would be reduced. For example, for a 6' x 2' x 2' equipment enclosure, the number of test points can be reduced from ~52 using the small loop antenna, to ~5 using a Helmholtz coil, dependent on coil size. Because the Helmholtz coil generates a relatively uniform magnetic field throughout the test volume, it is more effective than the small loop antenna for simulating distributed low frequency magnetic field sources present on certain Naval platforms. For these reasons, Helmholtz coils are planned to be used for RS101 testing in the Navy's new attack submarine (NSSN) program [4].

Strictly speaking, the military standard requires RS01 and RS101 testing to be conducted using the small loop antenna. Use of a Helmholtz coil as described herein would represent a "tailoring" of the military standard test method and possibly the test limit. For programs other than NSSN, use of a Helmholtz coil in lieu of the small loop antenna would require approval from the EUT procurement agency.

Designing a Helmholtz coil for AC magnetic field susceptibility testing presents several challenges, particularly when high magnetic field strengths and/or operating frequencies are required. Bronaugh prioritized (by frequency) four secondary effects that limit upper frequency performance of a Helmholtz coil [5]. This paper focuses primarily on the following two of those effects which are most pertinent to coils being designed for test method RS101:

- Drive current fall-off
- Self resonance

The third design consideration that this paper will focus on is the potential for experiencing a relatively large electric field component in the Helmholtz coil test volume. The presence of such a field can make it difficult to accurately interpret magnetic field susceptibility test results. A simple methodology to estimate electric field magnitude, along with design techniques to minimize that field will be identified.
**COIL DESIGN**

**Design Goal**

The goal is to design, build and test a Helmholtz coil capable of generating magnetic flux densities in excess of the MIL-STD-461D RS101 specification limit shown in Figure 1. Ideally, the coil will be capable of generating magnetic flux densities that meet the "test limit" which exceeds the specification limit by a minimum of 10 dB (not to exceed 183 dBpV).

![Figure 1. MIL-STD-461D RS101 Limit](image)

**Design Considerations**

Key considerations in the RS101 Helmholtz coil design are: self resonance, drive current fall off due to coil impedance and electric field magnitude in the test volume. In addition, there are several options for the coil's circuit configuration that must be considered. Each is discussed below.

**Coil Configuration.** Candidate coil configurations include a series or parallel circuit, each of which may be balanced or unbalanced with respect to ground. Lumped parameter expressions for the first resonant frequency of each of these configurations were presented by Millanta et al [6]. The effect of coil configuration on resonant frequency was determined to be insignificant for the three foot diameter coil design presented herein. Coil configuration becomes a more important criteria when designing larger coils, coils with many turns or coils operating at higher frequencies.

A balanced, series-connected configuration was selected for the RS101 Helmholtz coil. In addition to field uniformity (same current flows in each coil), the series configuration simplifies test conduct since only one power source must be controlled/monitored.

**Self Resonance.** The MIL-STD-462D RS101 test method requires a continuous frequency sweep over the 30 Hz to 100 kHz range, and the resonant frequency of the small loop antenna to be greater than 100 kHz. For a Helmholtz coil at parallel resonance, it may not be practical to generate sufficient current to achieve the necessary magnetic flux densities shown in Figure 1. At frequencies above resonance, secondary effects (e.g., non-uniform current distribution along the coil windings) may be experienced that adversely affect field uniformity in the test volume [5].

Therefore, the RS101 Helmholtz coil must be designed and built to ensure that the first indication of any significant self resonant behavior is greater than 100 kHz. Parameters that determine the self resonant behavior include: series inductance, mutual inductance between the coil pair, inter-winding capacitance and, for a balanced configuration, coil-to-ground capacitance. For a series balanced coil pair, a lumped parameter approximation for the first self resonant frequency is given by [6]:

\[
f = \frac{1}{2\pi \sqrt{(L + M)(C_o + C_g)}}
\]

where:
- \( f \) = resonant frequency, Hz.
- \( L \) = external inductance of coil, Henrys
- \( M \) = mutual inductance between the coil pair, Henrys
- \( C_o \) = coil inter-winding capacitance, farads
- \( C_g \) = coil capacitance to ground, farads

Useful expressions for coil external inductance and mutual inductance are provided below. For coils containing more than a few turns, accurate lumped parameter approximations for coil capacitance do not exist. Those parameters can be calculated using numerical techniques, or can be measured using a swept frequency impedance bridge. Specific efforts were not made to minimize parasitic capacitance in the RS101 Helmholtz coil design. However, by minimizing series inductance (as discussed below), the coil capacitance does get reduced to some degree.

