ABSTRACT

Recent tests of flight control system components show that digital flight control systems are vulnerable to microwave signals, but only at very high power levels, well above that produced by commercial radar installations. Test results of sensors, computers, data busses, and actuators reveal that long standing fears of inherent fly-by-wire flight control system vulnerability to microwave radiation are unfounded. Some components, such as sensors and data busses, aren't affected at all. Others, such as the digital computers, fail at high power levels. The tests show that as long as the component shielding remains intact, component vulnerability is minimized. Good EM1 design will give a harder system than simply relying on supposedly 'EM1 Proof' technologies, such as fiber optics. Testing revealed that inadequately designed fiber optic systems can actually reduce the system hardness to EMI. One conclusion is that the system shielding should be design controllable, that is, distributed between the airframe and component.

INTRODUCTION

Over the last few years growing concerns about the possible upset of digital, fly-by-wire (FBW) flight control systems by electromagnetic interference (EMI) have led to stricter design and testing requirements. However, the types of upsets that might actually be seen have never been determined a priori, just found and corrected after the unit is under test. There are concerns that postulated high power microwave weapons, as well as powerful commercial broadcasting stations, will disrupt the normal operation of digital FBW flight control systems.

As part of a multi-service investigation into DFCS upset, the Air Force Wright Laboratory and Naval Air Warfare Center are working to characterize the types of upsets that can happen within a DFCS when operating in an intense EMI environment. Our intent is to determine whether modifications to system architecture and algorithms, rather than filtering and shielding, will mitigate any EMI problems found.

Several prior papers reviewed the upsets of FBW FCS seen during EMI testing and operational experience, and reviewed results of Wright Laboratory DFCS upset testing [8,9]. These upsets shared the following characteristics:

- High gain-bandwidth analog input circuits were the most susceptible, the worst being AC excited sensors. Signals modulated at AC sensor excitation frequencies were more prone to upset those sensors.

- Most sensitive EMI carrier frequencies were between 3 MHz and 30 MHz.

- Upsets were caused for demodulated frequency components in the passband of the DFCS, roughly 0 to 10 Hz. These spurious signals confused the redundancy management software inside the DFCS.

- Upsets in the field were from continuous wave (CW) amplitude modulated (AM) broadcasts.

- Field intensities for upset were well above 50 V/m average E-field intensity at the inputs to the boxes.

- No upsets were observed from repetitively pulsed signals with duty cycles less than 50 percent.

This data shows that the most susceptible portions of current DFCS are analog inputs. These are susceptible to high power AM commercial broadcasting signals at high levels. The DFCS do not seem susceptible to low-duty cycle pulsed inputs, such as radars. The upset characteristics are determined by system construction and operating bandwidths. The low bandwidths of the entire DFCS mean pulsed signals lack the average power to disturb the systems. There are concerns that high peak power radars might upset digital portions of the DFCS.

Since then testing has been performed on an actual set of digital flight control computers to investigate upset from pulsed microwave sources. This paper covers some of the results of that testing pertaining to DFCS vulnerability to radar systems, a part of the high intensity radiated fields (HIRF) threat to avionics systems [3].

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Table 1: HIRF Levels In The 1 to 12 GHz Range

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Severe (Peak/Average Field Levels in V/m)</th>
<th>Certification (Peak/Average Field Levels in V/m)</th>
<th>Nominal (Peak/Average Field Levels in V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 - 1</td>
<td>1700/170</td>
<td>1300/170</td>
<td>960/110</td>
</tr>
<tr>
<td>1 - 2</td>
<td>5000/900</td>
<td>2500/180</td>
<td>1700/180</td>
</tr>
<tr>
<td>2 - 4</td>
<td>6600/840</td>
<td>3500/240</td>
<td>900/170</td>
</tr>
<tr>
<td>4 - 6</td>
<td>6850/250</td>
<td>650/280</td>
<td>4500/280</td>
</tr>
<tr>
<td>6 - 8</td>
<td>3500/670</td>
<td>1500/320</td>
<td>700/230</td>
</tr>
<tr>
<td>8 - 12</td>
<td>3500/1270</td>
<td>3500/215</td>
<td>1100/250</td>
</tr>
</tbody>
</table>

DISCUSSION

HIRF Threat

Table 1 is the current HIRF levels in both peak and average field levels for frequencies between 1 and 18 GHz [4]. These are levels that an aircraft may encounter when flying commercial routes. This data was determined by the DoD Electromagnetic Compatibility Analysis Center (ECAC) working for the FAA. Throughout this paper the "Severe" levels will be used to compare to component and system test data as a worst-case comparison. Testing for compliance will actually be to the "Certification" levels, significantly lower.

