SYSTEM FUNCTIONAL UPSET TESTING OF AIRCRAFT ELECTRICAL AND AVIONIC SYSTEMS: HOW TO APPROACH THE PLANNING AND CONDUCT OF THE TESTS

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Abstract

Since the introduction of digital "Fly by Wire" flight and engine control systems into commercial transport aircraft in the early 1980's, there has been a need to assure reliable operation of these systems in the lightning environment. The Multiple Stroke (MS) and Multiple Burst (MB) environments have the potential of introducing error signals into data processing and control functions. Similar concerns apply to integrated cockpit displays that depend upon digitally processed data.

Engineering definitions of the MS and MB environments were introduced into the airworthiness certification standards in 1985 and updated in the 1990's, and methods of generating and injecting MS and MB-induced transients into control and display systems have been developed. These tests must be applied to an operating system, so the test involves transformer coupling or direct injection of the transients into interconnecting cables. Standard methods for injecting single-pulse transients have been incorporated in RTCA DO-160 and EUROCAE ED-14 (Reference 3) for some years and in 2002, a procedure for injecting multiple pulse transients corresponding to the MS and MB environments was added. However, these standards apply only to tests of a single cable connected to a single item of equipment, and so do not provide guidance for applying MS and MB transients to a complete system that is comprised of multiple "boxes" and cables. Since the lightning environment induces transients into all cables of a system simultaneously, ways must be found to achieve this result in system lightning tests or to otherwise account for the effects of simultaneously induced transients. No standard for such a test is yet available, though these tests have been conducted on a regular basis in accordance with individual test plans tailored to the system and installation being certified.

System Testing

System testing is performed for the following purposes:

- Verify ability of a system to resist damage or system functional upset due to the multiple stroke and burst aspects of the lightning environment.
- Evaluate synergistic effects that may occur when transients appear at all pins of equipment connectors instead of at one pin at a time as in the pin injection test.
- Verify the protection effectiveness of interconnecting cable shields (including shield terminations) that are not present during individual equipment tests.

The system tests apply induced transients corresponding to the Multiple Stroke (MS) environment that represents cloud to earth strikes, and the Multiple Burst (MB) environment that applies induced transients due to an intra-cloud lightning strike to an airplane. System tests are applied as cable bundle tests, so that all interconnecting cables in the tested system or subsystem experience the induced effects of the applied transient waveform sets simultaneously, as happens when an aircraft is struck by lightning. The external MB and MS environments are described in Reference 2, along with typical transient waveforms and levels that correspond to these environments.

Test Approach

The MS and MB tests satisfy the requirements of CFR/JAR 25.1316 to verify system functional upset tolerance of the multiple pulse aspects of the lightning environment, and are intended to be applied to a system that is powered up and operating, usually on a test bench where system performance can be continuously monitored.

Each test should be applied so that test currents flow in all harness branches of a complete system interconnecting wire harness simultaneously. If it is not possible, due to test current generator limitations, to inject the specified transient levels into all branches of a system simultaneously, the harness branches that did not experience the levels specified in the test plan are tested individually at the specified levels. This situation often presents itself in tests of fully shielded systems, such as electronic engine controls, that experience induced currents in the 2,000 A to 10,000 A range, necessitating that test currents of 4,000 A to 20,000 A be injected into multiple cables.

The test arrangement for system lightning tests is generally in accordance with the housekeeping requirements of Reference 3 for tests of individual items of equipment. System components are positioned on a copper-clad test bench and interconnected with aircraft cables or electrically similar versions thereof, as discussed later. Systems are powered up and operating so power is supplied via (power) Line Impedance Stabilization Networks (LISNs) that; a) look like a typical aircraft power distribution bus impedance to ground, and b) provide some series impedance that isolates the power source from the injected transient when the system power supply harnesses are tested. Sometimes additional DC and/or transient blocking needs to be installed in the power supply circuits to be sure that the injected transients are not going into the power sources. Figure 1 shows part of a typical system test arrangement, where an injection transformer and a current monitoring transformer (CT) are shown, together with system equipment and interconnecting wire harnesses. Several LISNs are also pictured in Figure 1.

