Low-Cost Audio-Freq. H-Field Measurements

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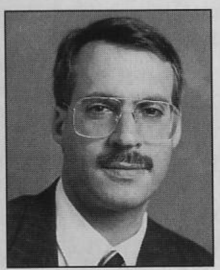

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Nontraditional magnetic sensors are investigated which yield low-cost instrumentation solutions to stringent audio-frequency magnetic emission measurement requirements.

Introduction

Many electromagnetic interference (EMI) test facilities have the capability to perform MIL-STD-461/-462 test RE01, a magnetic field measurement from 30 Hz to 50 kHz. A representative RE01 limit curve from MIL-STD-461C, part 2 is shown in Figure 1. The standard 36 turn, 13.3 cm diameter RE01 loop as described in MIL-STD-461A gives adequate sensitivity to measure 6 dB below this limit even with microwave spectrum analyzers which are not specified for use below 100 Hz. Because a single spectrum analyzer, such as the Hewlett Packard HP8566, gives adequate sensitivity for most military EMI measurements from 30 Hz to 20 GHz, it is often the only spectrum analyzer/EMI receiver at a given test facility.[1]

Difficulties may arise when a more stringent magnetic requirement is imposed. This is the case for some space programs, such as the Space Shuttle and Space Station.[3] The Space Shuttle specification MSFC-SPEC-521A requires a maximum magnetic emission of 60 dBpT from 20 Hz to 50 kHz. Figure 2 shows the magnetic emission limits from the Space Station and Space Shuttle programs. Figure 3 displays the voltage out of the MIL-STD-461A loop when immersed in a field intensity 6 dB below each of the Figure 1 - 2 limits. Figure 3 compares these voltage levels to the noise floor of the HP8566 at low frequencies, where local oscillator feedthrough and insufficiently narrow resolution bandwidth combine to pollute the noise floor of the analyzer.[4] The only limit curve for which an adequate ambient may be established is MIL-STD-461C, part 2 RE01. It may not be clear to some readers why the loop output must be at or above the noise floor of the analyzer. The analyzer noise floor represents the lowest measurable voltage out of the loop, and through the loop transducer factor (dBμV/pT) can be related to the lowest measurable field level. This is what is shown in Figure 4. Most engineers today are familiar with the modern technique of using a computer datafile for the transducer factor to reduce raw (dBμV) data to the same units as the limit. Figure 4 combines the loop transducer factor with the analyzer noise floor, and compares the resultant noise floor equivalent field intensity with the limits shown in Figures 1-2. In order to provide adequate performance, the noise floor equivalent field intensity should be 6 dB below the limit curves shown. Only the MIL-STD-461C, part 2 RE01 curve is high enough to be measured with the HP8566.

Two questions are of interest.

a. Why are the space magnetic emission limits so much tighter than the military limit?
b. Given that we have $60k invested in an HP8566 or similar microwave spectrum analyzer, how can we avoid spending tens of thousands of dollars more to extend our frequency range from 100 Hz to 20 Hz?

Control of Magnetic Emissions

Magnetic emissions fall off rapidly with distance from small sources such as those found in typical electronics enclosures. Intense 60-Hz sources (such as fan motors) measured within a centimeter of the

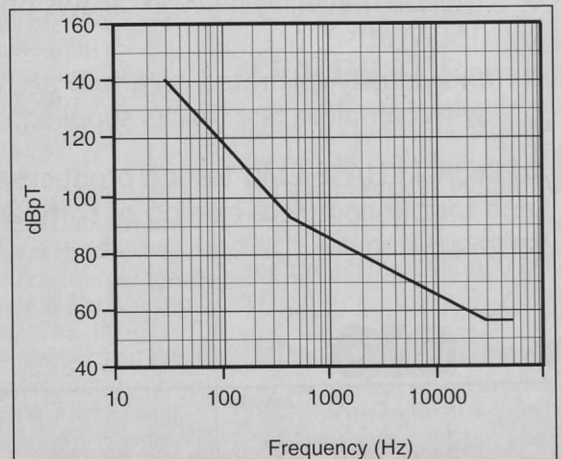

Figure 1. MIL-STD-461C, part 2, RE01 limit.