What follows is an examination of the microwave upset levels of DFCS components tested to date. These will be examined individually, then integrated to arrive at the vulnerability of DFCS to microwaves. For discussion purposes, the initial assumption is the fuselage will not add any shielding. The fallacy behind this assumption (at least for metallic fuselages) will be examined in a later section. Unless otherwise noted, all the following DFCS components tested have passed MIL-STD-461C RS03 at the 200 V/m flight critical component level.

Digital Flight Control Computer (DFCC)

Figure 1 shows the upset levels seen for a typical flight control computer tested in the 1 to 10 GHz frequency range. This figure is a compilation of free field tests results and calculated free field upset levels from direct microwave injection data. The injection data has been modified by the appropriate effective antenna aperture area to match the free field test results. No upsets are predicted for frequencies above 4 GHz due to internal attenuations in the computer [1]. Thus, the figure only shows upset levels in the 1 to 4 GHz microwave frequency range where upsets were seen during free field and injection tests, the test data matching upset predictions [1]. The data shows that the flight control computer is most susceptible at the resonant frequencies of the box [1]. These results should be typical for the class of DFCC using this level of technology (mostly Large and Medium Scale Integration - LSI, MSI). The boxes have roughly the same dimensions, giving resonant frequencies between 1 and 2 GHz. All signals run through ports on one side of the equipment. The wiring is essentially the same. The technology level inside is the same. Commercial systems can differ in the particular type of box connector (ARINC versus Bendix), box construction, and cooling. Similar input/output requirements will lead to roughly similar number of I/O wires. The connector shapes differ, but that seems to be a secondary effect while the wire bundles are attached since the attachment of the wires is the main reason for radiation entry. The I/O connection will still be the main point of entry as long as sound box construction techniques are used.

Figure 1 also shows that the upset levels for the DFCC were, even at the most sensitive point, above the "Severe" HIRF levels, so no upsets of this DFCC (unshielded) would be seen in operation aboard a commercial aircraft. The upset levels can be increased 10 dB (power) by very simple, light, cheap, shielding techniques [1]. Not on this computer, but being increasingly included in DFCCs, are filter pin connectors which offer 40 dB (power) of protection well into the microwave region.

Cooling requirements could influence upset level. The DFCC tested has to face weather effects, so it sealed against humidity and internal heat sinks move heat to exterior fins. Commercial equipment is located in internal bays, so cooling air can be directly blown through it. This leads to holes to vent the air, which leads to a port for microwaves to get in. These holes are well above cutoff for the frequencies which DFCC components and wiring can respond to, so as long as wiring is kept from the holes...
very little microwave coupling, and that which does couple
Analysis of similar holes in Navy DFCC equipment show
the major entry for the microwaves will be the I/O bundles.

Actuators

The test of a smart actuator during January 1993 [7]
resulted in many typical flight control system components
to be exposed to microwaves simultaneously. These
components included position sensors, digital communica-
tions links, and integral computers. The actuator itself
has two redundant computational and sensing channels,
capable of independent operation should the other chan-

Figure 2 shows two types of electronic upset with
respect to frequency over the 1 - 4 GHz frequency region.
Also plotted on Figure 2 is the Severe and Certification
HIRF levels in the same frequency range. The message
error bit (MEBIT) is an indication from the actuator
processor that incoming data to the processor has been
Corrupted. The STABIT indicates that some portion of
the actuator has been corrupted badly enough for the
microprocessor to declare a channel failure. Multiple
MEBITs have to be generated in a specific time window
to generate a STABIT, thus the STABIT curve is slightly
above, and closely follows, the MEBIT curve. Around 3
GHz the STABIT curve drops below the MEBIT curve,
indicating errors might be coming from another source,
but the upset level at that point is so high that it's a "don't
care" situation for all practical purposes. The failure levels
were above the Certification HIRF levels in all cases, but
below the Severe levels in the 1 - 1.7 GHz region.
Troubleshooting isolated the channel failures in the sensi-
tive 1 GHz region to a corrupted photonic receiver for the
fiber optic data link. The Very Large Scale Integrated
(VLSI) microprocessor remained operational throughout
the testing while the peripheral electronics were corrupted
with microwaves.