Figure 1. Typical Arrangement for a System Test

Lightning-Induced Transient Waveforms and Levels

The MS test levels are usually based on induced transients due to current Components A and D/2 of the external lightning environment, whereas the MB test levels are based on Component H of the external environment as described in Reference 2.

Airworthiness certification procedures require that the characteristics of lightning-induced transients in interconnecting wire harnesses be determined either by measurements of these transients in harnesses within a tested airplane or by verifiable analysis. Sometimes, the test levels have to be set before an airplane is available for test, in which case the levels are determined by analysis and verified later by aircraft test. By whatever means, lightning-induced transient levels for the system and equipment connector pins and interconnecting cables should be established for protection design and certification test purposes. These are known as the Equipment Transient Design Levels (ETDLs) as defined in Reference 1. The recommended ETDLs should normally incorporate a margin of at least 2:1 above the cable bundle shield and individual conductor voltages and currents determined by test or analysis. The 2:1 margin (sometimes expressed as 6 db) is intended to account for uncertainties in the aircraft test or analysis processes by which the actual transient levels in the interconnecting wiring are determined. (It is better to describe transient levels in terms of actual volts/amperes or direct ratios, rather than in dbs). Once the actual transient waveforms and levels are known (or have been estimated), standard waveforms and levels most closely approximating actual levels (plus the margin) are usually selected from the menu of waveforms and levels published in References 2 and 3.

It should be noted that the transient levels defined in standards such as References 2 and 3 do not always cover the actual levels present in an aircraft system interconnecting wiring. The transient waveforms (designated 1 through 6) that are defined in these standards are typical of transients measured in aircraft interconnecting wiring, but amplitude levels 1 through 5 also defined in these standards represent only the 'middle range' of possible transient amplitudes. The standard levels defined for individual conductors or equipment connector pins presented in Tables 5 and 6 of Reference 2 are reproduced below. It is often overlooked that the levels in these tables may be selected as either TCLs or ETDLs. In the latter case, an ETDL associated with Level 5 for Waveform 4 could be 3200 volts. (In fact, the maximum voltage amplitude of 3200 volts was originally selected because this is the approximate sparkover voltage of harness termination devices such as connector wafers and terminal strips, thus implying a maximum actual transient level (ATL).

TABLE 5 - Individual Conductor TCL, ETDL or Test Levels
Due to Current Component A

Level	Waveform 3 V/I	Waveform 4 V/I	Waveform 5 V/I
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	300/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600

TABLE 6 - Cable Bundle TCL, ETDL or Test Levels
Due to Current Component A

Level	Waveform 1 V/I	Waveform 2 V/I	Waveform 3 V/I	Waveform 4 V/I	Waveform 5 V/I
1	50/100	50/100	100/20	50/100	50/150
2	125/250	125/250	250/50	125/250	125/400
3	300/600	300/600	600/120	300/600	300/1000
4	750/1500	750/1500	1500/300	750/1500	750/2000
5	1600/3200	1600/3200	3200/640	1600/3200	1600/5000

In fact, peak voltages and currents (especially) higher than those listed in Tables 5 and 6 of Reference 2 are frequently measured in aircraft circuits that extend between fuselage avionics bays or the cockpit and equipment installed in the wings, empennage, landing gear or engine nacelles. The brief captions assigned to each of the five transient levels in Section 22.3.2 of Reference 3 can be misleading. In reality, transients induced in wiring exposed to "severe electromagnetic environments" may not be represented by Levels 4 and 5. Such environments often induce transient levels higher than those defined by levels 4 and 5 in Tables 5 and 6 of Reference 2. The magnitudes of induced transients in wiring in severe environments depend on how well the wiring is protected. Some wiring in severe environments may experience transients within levels 2 or 3, but less well-protected wiring may experience much higher transients. The menu of transient levels in Tables 4 and 5 is intended for application to a large portion of the avionic equipment destined for installation on conventional aluminium aircraft, but not for circuits that extend to aircraft extremities.

