EMC Applications for Military: Reverberation Chamber Tests

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***Abstract*—Electrical and electronic equipment installed on military platforms must have very low electromagnetic emission and good immunity for the whole operational frequency range. Reverberation Chambers (RC) are tools for sensitive emission measurements and immunity tests against strong electromagnetic fields, at a lower cost than other techniques. Method of RC should be suitable for testing Military's electronic devices such as radio or radar system. However, RCs must be large for tests at low frequencies; for example, at 80 MHz are conventional RC must have dimensions up to 7 m by 15 m by 8 m. For military concern, the lowest operation frequency can be as low as 2 MHz (underwater communication can be lower).**

Conventional RCs can only be used above a certain frequency, the lowest usable frequency (LUF), as they require a minimum mode density (number of modes per frequency interval) in order for the stirrer to perform effectively and alter field distributions. Technique of MIMO RC [1, 2] can make RCs usable down to much lower frequencies; it can mean the dimensions of the chamber can be up to 6 times smaller.

However, the composite Q-factor of RCs can be rather low at low frequencies, and this affects the sensitivity, and ultimately usability of an RC. This paper studies the possibility to increase composite *Q*-factor when RC is used at lower frequencies than conventional method.

Keywords*—*Reverberation chambers (RC), emission measurements, Q-factor, LUF

I. INTRODUCTION

By 1967, Electromagnetic Compatibility (EMC) had been recognised as an issue in the integration of electronic systems, which had little connection between standards developers in different parts of the world, most nations had no product-level regulation and different services used different specifications. In 1967, the_USS Forrestal disaster has brought EMC to the front of military minds. The USS Forrestal was an aircraft carrier operating in the Vietnam War, where it used F-4 Phantom aircraft loaded with Zuni rocket, which used an electrical signal to activate launch. Accidentally, in July 1967, one of the F-4 Phantoms on the carrier's deck inadvertently launched a Zuni rocket, which crossed the deck and struck the full belly fuel tank of another aircraft. The ensuing explosion and fire of the aircraft's 1000lb bomb caused a chain reaction of fires and explosions resulting in ultimately the loss of 134 sailors and the injury of a further 62 [3]. The flight deck was penetrated by the heat and explosions, causing fire to spread throughout the ship; the fires continued to burn on three levels below the flight deck for many hours afterwards.

Although the actual cause is unknown, two possibly assumptions of the incident are related to EMC. Firstly, it was a problem of shielding effectiveness, as a faulty cable shield allowed the extremely high power ship's transmitters to the launch command lines [4]. Second thought was an electrical transient happened during weapon loading resulting in activating of a false launch signal. EMC is a key suspect for both assumptions.

Fig. 1: The USS Forrestal disaster in 1967 related to EMC [3].

After that, military standards on EMC were released in USA At the centre were MIL-STD 461, 462 and 463.MIL-STD 461 is still in use, and the recent update is MIL-STD-461F from 2007 [5]; Militaries around the world also use MIL-STD-461F, unless they have developed their own standards. MIL-STD-461F provides both recommended test levels and the test procedures for a number of different tests. These are divided into four broad categories: CE - Conducted Emissions, CS - Conducted Susceptibility, RE - Radiated Emissions, and RS - Radiated Susceptibility. The requirements are drawn from the standard and shown as Fig. 2. Obviously, from the tables, the requirements for Navy Surface ships and submarines are the most demanding compare to Army and Air Force applications.

II. REVERBERATION CHAMBER FOR THE REQUIREMENTS

MIL-STD461f [5] is also used as reference for Royal Thai Military and many countries. To demonstrate compliance emission measurements and susceptibility tests must be performed; there are four main methods for radiated emission and susceptibility tests (RE and RS). Method of Reverberation Chamber (RC) is a test in an electrically-large, highly conductive, resonant cavity [6]. Emission measurements can be made more sensitive compared with an OATS or AC, and immunity tests can also be done at low cost because high field strengths can be generated with a moderate amplifier power. RC method provides a statistical result which is good for stability, repeatability and reliability. Besides, cost per square meters of RC is cheaper than AC (no need for any absorber).

For making emission measurements, RC method is only one method that has capable to measure indirect path loss by controlling the reflecting signals, while the others are measuring direct path loss by controlling the environment. As the result, normal method (for instance OATS) has some common limitations (figure 4) related to high ambient noise level, reflections, weather, and emission masking; RC can find problems, as emission problems cannot be hidden.