This test showed that the VLSI computers did not stop
operating even for very high field levels (in excess of 37
kV/m). The computers inside the actuator were more
resistant to microwave induced upset than the DFCC
(Figure 2). What did stop operating was the digital fiber
optic data link. Going to VLSI technology from LSI tech-
nology (such as in the DFCC) doesn't automatically lead to
lower vulnerability levels. At the highest level, computer
microwave vulnerability is driven by box design, board
design, and wiring practices. The type of board and wiring
design required to eliminate spurious radiation and cross
coupling by VLSI circuits reduces the chance the com-
puter will pick up microwave energy [10,12].

Actuator Position Sensors

Position and rate information about internal actuator
mechanics is provided by linear variable differential trans-
formers (LVDT). Extensive microwave testing of
LVDTs have not shown a hint of microwave vulnerability.
There was a concern that at high power levels LVDT core
saturation could lead to spurious harmonic and inter-

oculcating products. These could cause actuator health
monitors to shut down the actuator, or feed back into the
DFCC, tripping actuator output monitors [6].

During the ARL tests no upsets occurred that could
have been caused by microwave energy coupling into the
LVDTs. During tests of the DFCC, LVDTs were also
exposed to strong microwave fields [6], and the observed
signals coupled onto the monitoring circuits would not
have caused upsets.

Actuator Valve Drives

No upsets were ever seen during actuator testing which
could be attributed to the valve drive electronics. This isn't
surprising, since these components are buried deeply
within the cast aluminum actuator body.

Flight Control Sensors

Numerous sensors dispersed across the aircraft "tell"
the DFCS what the state of the aircraft is, and what it's
doing at the moment. These sensors include proximity
switches, accelerometers, gyros, LVDTs, air data com-
puters (ADC), and associated electronics. Tests of these
components in the microwave region show a maximum
induced voltage of 100 mV lasting for 20 ns for an external
field of over 25,000 V/m [2,12]. This is well below the
required signal levels to cause an upset. The DFCS pilot
control position sensing circuits are LVDTs similar to the
LVDTs discussed above, so similar, that the same level of
vulnerability can be assumed for them. Current technol-
ology ADCs are built using the same technology as the
DFCC, so the same upset levels can be assumed. Older
technology ADC are analog based, so no chance of
microwave induced upset are assumed for them. The
communication links between current ADC and DFCC

Figure 2: Smart Actuator Upset Levels Compared To
HIRF Levels In The 1 - 4 GHz Region
are MIL-STD-1553B, very resistant to microwave upset. Recapping, the DFCS sensors and associated electronics are not vulnerable to microwave radiation (but still must be evaluated for HF frequencies as pointed out in References 8, and 9).

**Digital Data Busses**

**MIL-STD-1553B Data Bus**

There has always been an assumption that the 1553B data bus is vulnerable to microwave radiation. This assumption was made without hard data to back this up. As a part of the DFCC test, a typical aircraft (properly terminated) 1553B bus, running continuously, was exposed to field strengths up to 60,000 V/m for frequencies in the 1-4 GHz region. The bus ran for the entire test period without a single error (over three weeks of testing, total). The combination of cable construction (twisted, shielded air), proper termination, high data signal levels, and fault-tolerant coding make the bus extremely resistant to microwave induced errors.

**MIL-STD-1773 Fiber Optic Data Bus**

The previously mentioned actuator upset levels reflect the upset level of a fiber optic data link, or more precisely, the receive/transmit electronics of the fiber optic link, that carries information between the DFCC and actuator. Since these electronics have a normal operating bandwidth which extends into the microwave region to match them with the information carrying bandwidth of the optical fiber, a sensitivity in this area is expected. These receivers are easily corrupted at levels of free field energy around 0.1 W/cm² (less than 200 V/m)7]. The electromagnetic energy coupled into the fiber optic receiver by way of the seams in the electronics enclosure. No effects were attainable when the seams were sealed with conductive tape. The proper fix for this would be to use correct EM1 seam connection techniques, rather than the press fit used 10.