ETDLs should be set for damage tolerance as well as system functional upset testing. The damage tolerance (i.e. pin injection) test levels should be based on individual conductor transients, and the ETDLs applicable for system functional upset testing should be cable bundle transients. If the cable is fully shielded, as in most engine and flight control systems, the cable bundle ETDL is a cable bundle current only. No cable–airframe loop voltage limit should apply since the voltage necessary to drive the desired shield current in the tested harnesses will not be the same as the loop voltage that would have existed in the aircraft installations. (This is because the coupling method chosen for the system test may not be the same as the coupling mechanisms in the aircraft, and the cable–airframe impedances are usually not the same as those existing on the test bench.)

<u>Damage Tolerance Tests.</u> Damage tolerance levels imply a specific voltage and current combination that individual equipment pin interface circuit elements should be capable of withstanding without burnout or degradation of a circuit element that would shorten the life of the circuit element following application of the lightning-induced transient. A cable bundle test usually cannot be a damage tolerance test because there is usually no information about the magnitudes of the transients that were applied to each

equipment connector pin in the bundle, and whatever transient levels do appear in the individual conductors in the test bundle are not likely to be the same as those that are induced in the conductors within the aircraft cable installation. The main attraction of cable bundle tests as a means of damage tolerance evaluation appears to be that the cable bundle test is easier to pass than a pin injection test, especially if the cable includes a ground wire.

The balance of this paper will focus upon system testing to verify functional upset tolerance.

System Test Levels. System test levels applied to cable bundles are usually thought to influence system functional upset, but system tests may also cause component failure. This is most often true of cables that include equipment power inputs that may be protected with diodes or metal oxide varistors (MOVs).

Examples of ETDLs applicable to a system to be installed in an all-aluminum aircraft are presented in Table 1. The Component A-related test levels for the pin injection and Multiple Stroke applications should be based on the results full vehicle tests or numerical analyses to determine the actual transient levels (ATLs) in the aircraft wiring due to Component A current flowing in the airframe. The Multiple Burst test levels are based generally on the guidelines of Table 7 of Reference 2 in which test voltages and currents recommended for Multiple Burst applications are set as fractions of the corresponding Multiple Stroke test voltages and currents for the same assigned level.

For the subsequent stroke transients (that are based on the external environment Component D/2) in the Multiple Stroke Waveform sets in the example of Table 1, the one-quarter amplitude relationship shown in Table 4 of Reference 2 has been followed, so that the Waveform 1 subsequent stroke current in Table 1 is one-quarter of 600 A or 150 A. The Waveform 3 subsequent stroke current of 12 A was set in accordance with the one-half amplitude relationship also in Table 4 of Reference 2.

Table 1. Typical ETDLs

Test	Level[1]	Based on Component	WF 3[2] (V/I)	WF 4/5A (V/I)	Comments
Pin Injection	3	A	600/24	300/60	Tests per Ref. 3 Section 22.5.1
Cable Bundle Multiple Stroke			**WF 3 (I)**	**WF 1 (I)**	Only current is specified since the cables are fully shielded
First pulse	3	A	24[3]	600[3]	Test setup per Ref. 3 Section 22.5.2
Subsequent pulses	3	D/2	12[3]	150[3]	
Cable Bundle Multiple Burst	3	H	**WF 3_H (I)**	**WF 6_H (I)**	Only current is specified since the cables are fully shielded
			6[3]	30[3]	Test setup per Ref. 3 Section 22.5.2
Note 1: As defined in Reference 3 if applicable					
Note 2: 1 and 10 MHz					
Note 3: The current amplitude should be achieved in the tested cable bundle shields					

The reason for the different first stroke/subsequent stroke relationships is the different coupling mechanisms that give rise to Waveform 1 and 3 transients. Table 4 of Reference 2 is reproduced below.

TABLE 4 - Response to D and D/2 as a Fraction in Response to A

Transient Responses	Waveform 1	Waveform 2	Waveform 3	Waveform 4	Waveform 5
Response to D	1/2	1	1	1/2	2/5
Response to D/2	1/4	1/2	1/2	1/4	1/5

Transient responses arising from Component H of the Multiple Burst waveform set will occur in the Multiple Burst sequence. The predominant waveform responses are voltage Waveform 3_H in a frequency range between 1 and 10 MHz or a current waveform (Waveform $6_{H)}$ which has the same shape as the external environment Component $_H$. The Waveform 3 responses are most likely in long cables, greater than 3 m of length. Waveform 6_H transient currents are experienced in shorter, usually shielded, cables.