**Drive Current Fall-Off.** For AC applications at higher frequencies and/or high field strengths, the coil's series impedance is normally the limiting design factor. This will likely be true for any Helmholtz coil designed for RS101 testing. The coil's high inductive reactance will impede current flow required to generate the relatively high magnetic flux densities shown in Figure 1.

In the lumped parameter equivalent circuit presented by Millanta et al for the Helmholtz coil, the dominant term for frequencies below 100 kHz is the cell inductance which is the sum of each coil's series inductance and the mutual inductance between the two coils [6].

\[
L_{Total} = 2(L + M)
\]
where:

\[ M = \alpha N^2 r \]  \hspace{1cm} (3)

The series inductance can be estimated using the following expression derived by Ramo et al for the external inductance of a circular coil where the wire bundle cross section is circular in shape and small compared to the coil radius [7]:

\[ L = N^2 \mu_0 \left[ \ln \left( \frac{16r}{a} \right) - 2 \right] \]  \hspace{1cm} (4)

where, for (2), (3) and (4):

- \( N \) = number of turns (same for each coil).
- \( \mu_0 \) = permeability of free space, Henrys/meter
- \( \alpha = 0.494 \times 10^6 \) Henrys/meter
- \( r \) = coil radius, meters
- \( a \) = diameter of wire bundle cross section, meters

Because the total inductance (and coil impedance) is directly proportional to the number of turns squared, the number of turns must be minimized.

**Electric Field Component.** For magnetic susceptibility testing, the magnitude of the electric field component will ideally be negligible compared to the magnetic field component to prevent any ambiguity when interpreting test results. For most submarine systems, the MIL-STD-461D RS 103 electric field susceptibility specification limit is 5 V/m over the frequency range of 10 kHz to 1 GHz. The MIL-STD-461C RS03 limit for submarines is 1 V/m.

By inspection, the RS101 coils will be electrically short (i.e., wire length \( \ll \lambda/10 \)). Consequently, they will be poor electric field radiators. For larger coils, or coils with many turns, radiation efficiency can be quantified by using well known loop antenna expressions for radiation resistance and loss resistance.

A series voltage drop will exist across each coil that is proportional to the product of the coil impedance and the coil drive current. Because these voltage drops are separated in space by a distance of one coil radius, a voltage gradient will exist between the two coils. For submarine applications, the magnitude of the electric field that results from that voltage potential should be kept below the electric susceptibility limit of 5 V/m. This electric field component can be minimized by keeping the number of turns as low as possible. It may be possible to reduce the magnitude of this electric field further by enclosing the coils in a non-continuous electrostatic shield.

**Helmholtz Coil Equation**

Equations (5) and (6) below establish the framework for the coil design.

One closed form solution for the magnetic flux density produced by a series-driven system of two identical coils is [8]:

\[ B_i = \frac{\mu_0 N r^2}{2} \left( \frac{1}{\left( z^2 + r^2 \right)^{3/2}} + \frac{1}{\left( (d - z)^2 + r^2 \right)^{3/2}} \right) \]  \hspace{1cm} (5)

where,

- \( B_i \) = magnetic flux density, Teslas
- \( I \) = current, Amperes
- \( d \) = coil separation, meters
- \( z \) = distance along common axis, meters

Field uniformity can be computed by iterating the above equation over the axial distance \( z \). For two circular coils separated by one radius, the magnetic field is relatively uniform throughout the cylindrical volume whose radius is approximately half the coil radius.

For a Helmholtz coil configuration, \( d = r \). At the center of the test volume (i.e., \( z = r/2 \)), (5) can be simplified:

\[ B = \left( 8.99 \times 10^{-7} \right) \cdot N \cdot I \]  \hspace{1cm} (6)

**Design Approach**

Based on the considerations discussed above, it is clear that the coil must be designed with as few turns as possible to minimize series impedance, minimize the electric field component and maximize the resonant frequency (i.e., a low impedance magnetic field source is desired). However, minimizing the number of turns means that current must be maximized to maintain the ampere-turn product in (5) and (6).