This was the first test that the authors are aware of to directly evaluate the effects of microwaves to flightworthy fiber optic communication components. The manufacturers of the data link pronounced it; and the actuator it serviced, "EM1 Proof," just based on the fact that it contained fiber optics. If anything, the fiber optics made it more sensitive to EM1. We are convinced that if a flightworthy 1553B configuration had been used for the communication links, no upsets would have been seen until much higher field levels were reached, and these upsets would have been due to the computers, not the data links.

Our tests show that fiber optics are not the solution for protection against electromagnetic interference (EMI), good EM1 mitigation design is. Fiber optics should be used where their extraordinary information carrying capability can be exploited. Multiplexing of command signals by way of an electronic communication bus, like MIL-STD-1553B, is more than adequate to satisfy the bandwidth, EMI protection, and reliability issues for today's, and future, flight controls. If optics are used, one is advised to carefully shield the optoelectronics, and design for reliable EMI protection over the aircraft's lifecycle.

**DFCS Failure Levels**

Figure 3 is the frequency dependence of upset levels for various "current technology" DFCS components in the microwave region (1-10 GHz). No vulnerability is seen for frequencies above 4 GHz. The most vulnerable part of the system is the actuator, driven by the fiber optic receivers optoelectronic's microwave sensitivity. If we ignore this, all the upset levels are above the "Severe" HIRF level. Even including the actuator upset levels, the levels are above the "Certification" levels. A change in box seam construction on the actuator electronics will bring the actuator upset levels above that of the DFCC [7]. In our judgement, other DFCS will exhibit the same upset trend as this particular system, minimum upset levels in the low GHz region at box resonances, rising as frequency increases. Good EMI mitigation techniques are more important that particular technology usage or architecture application, and a DFCS employing these will not be vulnerable to the HIRF threat at microwaves frequencies. The above vulnerability assessment was made without consideration to other mitigating factors. This will be examined below.

No hardware failures which could directly be attributed to microwaves happened during any chamber test. This includes the exposure to fields in excess of 60,000 V/m.

**Factors Which Mitigate Vulnerability Further**

In the above vulnerability determination, no fuselage shielding, or other non-DFCS factors, were invoked to reduce incident field levels on DFCS components prior to vulnerability determination. There are a number of other factors which combine to reduce vulnerability of DFCS to
microwave induced upset. These are inherent in the construction of today’s aircraft, but may change as technology progresses.

**Fuselage Shielding**

Some prior calculations showed fuselage resonance could play a factor in microwave vulnerability, causing "Hot spots" where the microwave energy resonated[11]. Our analysis and testing shows this isn’t the case. Tests to date have shown no reinforcement, only attenuation [12]. This isn’t surprising due to the highly overmoded, irregular shaped, filled cavities which exist in aircraft. The analysis assume fairly simple, symmetrical, empty structures. These simplifying aspects have to be carefully applied since in reality cargo bays are filled with loose, or containerized, luggage, the cabins with seats, passengers, and more luggage, and equipment may be anywhere. Actual fuselage tests show roughly 8 dB worst case attenuation for metallic fuselages at microwave frequencies, and this is only for a very small set of possible frequencies and illumination angles. Move off on frequency, or illuminate from a slightly different angle, and the attenuation can increase 30 + dB.

Composite materials can pose a problem to future DFCS shielding if the fuselage cannot contribute the assumed attenuation. This is not a problem in the microwave region for graphite fiber material which can afford protection approaching that of aluminum [14]. Relief might also be provided by metal mesh included for composite structure lightning protection assuming the grid size is small enough.

**Equipment Configuration**

DFCCs, like other avionics in commercial and military aircraft, are on racks in avionics bays that are heavily populated with other avionics system’s boxes, wire bundles, and cooling ducts. There is usually little open area compared to that taken up by the avionics. In commercial aircraft, the bays are roughly same shape as lower section of aircraft, but heavily broken up by boxes, wiring and other structure. Testing shows that heavily loaded avionics bays at microwave frequencies act as heavily loaded cavities, with many (low amplitude) resonant frequencies and small Q factors [12]. The avionics bays do not show resonances high enough for any mode reinforcement, all tests show attenuation. Avionics bays are so oddly shaped, filled with equipment, and overmoded at microwave frequencies that no mode contains enough significant energy for good coupling into DFCS electronics. These are military aircraft bays, but one should note that these provide a "good" worst case for commercial airliners since these military cavities are nearer to resonance at microwave frequencies, and are closer to relatively larger radiation entry areas. (Commercial aircraft hatches have small gaps, tighter than military avionics bays hatches, since they also have to hold pressure. These hatches don’t have EMI gasketing, thus this could be an interesting trade-off analysis.)

