How to Design an Enclosure for low Radio Frequency Emissions and Susceptibility

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Overview

This note discusses the essentials of enclosure design for electronic equipment and connection design to that equipment to minimize emitted radio frequency (RF) energy and to also minimize susceptibility of that equipment to external radio frequency fields from nearby transmitters such as walkie-talkies. These two issues (known as electromagnetic compatibility or EMC) are interrelated and have the identical solution. Whatever is done to address one problem also addresses the other. This note is divided into two parts, enclosure design and connector/cable design. All that is required for successful enclosure design is the understanding and application of the basic fundamentals.

The Fundamentals

Radio frequency energy will not enter or exit a fully enclosed conductive enclosure (i.e. metal) provided that

1. **The thickness of the conductor exceeds about three the skin depths.** This requirement is easily met by practical enclosure thicknesses used unless the frequency of interest is very low (much less than 100 kHz).

2. **That there are no conductive discontinuities in any direction around the enclosure** (i.e. there can be no junctions of enclosure parts, windows, ventilation holes, etc. – the enclosure must be a continuous solid.).

3. **That there are no external cables bringing signals into or out of the enclosure**. Unless implemented properly, cables become antennas that can couple RF energy into or out of an otherwise perfect enclosure. This includes the AC line cord or external power cables.

Obviously, a practical enclosure can not meet the above requirements as stated. However, there are many clever methods that can be applied to practical enclosure design so that all requirements are effectively met. The requirements do not have to be perfectly met – all one has to do is get close enough. These methods are described in the next section.

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Enclosure Design

The shielding effectiveness of an enclosure is a function of how uniform the high frequency conductivity is in *any* direction around the surface of the enclosure. Any discontinuity or gradient in this conductivity causes non-uniformity in the surface currents induced by RF fields thus forming a surface antenna which can couple RF energy into or out of the enclosure. Surface antennas represent an undesirable transparency of the enclosure to RF. Although high conductivity is desirable, it is more important for the conductivity to be uniform in all directions. For example, although steel is much less conductive than aluminum, a solid steel enclosure with uniform conductivity all around is superior at RF to a multipiece aluminum enclosure with gradations in conductivity at metallic junctions. As a simplistic example, imagine that you are an electron that is traveling any circumference of the enclosure. Any path you take that requires a detour from direct represents a discontinuity that can form an undesired antenna. The goal of enclosure design is to minimize the effect of necessary obstacles. Detours should be no more than about five percent of a wavelength at the highest frequency of interest (this is about half an inch for a 1 GHz upper limit).

Some physical discontinuities are a necessity for a practical enclosure – any enclosure is generally going to be at least two assembled pieces, there has to be holes for electrical connectors, ventilation holes may be needed, or some sort of optical window may be needed, etc. With careful design, these issues can be resolved with minimum effect on the RF integrity of the enclosure.

Mating surfaces: Where different surfaces of the enclosure meet there must not be any paint or other coating that would inhibit conductivity between them. A painted surface against a painted surface is a barn door wide open for RF. Even bare metal against bare metal is very poor as most of the contact area is actually air gap – however small. Some coatings may be added to enhance conductivity. It is very important that different surfaces mate under pressure. A very bad situation is an edge meeting an edge as there is no way to seal this. The best situation is where there is sufficient overlap of the different pieces so that an RF gasket can be installed. An RF gasket fills imperfections where two surfaces meet thus insuring a continuum of conduction to prevent open spots which form antennas. Two pieces of metal may visually appear to mate very well but that is not sufficient. Some sort of RF gasket must also be used to prevent conductivity gradients between the two pieces. Mechanical force must exist on all parts of the gasket for it to do its job. Think of it this way – if the bare metal mating surfaces would not form a crude pneumatic seal then they will not form an RF seal either. In both cases the appropriate type of gasket is needed. In the case of RF, energy does not enter or exit via the minute gap but is radiated through the metal via the antenna formed by the gap. As an example, consider sitting in a fine parked car with all the windows tightly raised. Outside noise barely gets through. Now crack open a window by a tiny amount and note how much the outside noise increases. This example illustrates the importance of sealing all mating surfaces. Any surface not sealed is a gaping hole.

Screws: Liberal use of screws should be incorporated to maintain close pressure points on the RF gasket so that gradients in conductivity between the two pieces are minimized. Ideally, the spacing of the screws should be no more than about ten percent of a wavelength at the highest frequency of interest (about 1.25 inches for a 1 GHz upper limit). This may result in an exorbitant number of screws. The spacing can be increased if the two pieces have little flex – the issue is how much lower the pressure is on the gasket material half way between the screws. Low pressure on the gasket material will reduce conductivity and antennas may be formed. With stiff surfaces and good RF gasket material, a screw spacing of two inches will probably be fine for a 1 GHz upper limit – three to five inches might be the extreme before problems become serious. The important issue is sufficient pressure on the RF gasket – any method that accomplishes that regardless of the number of screws or spacing will work. Once the limit is reached of what will work, RF problems increase very rapidly for small excursions over the limit.