A high quality factor (Q) allows generating strong signals with very low source power, or measuring the emission from weak emission with conventional EMC receivers. The benefit also applies to immunity tests. This is important for military equipment on deck/platform which can be subject to high field strength at low frequencies (HF transmitters) up to very high frequencies (RADAR system). Besides, from my point of view, method of RC could be suitable for simulating a hybrid environment as most rooms on the ship or tank will probably have similar characteristics as resonant cavities.

Conceptually, method of RC is stirring standing waves, as they occur in an enclosure, by using a metallic paddle (called stirrer) to change boundary conditions for, and such change the spatial distribution of electromagnetic fields inside the cavity. However, the lowest usable frequency (LUF) is one of the most concerns for every RC, as the chamber can only be used above a certain frequency. The LUF is affected by composite Q-factor; higher composite Q-factor can affect in having more sensitive emission measurements but also resulting in higher the LUF.

According to [6], the LUF for a conventional RC (i.e. one which is used according to IEC 61000-4-21 [6] can be predicted by (1), or (2) with approximation of the 60th mode with a rectangular empty cavity with dimensions L, W, and H (in m), with no information of composite Q-factor. The LUF (in Hz) can be calculated by:

$$N \approx \frac{8\pi}{3} LWH \frac{f^3}{c^3} - (L + W + H)\frac{f}{c} + \frac{1}{2} \qquad (1)$$

$$F_{l,m,n} = \frac{c}{2}\sqrt{\left[\left(\frac{l}{L}\right)^2 + \left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2\right]}; \qquad \mu_r, \epsilon_r = 1; \quad (2)$$

where c is the speed of wave propagation in the enclosure (m/s). l, m, and n are the mode indices (at least two of them are nonzero). N is number of mode.

Operational frequencies for the Royal Thai Navy cover a very wide range; HTMS Makutrajakumarn as an example, uses frequencies from HF (2 MHz) to Ku band (up to 18GHz). To be usable at frequencies down to just 30 MHz would require a conventional RC with dimensions in the order of 30 m by 11 m by 6 m [7]. Lower frequencies would require even larger chambers. A special technique developed at the International Centre for Radio Astronomy Research (ICRAR) at Curtin University, Western Australia, [1, 2] allows RC to be used at much lower frequencies [8]; the technique is called Multiple Input Multiple Output RC (MIMO RC) (see Fig. 6). As the MIMO RC is used at much lower frequencies than a conventional RC, the quality factor of a resonant cavity at low frequencies must be considered, and this is this paper's topic.

TABLE V. Requirement matrix.

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																	
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS106	CS109	CS114	CS115	CS116	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	S	S	A	L	A	S	A	A	A	L	A	A	L
Submarines	A	A	L	A	S	S	S	A	L	A	S	L	A	A	L	L	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S			A	A	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S			A	A	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S			A	A	A		A	L		A	
Ground, Army		A	L	A	S	S	S			A	A	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S			A	A	A		A	L	A	A	L
Ground, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	

Legend:

A: Applicable
L: Limited as specified in the individual sections of this standard
S: Procuring activity must specify in procurement documentation

TABLE IV. Emission and susceptibility requirements.

Requirement	Description
CE101	Conducted Emissions, Power Leads, 30 Hz to 10 kHz
CE102	Conducted Emissions, Power Leads, 10 kHz to 10 MHz
CE106	Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz
CS101	Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz
CS103	Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz
CS106	Conducted Susceptibility, Transients, Power Leads
CS109	Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz
CS114	Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz
RE101	Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz
RE102	Radiated Emissions, Electric Field, 10 kHz to 18 GHz
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz
RS101	Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz
RS103	Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz
RS105	Radiated Susceptibility, Transient Electromagnetic Field

Fig. 2: The requirement matrix, emissions and susceptibility for military.

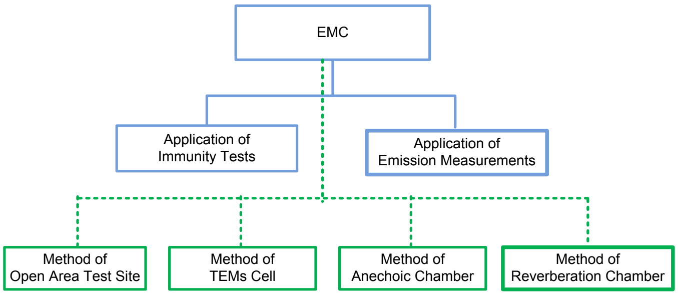
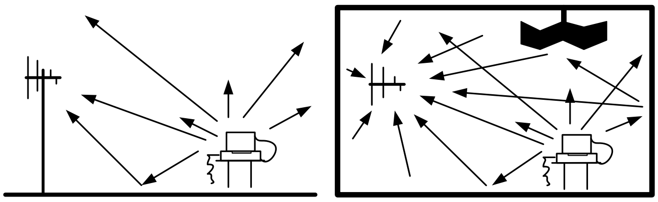