The relationships between Multiple Stroke and Multiple Burst test levels in Table 7 of Reference 2 are based upon measurements of lightning-induced transients in wiring of many aircraft. These relationships are shown in Table 7 from Reference 2, reproduced below. The Waveform 3_H transients are about 60% of the amplitudes of their Waveform 3 counterparts induced by Component A, and the Waveform 6_H transient currents are 1/20 of the amplitudes of the same level transients due to Component A, since the external environment Component A (200 kA) is 20 times the amplitude of external environment Component H (10 kA).

TABLE 7 - Cable Bundle TCL, ETDL or MB Test Levels
Due to Current Component H

Level	Waveform 3_H V/I	Waveform 6_H I
1	60/1	5
2	150/2.5	12.5
3	360/6	30
4	900/15	75
5	1920/32	160

Thus, the Waveform 6_H level of 30 A for MB testing in the example of Table 1 is, therefore, 5% of the Multiple Stroke Waveform 1 level of 600 A. This reflects the relationship between current Component A and Waveform H amplitudes in the external environment, since the amplitudes of induced currents are always proportional to the amplitudes of the lightning current in the airframe. The Waveform 3_H test current of 6 A in the example of Table 1 is the level for Waveform 3_H that corresponds to the Waveform 6_H current level in Table 7 of Reference 2.

The levels shown in Table 1 are currents since this hypothetical system is interconnected with fully shielded cables. Equipment and system test levels for voltage Waveform 3_H, which would be applicable to a system with unshielded wire harnesses, typically have an amplitude of 60% of the Waveform 3 voltage response to Component A.

Test Current Applicability to Harness Branches. There is usually a large variation in the currents induced in the individual harness branches within a system, but no attempt is usually made to replicate these specific currents in the system tests. Since the damage tolerance of system equipment will have been verified by pin injection tests at transient levels based on the Component A-induced transients in each circuit, it is not necessary to reach actual induced transient amplitudes in all branches of a tested system. It is desired to reach sufficient harness current amplitudes to induce conductor transients that would be likely to be ‘read’ along with system signals.

It is not intended that the ETDLs assigned to interconnecting wire harness conductors be achieved in all conductors within the test cables during system functional upset tests, since such tests are not intended for damage tolerance evaluations (that is the purpose of the pin injection test).

But, since system upset is to some extent related to the amplitudes (as well as the multiplicity) of induced transients, an attempt should be made to have the conductor V_{OC}s approximate the ETDLs assigned to the interfacing equipment.

Cables with Intermediate Connectors. If the aircraft circuit being considered runs inside shields that are grounded at intermediate locations (such as engine and flight control circuits frequently are) as shown in the example of Figure 2, the shields should be in this configuration when the individual circuit conductor V_{OC} and I_{SC} are measured during a full vehicle test. The measured voltage/current should be used in verifying or establishing the ETDLs for the associated equipment, and the equipment damage tolerance would be verified by a pin injection test at the corresponding ETDL V_{OC} and I_{SC} levels.

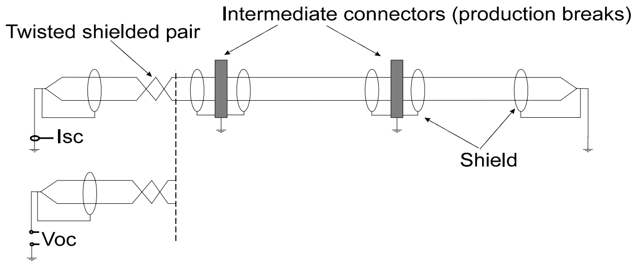

Figure 2. Segmented Cable

If the cable is part of a system for which functional upset tolerance must also be verified, cable bundle currents should also be measured during the full vehicle test or determined by analysis. Since the currents in each section of the cable (which are labelled A, B, C in Figure 1) are confined within separate loops, these will likely be different from each other.

Currents in each of the three cable segments should be measured during the full vehicle test. Sometimes the cable shield current is much higher in one segment – such as a pylon or wing circuit – than in the other segments, but the other segments should not be ignored. Cable segments with lower shield currents may be longer than the segments that experience the highest shield currents, others, and the conductor voltage is proportional to cable length as well as shield current.