Ventilation Holes: The ideal hole for ventilation is an array of small round holes – each hole diameter should be no more than about one percent of a wavelength at the highest frequency of interest (about 0.1 inch for a 1 GHz upper limit). Center to center-center hole spacing should be no closer than about 1.5 hole diameters so that there is sufficient metal for conduction. Slots can be used provided the slot width is not more than about one percent and the slot length is not more than about five percent of a wavelength at the highest frequency of interest. If longer slots are needed then break them up into a series of shorter slots. Although this array would appear to be transparent to RF (it is obviously transparent to light) in actuality it is opaque if done right. As an example, observe the fine array of holes forming the door window in a microwave oven. You can easily see through that but the door is totally opaque to the 2.45 GHz RF inside.

For forced ventilation, a metal fan screen should be used for the opening. There are a number of aluminum mesh screens made just for this purpose. It is very important that the metal screen have good contact to the enclosure on all sides. Attachment at the four screws in the corners is not enough – some kind of gasket is needed around the circumference – otherwise an antenna may be formed. A common error is to place the screen over a painted surface.

Optical Windows: There are two methods to address this problem. One method involves using a flat metal screen such that optical effects are minimal – but there will always be some loss and refraction effects may reduce resolution. Manufacturers that sell RF gasket materials frequently have some kind of optical screen in their offerings. It is very important that the screen contact the enclosure completely on all edges. An alternative is a thin metallic coating on a glass or plastic plate mounted such that the metallic coating contacts all edges of the enclosure surface. This coating will have an optical loss of perhaps fifty percent or more but generally causes minimal reduction in optical resolution. The problem with both of these solutions is that there is an unavoidable gradient for RF energy that should freely circulate around the enclosure. Each approach is far better than nothing. When possible, the ideal solution for this situation is for the optical stuff to be mounted in a cavity such that all sides except for the optical path are continuous with the enclosure with only electrical feed throughs to access the optical transducer.

Copper tape: Copper tape can be used to provide RF sealing where two surfaces meet and an RF gasket is not practical. The disadvantage is that the tape must be removed to separate the surfaces and tears and adhesive gaps will ultimately impair performance unless fresh tape is applied afterwards. This solution may be fine if the two surfaces will either never or only rarely be separated. Copper tape is great for experimental purposes to solve RF sealing problems in a prototype enclosure. Copper tape will do nothing if installed on a painted or insulated surface. Do not make the error of using commonly available aluminum tape intended for taping metal ductwork. Because the adhesive is an insulator, this stuff is absolutely useless for RF work. The adhesive on copper tape made for RF work is conductive. Copper tape is not a substitute for a good RF gasket and the RF performance of a copper taped system can never be as good as when an RF gasket is properly used.

Commercial Enclosures: There are a variety of metallic commercial enclosures made for prototyping or small production runs. Most of these have poor to awful RF performance. One common small enclosure consists of two U-shaped folded aluminum boxes that would appear to be excellent for RF as they completely close. But note that the surfaces to not mate under pressure (except at widely spaced screw points) and that there are edge to edge junctions. Thus, this enclosure is poor. Another common type of enclosure consists of a cast aluminum tub with a cast lid. It would seem that this would make an RF tight enclosure when the lid is screwed down. Wrong! The pressure points on the lid screws are too widely spaced. If an RF gasket is used between the lid and the tub then this enclosure can work well. Full-sized enclosures for rack mount or instrument desk top applications look very nice but have so many RF holes that it is virtually impossible to seal them. Unless the enclosure is specifically designed to be RF tight (you will pay a premium price for this) then expect it to be wide open for RF.

Enclosure Design concepts

Strive for the minimum total length of RF sealing. However, this should not be the sole driver. Convenience of access is important too. The object is to find balance between conflicting needs. Clever engineering may simultaneously accomplish conflicting needs without compromise. The following are brief descriptions of some concepts that can work and are provided as starting points for possible design.

Four sided case with rear: One concept that works well is for the instrument to be constructed on an inner framework and the enclosure consists of a formed tub that slides over the frame from the back and RF seals against the rear of the front panel. Except for any front panel connections, all external electrical connections are made through a rear cut-out in the enclosure and directly to a rear panel that has a gasket seal with screws to the outer enclosure. The enclosure may have various small holes or slots for ventilation but no internal device mounts to the enclosure. This design is remarkably simple and works well. Sliding the case off the rear enables access to all sides of the instrument for service. This concept generally involves the least length to be RF sealed. The disadvantage of this approach is that it may be awkward to slide the case on and off.