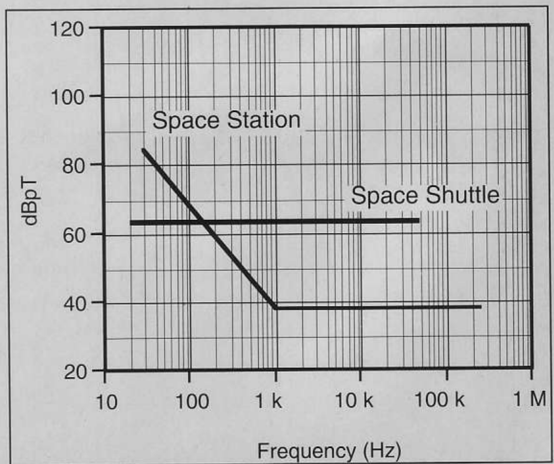

Figure 2. SSP30237 (Space Station) RE01 limit and MSFC-SPEC-521A (Space Shuttle) RE04 limit.[2]

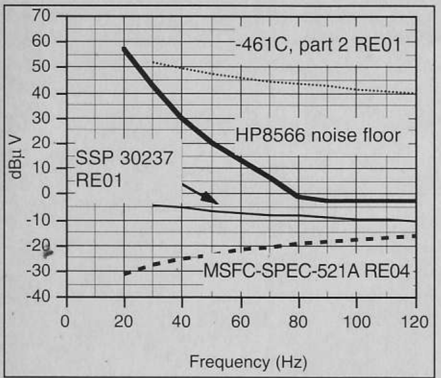

Figure 3: RE01 loop output for different limits.

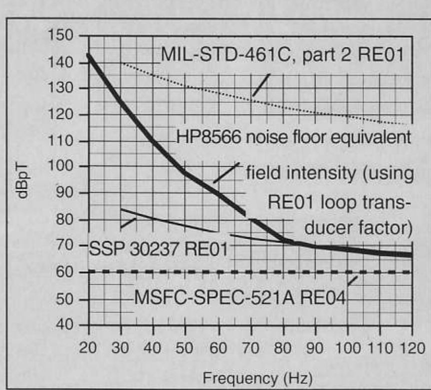

Figure 4: HP8566 noise floor equivalent field intensity (using RE01 loop) compared to several ac magnetic emission requirements (frequency range not specified for operation by HP).

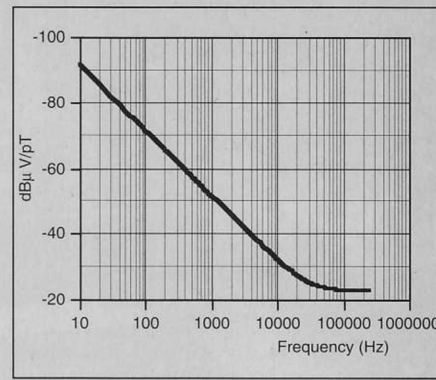

Figure 5: RE01 loop transducer factor (when loaded with 50 Ω).

EUT may well measure below background levels at one- meter separation. It is not possible to correlate measurements made close to the EUT with measurements made an order of magnitude greater distance away.[5] Therefore, if the EMC issue of interest is side-by-side compatiblity, one must measure the magnetic field immediately adjacent to the source. This is the case for the military RE01 limit imposed at 7 cm from the EUT. If, however, the EMC issue is control of general magnetic field intensity in a larger volume centered on the EUT, as it might be if sensitive instruments were measuring plasma fields in space, then it makes sense to measure the field at a distance more representative of the actual sensor to EUT separation. This is the case for the two space-related limits. The military limit, measured a few centimeters from the EUT, is necessarily set at a much higher level than the one- meter separation requirements. The combination of RE01 loop and microwave spectrum analyzer which is just able to measure at the centimeter separation limit is not adequate to do the job for the one-meter limits.