Over the course of DFCS testing evidence arose that system effects, the actual DFCS architecture implemented, can influence vulnerability. How one configures the DFCS, and does redundancy management can affect upset levels. This will be the topic of a later paper. The important point that our tests brought out is that architecture effects are secondary compared to common sense EMI system design [2,13]. If proper EMI mitigation techniques are used then architecture modifications are not required.

**CONCLUSIONS**

If one integrates all the data learned so far on the induced upset of DFCS due to microwaves, one comes to the conclusion that there isn’t a problem meeting HIRF “Severe” (as well as "Certification") levels as long as common sense EMI construction practices are adhered to, backed up by testing. No technological breakthroughs are required, no DFCS architecture changes needed, no massive shifts to fiber optic cables - just insure that EMI personnel are on the DFCS design team from the beginning. This is more a program management function than engineering function. Although microwaves are not a problem, HF radiation is another matter. It is our determination that aggressive testing should be done in the HF region to eliminate upsets that have been seen [8].

The upsets that have been seen have been cured by simple, light shielding techniques, covering up design inadequacies which an EMI engineer would have discovered in the first place.

The results of the DFCS component microwave tests show that the optoelectronics are more sensitive to microwaves than are their associated electronics. Fiber optics are not an EMI panacea, and shouldn’t be thrown into a system because they are "EMI Proof". Fiber optic links must be included in EMI calculations just like any other system components.

The Smart Actuator VLSI microprocessor remained cognizant throughout microwave testing while the LSI DFCC processor was upset. The shielding of the enclosures was comparable, the difference was in the board construction and internal wiring. Modern techniques radiate less and pick up less, so fears about faster, smaller processors, and the systems which contain them, being inherently more EMI vulnerable are misguided.

Metallic and carbon fiber fuselages do contribute shielding at microwave frequencies, at least 8 dB (power), and usually much more. They should not be considered as smooth resonant cavities, but very irregular, overmoded, lossy ones. Ignoring this will lead to overdesign in EMI protection of the internal system components, with the attending increase in cost and weight.
Design Controllable EMI

The above paragraph outlines one of our major concerns over "current practice" - our way of invoking EMI threat levels on a new aircraft procurement. In military aircraft specifications, typically the frequencies and flux levels expected are defined. The airframer is responsible to come up with hardening measures from the fuselage right down to the box level. Unfortunately, what's normally done is a top level hardening approach which "shows" a level of effective fuselage shielding (combination of aircraft skin plus any internal avionics bay structure) sufficient to drop internal incident flux levels down to the 200 V/m RS03 levels, regardless of incident flux. In one example, the airframer showed a fuselage shielding level of 50-60 db from VHF right through 18 GHz! There is no way this level of shielding can be built and maintained, and measured shielding values on actual aircraft confirm this.

This is a non-design-controllable situation. Hardening becomes based on application of simple first order principals ignorant of the more complex physics at work. We believe this drives the FAA position that no amount of shielding can be attributed to the fuselage for purposes of showing HIRF resistance in commercial transport aircraft, which could lead to overdesign of internal components.

In contrast, we believe a design-controllable hardening approach is required, one which has all or most of the following attributes:

- Divides hardening systematically into separate levels of fuselage, avionics bay, LRU and cable shielding.
- Sets upper limits on each of the above consistent with what can reasonably be obtained and maintained without undue special maintenance practices.
- Provides skin/avionics bay/LRU shielding integrity through methods which are, as much as possible, inherent in the geometry of the design, rather than relying on fasteners, gaskets, metal-to-metal contact, etc.
- Provides means for detecting breaches in electromagnetic hardening during product life.
- Provides fool-proof means for ensuring integrity of shielding.

The whole hardening problem is analogous to answering the question, "is my 5 year old low observable aircraft still low observable?" The EMI protection ought to be easy to see and difficult to screw-up, i.e. design-controllable and not requiring specialized inspection/maintenance procedures or blind faith that factory-installed hardening has not degraded.

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