Three sided case with rear: One possible issue with the preceding concept is that the feet (for desktop operation) have to mount to the case. That may not be desirable for a heavy system. One modification is for the case to not have a bottom so that the feet can mount directly to the internal framework. The bottom portion of the framework thus must be an RF seal. The three sided case then slides over the framework and has to seal at the front as well as the bottom. This concept requires more length to be RF sealed but may be simpler to work with.

Three sided case without rear: For this concept the chassis is constructed in a U structure with a direct front and rear panel and with a solid bottom panel. The case is also a U structure that goes down on top. This concept is simple but requires a long length to be RF sealed. Also, a significant number of screws are required around the length to be sealed. In spite of the issues with RF sealing, this concept is popular because of easy access. The engineering trick is to find ways to minimize the number of screws and yet maintain the necessary pressure on the RF gasket.

Connector/cable Design

Electrical feed through connections into or out of an enclosure form a path for conducted RF emissions and susceptibility – i.e. external cables are antennas. Improper use of connectors can render a perfect RF enclosure useless. For this RF discussion, electrical connections can be divided into two types – those for which there is no intent to conduct high frequency and those that are intended to conduct high frequency. Each type has to be addressed differently.

Medium and Low Frequency Connections Including DC

The worst conducted RF problems generally occur with connections that are intended for use at very low frequencies – perhaps DC or the AC line cord. The error is to assume that GHz design practices are not needed for a low-frequency signal. Wrong! GHz design practice is required for all signals including power supply voltages. Ideally, all signals including power supply voltages are in coax cable or multiconductor shielded cable. The best cable shielding is a combination of braid and foil. Braid by itself forms a window roughly 5 to 15 percent of the area. Foil by itself tends to have problems at high frequencies. One of the worst ways to make connections into or out of an enclosure is with plastic shell connectors. It is impossible to seal these to RF. The portion of the conductors inside the enclosure may act as antennas to couple the inside of the enclosure to the outside.

The solution is to make every conductor be at the same RF potential as the enclosure. This is accomplished by using physically small capacitors connected with very low inductance between every signal pin and the enclosure. The series resonance of this connection must exceed the highest frequency of interest (typically 1 GHz). About the only way this can be accomplished is to purchase special connectors that have surface mount capacitors attached between each signal pin and the metal shell. The shell must then be attached to the enclosure (there must be no paint or insulation around the mating area) using a small RF gasket. These connectors are known as filtered connectors and cost significantly more than standard connectors but are the easiest way to solve the problem instead of treating symptoms with standard connectors. The key to successful operation is for a complete distributed connection all around the connector shell. Point grounding is very poor at RF because of relatively high impedance.

Various filtered connectors can be used with signals up to a few MHz. At higher frequencies, the capacitance of the connector will shunt the desired signal. For low frequency signals that use coaxial connectors such as BNC, filtered BNC connectors are available that shunts all high frequency signals to the ground or case. The specifications of the filtered connector have to be checked to make sure that desired signals are not adversely affected.

When there is a need for an array of coaxial signals, there are special D connectors with coaxial inserts. These have been used for years to address this issue. This approach is good for low or high frequencies.

A particularly troublesome situation is when a ribbon cable must be used to conduct a large number of signals into or out of an enclosure. The problem is made worse when a plastic ribbon cable connector is used instead of a filtered connector. Bare ribbon cable is just asking for trouble. The ribbon wires should be laid out as signal, ground, signal, ground, etc. to form a low-impedance transmission line. The ribbon cable must be shielded. Consider as a minimum a metal foil shield around the ribbon cable with an excellent high frequency ground connection to the enclosure (any pigtail wire on the shield to the enclosure should be very short). The best approach is to attach the ribbon to a metal shell connector (standard type - not filtered) and use a solid metal shell (not metal plated plastic) and roll the ribbon cable so that it can slide inside of a large metal braid. The metal braid then attaches to the metal shell all around on the inside. The metal shell then makes a good connection to the enclosure when it is bolted to the mating connector (a filtered type) attached to the enclosure. Pigtails should be avoided as they become significant inductances at UHF and the shield then becomes an antenna. A distributed ground connection is always preferable to a point connection.

When high frequency signals must be sent and coax cable is not appropriate then the signals must be differential. Differential signals have very low emission as the close proximity of equal and opposite fields cancels for the most part although the cancellation is usually far from perfect. Braid shielding is still needed as discussed earlier. Differential signals work best when each differential pair passes through a common mode choke to reduce any common mode signal that would radiate. There are a number of miniature surface mount filters made just for this application. Some will band limit the desired signal to just the bandwidth needed (this reduces radiation of high frequency harmonics).