Extending Measurement to 20 Hz

The most obvious solution to making a sensitive 20-Hz magnetic measurement is to acquire a more sensitive receiver. These are commonly available from several manufacturers, but if not already in-house, entail an expenditure

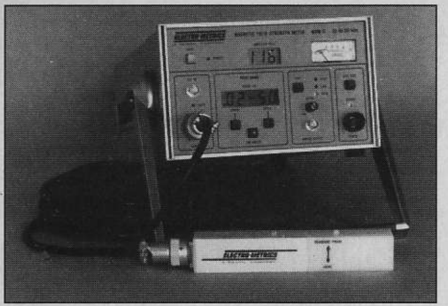

Figure 6. Electro-Metrics's MFM-11.

of tens of thousands of dollars. Many test facilities balk at spending that type of money for such a limited expansion of their test capability. Another solution is to find a more efficient transducer. The loop transducer voltage output is proportional to both the amplitude and frequency of the magnetic field. This is why it is so inefficient at low frequencies. Equation 1 gives the ratio of loop output voltage to B-field into a 50-Ω resistive load, and Figure 6 is a graph of equation 1.

$$V/B = \frac{2\pi f n_{turns} A_{loop}}{\sqrt{\{(1+(R_w/R_L))^2+(2\pi f\, L_w/R_L)^2\}}} \qquad (1)$$

where R_w and L_w are respectively the loop resistance and inductance, and R_L is the load resistance.

If we can find a sensing mechanism whose transducer factor is purely amplitude-dependent, not frequency-dependent, then we have a better chance of making low frequency measurements. Several techniques are available. Two of the most sensitive are discussed below.

Variable-μ Magnetometer

An inductor is wound on a core material whose permeability is proportional to the strength of the magnetic field which is to be measured. The inductor resonates with a capacitor and forms part of an oscillator circuit. As the magnetic field changes in intensity, the changing inductance of the sensor element changes the oscillator frequency, effectively frequency modulating the tank circuit. Just as in an FM receiver, the frequency deviation is proportional to signal strength, and the rate of change of the deviation gives the frequency spectrum of the signal. A commercially available variable-μ magnetometer is the Electro-Metrics MFM-11,[6] shown in Figure 6. This magnetometer has a sensitivity of 13 dBpT/√Hz, and a broadband sensitivity over its bandwidth of 20 Hz - 50 kHz of 60 dBpT. Figure 7a is a plot of an ambient taken in a shield room using the analog output of an MFM-11 connected to an HP8566 spectrum analyzer. For comparison, Figure 7b is a plot of the ambient in the same facility but using the RE01 loop instead of the MFM-11. The raw data has been adjusted for transducer factor for both Figure 7 plots. The large low-frequency "ambient" of Figure 7b may be seen to be an unrealistic adjustment of the HP8566 noise floor. Disagreement in levels of real 60-Hz and harmonic ambient may be ascribed to unknown field gradients with respect to sensor polarization. The MFM-11 is a very sensitive device.[7] Connected to a low-frequency EMI receiver or dynamic signal analyzer, it will allow measurements down to 13 dBpT, sensitive enough for any conceivable EMI limit. The MFM-11 costs about $10,000.

Induction Coil Magnetometer

A technique that falls between the variable-μ magnetometer and 13.3-cm loop in both cost and sensitivity is the induction coil magnetometer. It relies on Faraday's Law (as does the 13.3-cm loop) but with increased sensitivity due to a ferrite coil core and more windings on the core. The number of turns and core material are chosen according to the desired frequency and amplitude dynamic ranges. Coil output current is independent of frequency if coil inductive reactance exceeds its resistance and load impedance. This is accomplished by using a suitable gauge of wiring in the coil to provide the desired low-frequency coverage, and by loading the coil using the virtual ground of an op amp. Op amp voltage output is the feedback resistance multiplied by the coil current. An example of an induction coil magnetometer is the Walker Scientific VLF-80D,[8] shown in Figure 8. The VLF-80D has a frequency range of 20 Hz to 50 kHz. With a transducer factor of -5.6 dBμV/pT, it was capable, when connected to an HP8566, of measuring to the Space Station limit of Figure 3, but not the Space Shuttle limit of Figure 2. At 30 Hz, the dBμV adjusted Station limit is 78 dBμV (84 dBpT + {–5.6 dBμV/pT}), just above the Figure 9 reference level. Figure 9 shows the noise floor of the VLF-80D/HP8566 combined test set.