For the functional upset test of the system utilizing the cable in Figure 2, it may not be practical to have all three segments (A, B, C) of the cable present or to inject currents of three different amplitudes, simultaneously, into the three cables with the intermediate connectors grounded to the test bench. However, the tested cable(s) should produce induced transients in the shielded conductors that are based upon the actual transients measured in the circuits running through all three-cable segments in the aircraft. This can be done by assuming that the conductor-induced voltage (V_{OC}) is the sum of the voltages induced in each segment of the circuit, as follows:

$$V_{oc}\,(\text{total}) = (I_A \times Z_A) + (I_B \times Z_B) + (I_C \times Z_C)$$

where I_A, I_B and I_C are the cable shield currents in the three sections and Z_A, Z_B and Z_C are the transfer impedances of each cable segment.

For many cables, the transfer impedances (Z) are the shield DC resistances. If the shield transfer impedances and currents are known, the characteristics of a single "equivalent" cable and a single uniform cable bundle (shield) current can be defined, and such a cable provided for the system test with sufficient current injected in it during the system test to produce V_{OC} (total).

Sometimes, because the total of the length(s) of cables A, B and C is long, it turns out to be impractical to inject sufficient current into the "equivalent" cable shield to reach the necessary conductor V_{OC}. In this case, a sufficiently high V_{OC} can often be achieved (although at a different waveshape) by ungrounding the test cable shield at one end and inducing voltage (and current) directly into the shielded conductors.

Since some cables within a system extend beyond the fuselage avionics bays to other locations in an aircraft, transients as defined in Tables 5, 6 and 7 of Reference 2 may be chosen. Waveform 2 is the dominant voltage in the loops between shielded cables and the airframe since such cables are most likely to be exposed to magnetic fields penetrating apertures such as windows, vents and engine nacelles. This voltage drives current Waveform 1 in the shields which, in turn, produces Waveform 4 voltages in the shielded conductors. The conductor voltages drive currents of somewhat longer duration in the shorted conductors which are best represented by Waveform 5A. Some oscillograms of a typical Waveform 4 voltage and a Waveform 5A current are shown in Figures 3 and 4.

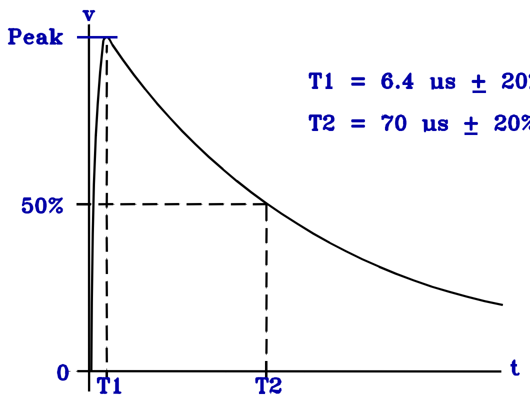

Figure 3. Typical Current Component A and Voltage Waveform 4 Voltage

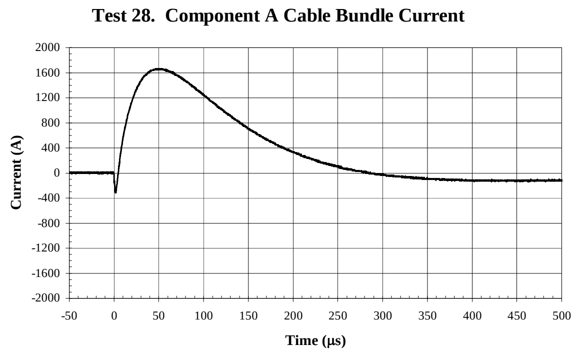

Figure 4. Typical Cable Bundle Current due to Component A

Simultaneous Injection Locations

Techniques for injection of transients into simple systems comprised of one item of one "equipment under test" (EUT) and a single cable between this "box" and dummy loads representing remote equipment, or a second box, are described in Reference 3. These include transformer injection and ground injection methods, and either method is potentially able to inject the specified transients into the system. Injection of transients into a system comprised of several EUTs and more than one interconnecting cable is done using the same injection methods, except that transients usually have to be injected simultaneously into more than one location in the system. An example of transformer injection at two locations into a system comprised of four EUTs and three interconnecting cables is shown in Figure 5.