The maximum RS101 specification limit is 175 dBpT (~ 5.6 Gauss) from 30-60 Hz as shown in Figure 1. The three foot Helmholtz coil was designed to generate maximum flux density at 60 Hz (vice 30 Hz) since that is a predominant source of low frequency emissions on Naval platforms. The coil impedance at 60 Hz was matched to the power amplifier’s output impedance where it generates maximum current. The number of turns was set to the minimum needed to meet the RS101 test limit at 60 Hz, given ~45 amperes of available drive current.
TEST RESULTS

A three foot diameter Helmholtz coil was constructed using 18 turns of 4 AWG stranded wire. A smaller gauge wire (i.e., 6 AWG) would be sufficient based on the maximum AC coil current. The larger wire size was chosen to give the coils the additional capability to conduct DC magnetic field susceptibility testing, in accordance with DOD-STD-1399 which may be invoked for equipment planned for installation on naval ships [9]. In addition, use of larger wire increases the bundle cross section area in (4), thereby providing a slight reduction to the coil series inductance.

An audio frequency power amplifier rated at 1000W was used to drive the coils. It is capable of generating ~45 amperes into a 0.5 ohm load. Coil current was monitored by two probes. One was clamped at the amplifier output, and the second was clamped around all conductors in one coil to detect non-uniform current distribution. For the coil size and frequencies of interest here, laboratory measurements confirmed the presumption of uniform current distribution.

Because the three foot diameter Helmholtz coil's upper frequency performance was based on its ability to meet its design goals at 60 Hz, initial laboratory measurements concentrated on coil impedance at 60 Hz. As shown in Table 1 below, there was good correlation between calculated and measured values of coil impedance at 60 Hz. By matching the coil impedance to the amplifier's 0.5 ohm output impedance, maximum power transfer (and drive current) was achieved at 60 Hz.

<table>
<thead>
<tr>
<th>Table 1. Coil Impedance at 60 Hz.</th>
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<tbody>
<tr>
<td>$R_{eq}$ (ohm)</td>
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<tr>
<td>Calc</td>
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<td>0.094</td>
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Additional measurements were made of magnetic flux density vs. frequency, impedance vs. frequency, and self resonant frequency. Each is summarized below.

Maximum Magnetic Flux Density

Maximum magnetic flux density was measured at discrete frequencies from 30 Hz to 100 kHz at the center of the test volume. Measurements were made using a small loop antenna designed for MIL-STD-461 low frequency magnetic field emissions measurements (i.e., 13.3 cm. diameter, windings enclosed by an electrostatic shield). A comparison of the measured maximum values (dashed line) to the RS101 specification limit (solid line) is shown in Figure 2.

Although the coils exceed the RS101 specification limit across the band, measured flux densities were only ~3-4 dB above the limit at 30 Hz and 400 Hz. The 30 Hz shortfall may be due to the impedance mismatch between the amplifier and coil, and the close proximity to the amplifier's lower cutoff frequency. For a coil designed to generate maximum flux density at 60 Hz, the 400 Hz test limit can be difficult to achieve. The coil impedance increases at 20 dB per decade, yet the RS101 limit decreases at by only 10 dB per decade between 60 and 400 Hz.

Higher flux densities (1 to 11 dB greater than shown) were measured from 40-100 kHz by increasing the amplifier's output impedance to more closely match the coil impedance.

Coil Impedance

Coil impedance was measured at discrete frequencies from 30 Hz to 100 kHz. Initial measurements were made with an impedance bridge, and were confirmed by measuring the voltage drop across the coils, the current flow through the coils, and computing the impedance using Ohm's law. The results are shown in Figure 3. The coil impedance is relatively flat and increases at 20 dB per decade as expected for a series inductive load.
Resonance

Swept frequency measurements were made on the coils from 30 Hz to 750 kHz. In the RS101 frequency band, minor parallel resonant effects were measured at 10.7 kHz and 25.5 kHz as shown in Figure 4. The magnitude of the resonant null at 10.7 kHz decreased by ~2 dB and shifted slightly higher in frequency when the coil separation distance was increased from 18 to 36 inches. This may be due to the reduction of the coil mutual inductance; additional investigation is required to determine the exact nature of these resonance's. As seen in Figure 2, there is margin available to overcome these resonances because their impedance is only ~4-5 dB greater than expected for a pure resistive-inductive load.

The first significant parallel resonance was measured at 171 kHz where coil impedance abruptly increases by ~18 dB, as shown in Figure 5. The initial onset of this resonance is far enough out of band to have no effect on RS101 testing.