Fig. 3: The two applications and four methods of EMC.



a) Open Area Test Site (OATS) b) Reverberation Chamber (RC)

Fig. 4: Example of making emission measurements

III. OBJECTIVES

The quality factor (Q-factor) of a resonant cavity, and thus of the MIMO RC, depends on the losses due to currents in the walls, and due to absorption from antennas. The objective of this research is to study possibility of controlling the composite *Q*-factor below the typical LUF of a RC.

Besides, this research also studies on possibility of scaling the concept model of MIMO RC for the Royal Thai military; i.e., studying on how composite *Q*-factor can affect the sensitivity of MIMO RC when the concept model is scaled up (rescaling to HF range for the military). The outcome of this research could be for making a MIMO RC for the military.

IV. METHODOLOGY AND EXPERIMENTS

To investigate behavior of composite *Q*-factor, a shielded room which is 5 times bigger than the prototype of MIMO RC (Fig. 6) is modeled on HFSS simulation program. This is just as same as scaling of a dipole antenna; i.e., if a dipole is scaled up for X times, its operation frequencies will be scaled down for exactly X times. The shielded room is 5 times bigger than the prototype model of MIMO RC; they are modeled with ANSOFT HFSS simulation program as shown Fig. 7. Characteristics of both models are summarised in Table I.

According to [9], the composite Q-factor (Q_g) can be defined as (3).

$$Q_g = \frac{f_{m\,n\,p}}{\Delta f_{m\,n\,p}} \tag{3}$$

where: $f_{m\ n\ p}$ = modal frequency, $\Delta f_{m\,n\,p}$ = the modal bandwidth, which is determined by the 3dB fall of the S_{21} parameter.

A. *Composite Q-factor by Calculation*

The comparisons in Table I show simulated Q_g of both enclosures are not scaled for each other. According to [9], Q_g is combination of the effect of the walls (Q_1) and effect to of the receiving antenna (Q_2). The Q_g can be calculated as:

$$Q_g = \frac{Q_1 Q_2}{Q_1 + Q_2} \tag{4}$$

$$Q_1 = \frac{3}{2}\frac{V}{S}\sqrt{\frac{\omega_0 \mu_0 \sigma}{2\mu_r}} \tag{5}$$

$$Q_2 = \frac{2}{\pi}\frac{\omega_0^3}{c^3} V \tag{6}$$

where: V= Volume, S= Surface of the cavity, σ= the electric conductivity, μ_0= the permeability of free space, μ_r = relative magnetic permeability, ω_0 = angular frequency.

Fig. 8 shows plots for composite the Q-factor (Q_g) for the scaled model (lower frequency axis, black curve) and the full sized shielded room (upper frequency axis, blue curve) with dimensions 5 times larger. The same modes appear at 5 times the frequency in the scaled model as in the full size shielded room, and thus appear at the same place along the horizontal axis in Fig. 8. At low order modes (low frequencies) the composite Q-factor is dominated by Q_2 and is not affected by scaling (5 times larger size results in a 125 times larger volume, and this is compensated the influence of ω^3) At higher frequencies, where the composite Q-factor is dominated by Q_1, the scaling affects the results, and generally a larger room has a higher Q-factor for the same mode. This can also be explained by the equations (4), (5), and (6).

Fig. 5: HTMS. Makutrajakumarn, Royal Thai Navy.

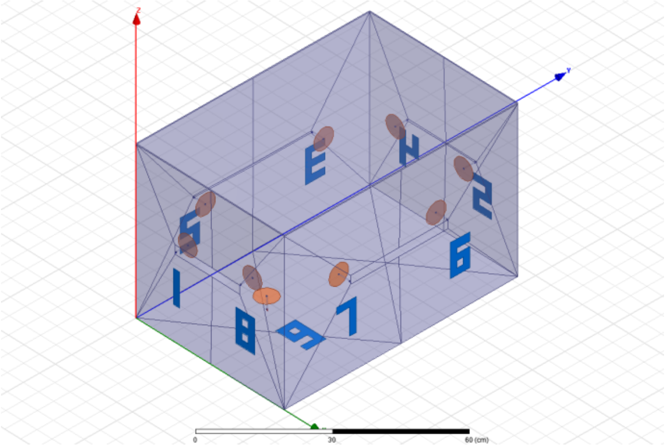


Fig. 6: The model concept of MIMO RC (using of multiple antennas instead of only one)