Ferrite clamps: For some types of problems, ferrite clamps around a wire or cable of wires can provide significant reduction in radiation or susceptibility. A ferrite clamp around a differential pair does not impede the differential signal but does impede any common-mode signal. The troublesome signals are generally common-mode. Unfortunately, in many applications it is hard to tell if the ferrite did anything. Ferrite is a very lossy material at high frequencies and converts the wire it surrounds to a frequency dependent resistor whose resistance increases with frequency. Inductive effects are generally negligible. It is not uncommon for a ferrite clamp to provide about 100 Ohms of resistance at 100 MHz although this can vary a lot depending on size. If the conductor has a low RF impedance to the enclosure then a ferrite clamp mounted on the cable just outside the connector to the enclosure forms a natural low-pass filter and can significantly attenuate high frequency common-mode signals. If the conductor has a high RF impedance to the enclosure then the ferrite clamp will do little or nothing – even a long string of clamps will do little.

High Frequency Connections

High frequency connections should always be made via a coaxial connector whose ground has a very low impedance to the enclosure. Common connectors used include BNC, N, and SMA. BNC is generally inferior because it has no means to insure a low impedance ground connection – this problem gets worse as the connector ages – people sometimes wiggle a BNC connector searching for a sweet spot to lower the ground impedance. A faulty ground on a connector can cause signal degradation, emission, and susceptibility problems. TNC is similar to BNC but solves this problem since the connectors solidly screw together.

Some Advanced Topics

Sometimes things really go wrong. The enclosure may have been carefully designed for low RF gradients and filtered connectors have been exclusively used. But there is still either an emission or susceptibility problem. If the problem seems to be confined to just certain bands of frequencies then it may be that the dimensions of the enclosure form a resonant cavity that magnifies what would be weak RF coupling in a carefully designed enclosure. It is desirable to make the dimensions of the enclosure as small as possible so that resonant modes are pushed up in frequency. Enclosures that are nearly square in all dimensions will have many active resonant modes. Enclosures that have one dimension that is very short in comparison to the other dimensions will generally have weak lower frequency resonant modes as the short spacing of the walls does not provide for good lateral propagation of lower frequency modes that exist along the longer dimensions. This is known as a waveguide beyond cutoff and highly attenuates signal propagation. Computing the resonant modes of an empty cavity is very straightforward using the following equation.

F_{LMN} = c * sqrt[$(L/2A)^2 + (M/2B)^2 + (N/2C)^2$]

where
F_{LMN} = resonant mode in Hz – an example might be F_{101}
L, M, N = integer mode numbers (0, 1, 2, 3, etc.) only one of which can be 0 at any time
c = speed of light (use 300,000,000 meters / second) (or 11.8E9 in. / sec.)
A, B, C = dimensions of enclosure in same distance units as c (use meters)

The lowest resonant frequency of the enclosure is found by using the two largest dimensions in the above equation with 1 for the mode numbers. This resonance is weak (if significant at all) if the shortest (of the three) dimension is less than a quarter wavelength (i.e. shortest dimension < 0.25*c / F) of the computed resonance (i.e., the cavity is operating in the waveguide beyond cutoff mode). The lowest strong resonant frequency is found by using the two smallest dimensions of the enclosure in the above equation with 1 for the mode numbers. For example, an empty 12” x 8” x 2” (A x B x C) enclosure has a first resonance, F_{110}, at 887 MHz although this resonance is weak because of the 2” dimension. The lowest strong resonance, F_{011}, occurs at 1.65 GHz. Ideally, the lowest strong resonant frequency of the enclosure cavity should be much higher than the highest frequency of interest (frequently 1 GHz). Ideally (for RF suppression), the enclosure is long, narrow, and thin.

When the cavity contains lots of various objects then resonance calculation becomes impossible. Significant metal surfaces within the cavity tend to raise the resonant frequency because smaller sub cavities are formed. That is good. Ideally, the sub cavities would be designed to increase the mode resonances beyond what might be a problem. Significant volumes of either a high permeable or high permitivity material tend to lower the resonant frequency because propagation through these materials is slower. If lossy at high RF, such materials may reduce EMI via absorption.

Electronic issues

It helps if the electronic circuits within the enclosure are laid out such that loop antennas are not formed at high harmonics of the operating frequency.

The power supply system should be designed as a transmission line and should be decoupled with high frequency capacitors spread over the entire board. One hazard in power supply distribution is resonance caused by decoupling capacitors and wiring inductance. Resonance can cause some select harmonic to be made much stronger – this can lead to emission problems or even random logic error problems. Resonance is certain to occur somewhere – typically in the low tens of MHz. The best way to either prevent power supply resonance or fix it is to add small resistances in series with the power supply voltage to small clusters of electronics with the bypass capacitors on the down stream side. These resistors damp any resonance.