Electric Field Component

Electric fields were measured from 10-100 kHz using a laboratory field strength meter. Maximum field strength was measured at the outer circumference of the test volume directly between the windings of the coil pair. Relatively high electric fields (~3 V/m) were measured when generating the RS101 test limit (i.e., 10 dB greater than the spec limit). Electric field strength dropped to less than 1 V/m when the RS101 spec limit was generated. In both cases, the worst case electric field magnitude could be roughly approximated by dividing the voltage drop across the coils by the distance separating the coils. These electric field levels are high enough to warrant extra care when interpreting magnetic field susceptibility test results. Frequencies of susceptibility experienced during RS101 testing should be noted and monitored carefully during electric field susceptibility testing.

Coil Separation Distance

For a Helmholtz cell, the two coils are separated by a distance of one radius. This configuration provides a uniform field throughout the test volume. Using three foot coils, it becomes necessary to abandon the Helmholtz configuration (by increasing the distance between the coils) to accommodate equipment with a width or depth dimension greater than 14 inches. Using equation (5), and the maximum flux density measured at 60 Hz (~15.5 G), the effect of coil separation versus flux density along the axis separating the two coils was calculated and is shown in Figure 6. The solid trace corresponds to a separation of 1/2 diameter (i.e., 18 inches), the dotted trace corresponds to a separation ~3/4 diameter. (i.e., 26 inches), and the dashed trace corresponds to a separation of one diameter (i.e., 36 inches).

When separated by 1 radius, the coils are capable of generating 60 Hz magnetic flux densities at 5 cm. that exceed the specification limit by 8 dB and meet the test limit. When separated by ~3/4 diameter, the coils exceed the specification limit by 6 dB at the center of the test volume, but do meet the
When separated by 1 diameter, the coils exceed the specification limit by 6 dB at a 5 cm. distance, but do not meet the test limit. Although this particular set of the three foot coils is not in strict accordance with the MIL-STD-462 RS101 test requirement at all frequencies below 700 Hz, they do exceed the spec limit at all frequencies. Because their field strength does not roll off as quickly with distance as do fields generated by the 12 cm loop antenna, in most respects, they provide a more rigorous susceptibility test.

**FUTURE WORK**

Efforts are planned for the near future to design and build a larger Helmholtz coil for RS101 testing at NUWC. It is expected that increased coil size will necessitate incorporating one or more of the following into that design:

- incorporate one or more "taps" into the coils so the number of turns can be reduced as frequency increases.
- apply an electrostatic shield to the coils to mitigate electric field (near field) effects.
- investigate further the effect of coil configuration on resonant frequency behavior.
- investigate power amplifier options such as increasing the output impedance setting at higher frequencies, or using one amplifier per coil driven by a common signal source.

**CONCLUSION**

Application of the guidelines and analytical expressions presented herein should enable users to design and construct Helmholtz coils for low frequency magnetic field susceptibility testing of military equipment. Because the Helmholtz coils are large relative to the MIL-STD 461 loop antenna, they are well suited for testing fully populated equipment racks in their entirety. This represents a rigorous, more realistic test bed, and will reduce EMC qualification test time and cost.

There are limitations and tradeoffs that must be considered when designing a Helmholtz coil for the MIL-STD-461D RS101 test method because it requires high magnetic flux densities over the 30 Hz to 100 kHz frequency range. It may not be practical or cost effective using commonly available laboratory power amplifiers to achieve the RS101 test limit at a 5 cm. distance for coils substantially larger than 3 feet in diameter. Consideration should be given to tailoring the RS101 test limit when a large Helmholtz coil is used because the Helmholtz coil field is significantly higher throughout the test volume (even when separated by more than one radius) than the field generated by the small loop antenna. For example, depending on coil size, it may be reasonable to propose that the test limit exceed the specification limit by only 3 dB (vice 10 dB), or that the test limit be set equal to the spec limit (i.e., ensure the existing spec limit is met).

It must be re-emphasized that MIL-STD-461 requires magnetic field susceptibility testing to be conducted using the small loop antenna specified in MIL-STD-462. Use of Helmholtz coils as presented herein would represent a "tailoring" of the military standard test method and possibly the test limit. For programs other than the Navy's new attack submarine (NSSN), its use would require approval from the agency responsible for procuring the EUT.

**ACKNOWLEDGMENT**

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