B. *Analysis the results*

The Q_1 of both enclosures are not in proportional to each other. Instead, at any on X-axis, the Q_1 of the shielded room is equal to Q_1 of the model MIMO RC multiplied by $\sqrt{5}$. Indeed, they are not in linear scaled.

$$Q_1 = \frac{3}{2}\frac{V}{S}\sqrt{\frac{\omega_0 \mu_0 \sigma}{2\mu_r}} \;\rightarrow\; Q_1 = \frac{V}{S}\sqrt{f_0} \;\rightarrow\; Q_1 = \frac{5\times5\times5}{5\times5}\sqrt{\frac{1}{5}}$$

$$\rightarrow\; Q_1 = \frac{5}{\sqrt{5}} = \sqrt{5}$$

In contrast, the Q_2, is not affected from neither the electric conductivity (σ) nor relative magnetic permeability (μr). In fact, the Q_2 is affected by properties of the antenna (hence the ω^3 term) and the total energy in the room (hence the *V*); so, their Q_2-values are linearly scaled (inversely proportional) to each other. For instance, at any on X-axis, the Q_2 of the scale model will equal to Q_2 of the shielded room divided by 5.

Where Q_1 their Q_g which is combination between Q_1 and Q_2 cannot be linearly scaled. In other word, if two enclosures are scaled, the bigger room has got higher Q_g at every scaling frequency, and the different also depends on type of material.

C. *Controlling the Composite Q-factor on MIMO RC*

The analysis reveals possibility to control Q_g by either changing value of Q_1(related to walls and thus not practical) or value Q_2 (related to antennas). The model of prototype MIMO RC installed with 9 antennas [1, 2]; therefore, changing value of Q_2 can be done easier by changing the load on antenna ports, for instance leaving them open, terminating them with 50 ohm, matching them for maximum power absorption. E.g. open ports can increase values of Q_2 compared to 50 ohm loads. Fig. 9 shows results that confirm this reasoning; the composite Q-factors (Q_g) are higher when all but one antenna (the one used to measure S_{12}) are open. unused antennas are opened instead of terminated with 50 ohm loads. Thus, this can mean that more sensitive measurement on MIMO RC can be done when the unused antenna ports are opened.

V. CONCLUSION

Method of RC requires high composite Q-factors (Q_g) to make more sensitive measurement, but it forces RC to be usable at only high frequencies. Although novel method, MIMO RC, can be used at lower frequencies than a conventional RC, the sensitivity can by quite low mainly because of power absorbed by antennas.

It is found in this research that Q_g on MIMO RC can be increased when the rest of antennas are opened (without any load terminated). This can be explained by (4) that when antennas is unloaded Coefficient relative to the receiving antenna (Q_2) can be increased resulting in increasing of (Q_g). As the results, MIMO RC can make more sensitive measurement. The outcome shows promising possibility of MIMO RC for military concern since HF (2 MHz) to Ku band (up to 18GHz).

REFERENCES

[1] C. Choeysakul, F. Schlagenhaufer, and P. Hall, “Characterisation and Design of a Reverberation Chamber for Electromagnetic Emission Measurements for Radio Astronomy Applications,” EMC Society of Australia Newsletter, Issue Number 59, Dec. 2012.

[2] C. Choeysakul, F. Schlagenhaufer, and P. Hall, “Reducing the LUF of a Reverberation Chamber based on the concept of MIMO for Electromagnetic Emission Measurements for Radio Astronomy Applications,” *Asia-Pacific Symposium; APEMC*, Melbourne, May 20-23, 2013.

[3] The Forrestal Fire, July 29, 1967 Ship's Logs Contributed by Ken Killmeyer, USS Forrestal Association Historian, aboard July 29, 1967, [cited Sep 26, 2013]. Available from URL: http://www.navsource.org/archives/02/cv-59/59f-0729.htm.

[4] T.J. Duggan, “Military Aircraft Electromagnetic Compatibility: Release to Service Testing in the United Kingdom, Past, Present and Future,” *IEEE International Symposium on Electromagnetic Compatibility 2007: EMC 2007*, Honolulu, July 9-13, 2007.

[5] “Requirement for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment,” MIL-STD-461F, Department of Defense Interface Standard, USA, 2007.