Performing the test which resulted in the Figure 9 test data was crucial in determining the suitability of the VLF-80D for use in making space-related magnetic measurements. The advertised transducer factor of approximately 52 mV/mG, or –5.6 dBμV/pT, could be directly applied to the specification limit and compared to the noise floor of the spectrum analyzer. The result of that exercise indicated that the VLF-80D was a candidate sensor. What remained to be determined was the noise output of the VLF-80D. As shown in Figure 9, the noise output was low enough to not affect the Space Station limit. Testing to the Shuttle limit was proscribed due simply to the noise floor of the spectrum analyzer. Final testing of the VLF-80D placed the sensor in a Helmholtz coil. A Helmholtz coil generates a uniform magnetic field within its interior. This is very important, since the voltage output of any magnetic sensor will be dependent on the orientation of the field and the average intensity of the field over its physical aperture. If the field gradient is unknown, calibration is impossible. Figure 10 shows a calibration setup for measuring at the Space Station magnetic field limit at a frequency of 20 Hz. Because the limit only extends to 30 Hz, and because the spectrum analyzer noise floor improves with increasing frequency

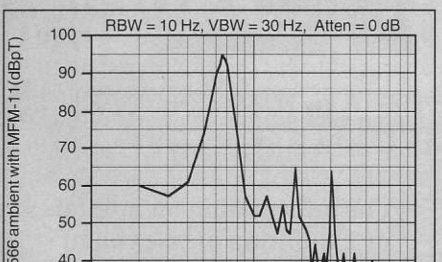

Figure 7a: HP8566 measured shield room ambients using MFM-11 as sensor.

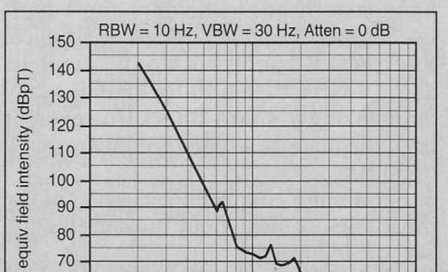

Figure 7b: HP8566 measured shield room ambients using RE01 loop sensor.

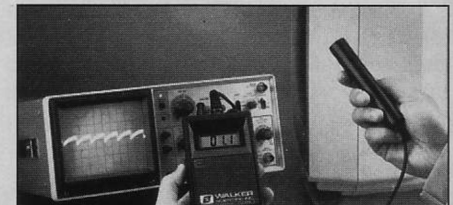

Figure 8. Walker Scientific's VLF-80D.

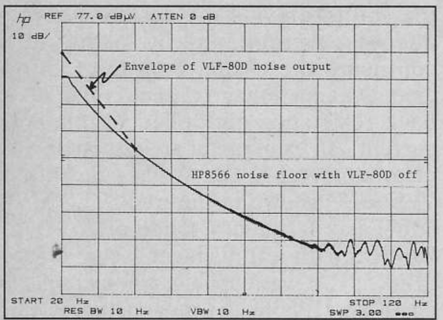

Figure 9. Noise floor of VLF-80D and HP8566 test set.

faster than the limit falls, ability to make the measurement at 20 Hz guarantees adequate performance over the entire frequency range of the VLF-80D. The Helmholtz coil current to B-field magnitude ratio was given as 15 Amps/11.4 Gauss at DC. This is 37.7 dBpT/µA. In order to generate a specification level field of 84 dBpT it was necessary to induce 84 – 37.7 = 46.3 dBµA = 200 µA current in the Helmholtz coil. The agreement was within 2 dB, the stated accuracy of the spectrum analyzer. As a check on the calibration, an RE01 loop was substituted for the VLF-80D, and the HP8566 was replaced by an Electro-Metrics EMC-11, a sensitive EMI receiver operating from 16 Hz to 50 kHz with a noise floor adequate for use with the RE01 loop and either of the Space magnetic limits mentioned in this article. Figure 11 shows this setup and the excellent agreement between coil current and measured field intensity.

The VLF-80D sells for less than $750.

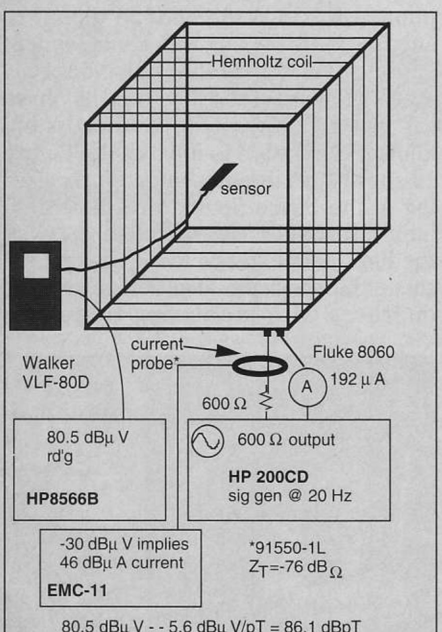

Figure 10. Calibration check of VLF-80D/HP8566.