[6] “Reverberation chamber test method,” IEC 61000-4-21:2011, EMC, Part 4-21: Testing and Measure Technique, April 2011.

[7] A. Walters, T. Doan, and C. Denton, “Field Characterisation of an Aircraft Sized TEM Cell,” *Electromagnetic Compatibility Symposium*, Adelaide, Aug 16-18, 2009, page 47-52.

[8] C. Wilson, “RFI Standards for Equipment to be Deployed on the MRO,” February 2009, [Online]. Available: http://snebulos.mit.edu/projects/mwa/file_cabinet/0/01080/01080_r05m.pdf.

[9] P. Besnier, and b. Démoulin, "*Electromagnetic Reverberation Chambers*," ISTE Ltd, London, 2011, pp. 135-191.

TABLE I
SIMULATED COMPOSITE Q-FACTOR FOR STEEL, AND COPPER

Parameters	Shielded Room	Prototype of MIMO RC	Scale
Dimensions	3.6m×2.4m×2.4m	0.76×0.48 ×0.48m	
Surface of cavity	48.81m^2	1.8432m^2	1:5.15
Volume of cavity	22.61m^3	0.1759m^3	1:5.02
The 1st resonance	75MHz	375MHz	1:5
Conventional LUF	242MHz	1,214MHz	1:5
FOI	DC to 600 MHz	DC 3,000 MHz	1:5
Composite Q-Factor			
STEEL : start FOI	28.33	25.73	1.10:1
(μ_r =10): stop FOI	903.48	712.50	1.26:1
COPPER: start FOI	28.56	26.17	1.09:1
: stop FOI	903.48	955.86	1.09:1

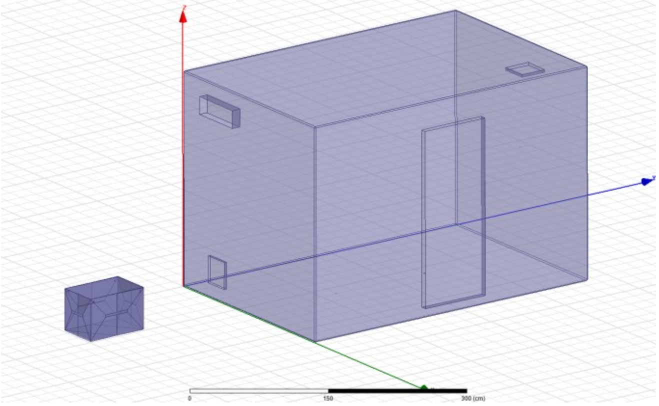


Fig. 7: Models of the prototype of MIMO RC and the shielded room (5 times bigger) on ANSOFT HFSS.

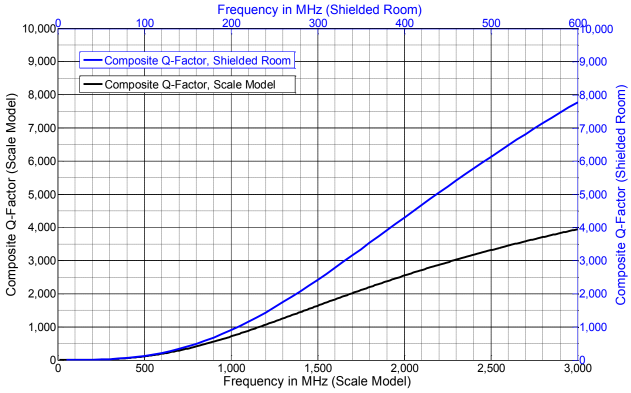


Fig. 8: The double plots show the calculated composite Q-factors (Q_g) of the prototype MIMO RC and the shielded room.

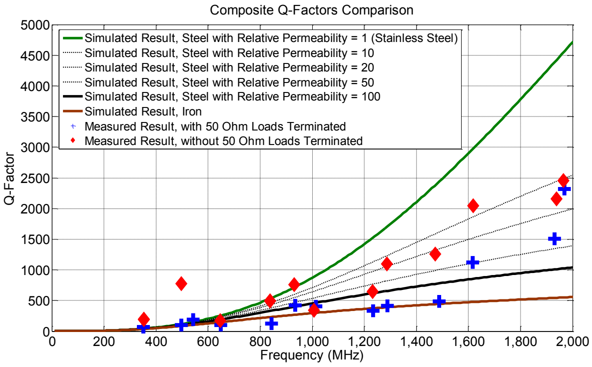


Fig. 9: Comparison between measured and calculated composite Q-Factors, the 1:5 scale model.