Conclusion

This article explains the background of some magnetic radiation EMI limits and shows some cost-effective methods of instrumenting for compliance testing. A variable-µ magnetometer may be used to measure to the most stringent magnetic EMI limits. An induction coil magnetometer is useful for applications requiring better sensitivity than a loop but not as sensitive as the variable-µ magnetometer. The price-to-performance ratio of the magnetometer is a bargain at less than 10 percent of the cost of the variable-µ magnetometer, which itself is less than one third the cost of an EMI receiver compatible with the RE01 loop transducer factor and Space magnetic EMI limits.

Notes

1. The HP8566 spectrum analyzer specifications are given for a frequency range of 100 Hz to 22 GHz. Degraded performance down to 20 Hz is available but not advertised or specified by the manufacturer. Depending on the frequency range and antenna type, stringent HF and VHF limits may require external signal preamplification. Local oscillator harmonic mixing above 2 GHz reduces the sensitivity and may necessitate the use of low-noise preamplifiers, available from several manufacturers, including HP.
2. This limit is borrowed directly from MIL–STD–461 RE04, a 1967 requirement which is now obsolete. RE04 protected a particular AC magnetometer. For more on this subject, see the second reference under footnote 5, and footnote 7.
3. Nor can the new MIL-STD-461D 50 cm RE101 limit be measured at low frequencies with a combination RE01 loop and HP8566 spectrum analyzer.
4. The minimum resolution bandwidth (RBW) is low-side bounded by the residual FM of the local oscillator. The minimum RBW must be greater than the residual FM, or the signal of interest will appear to wander in and out of the IF bandpass. If one considers the advertised upper frequency range of a typical microwave spectrum analyzer at or above 1 GHz, then a 10-Hz RBW is really an amazingly sharp filter. However, it isn't adequate at a tuned frequency of 20 or 30 Hz.
5. For a more complete discussion of the intricacies of near field measurements, see the following:
Javor, K. "Military Radiated Emissions," *EMC Test & Design*, March 1993.
Javor, K. *Introduction to the Control of Electromagnetic Interference, A Guide to Understanding, Applying, and Tailoring EMI Limits and Test Methods*, EMC Compliance, P.O. Box 14161, Huntsville, AL. 35815–0161.
6. Electro-Metrics, 100 Church Street, Amsterdam, NY 12010. Phone (518) 843–2600. FAX (518) 843–2812.
7. The MFM-11 is the direct descendant of the EMCO 6640, which was the device protected by MIL–STD–461A limit RE04. MSFC–SPEC–521A limit RE04 is identical to the MIL–STD–461A version. Therefore the MFM-11 is quite suitable for making the measurement.
8. Walker Scientific, Rockdale Street, Worcester, MA 01606. Phone (508) 852–3674. FAX (508) 856–9931.

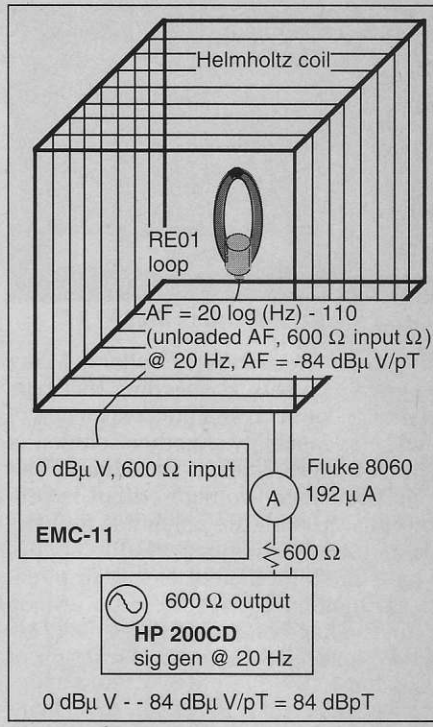

Figure 11. Check of Helmholtz coil calibration at 84 dBpT at 20 Hz with RE01 loop connected to EMC-11 EMI receiver.