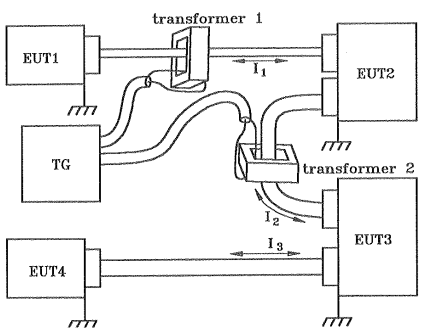

Figure 5. Transformer Injection of Transients

The transient generator (TG) in Figure 5 drives current into the primary turns of each of the injection transformers simultaneously. (In fact, the same primary conductor is sometimes routed through all of the injection transformers.) The following means can be used to control the amount of test current (or voltage) in each cable:

- Adjusting the number of turns in the primary winding (one or two turns is most common)
- Adding impedance between each EUT and the test bench ground plane
- Changing the cable impedances by adjusting the distances between the cables and the ground plane

The ground injection principle is illustrated in Figure 6.

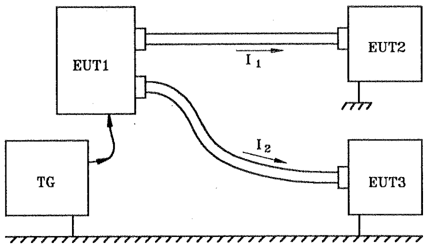

Figure 6. Ground Injection of Transients

The magnitudes of cable currents also depend upon cable impedances and EUT ground impedances which can be adjusted. The loop voltages are the test generator injection voltage. The ground injection method requires that one EUT be operable when it is not grounded directly to test bench ground. This is always possible if power to this EUT can be furnished through one of the tested cables or from an independent source that does not need to be grounded to the test bench.

Cable currents and loop voltages. Many systems that perform critical functions are protected from lightning and other electromagnetic effects by enclosing the interconnecting circuits within flexible copper braid shields or 'screens' which are connected to the EUTs via the cable connectors. When all of the interconnecting cables are shielded in this manner, the specified transient needs to be a shield current since this is responsible for inducing transients in the shielded circuits.

However, when some or all of the circuits within a cable are not enclosed within shields, both a voltage and a current need to be specified. Usually this is a current test level, I_T, together with a voltage limit V_L. There are other situations in which the reverse is true, with a V_T and I_L being specified. The following guidelines apply:

- When all conductors are shielded, only an I_T applies. A V_L is not applicable. The test current must be reached in the cable regardless of the loop voltage.

- When some conductors in a cable are shielded and others are not, an I_T is applicable together with a V_L. If the test current level in the cable cannot be reached when the loop voltage reaches V_L, the test is stopped and considered successful.

- When all conductors are unshielded and terminated in high impedance loads to ground, only a V_L may be necessary.

The locations of the cable currents and the loop voltages are illustrated in Figure 7.

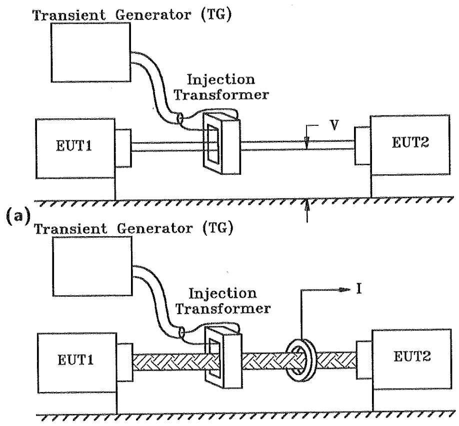

Fig. 18.2 Transformer injection.
(a) Injection of voltage
(b) Injection of current

Figure 7. Cable Current and Loop Voltage
a) Loop voltage
b) Cable current

Achievement of Specified Test Current Levels in Shielded Systems. When high currents must be injected into multiple cables, as is often required for electronic engine controls, transient generator limitations prevent reaching the specified levels. Two approaches may be followed to surmount this problem:

1. Use the same current in more than one location by having some EUTs ungrounded so that test current is conducted into an EUT on one cable and out of this EUT on one or more other cables.

2. Test all cables simultaneously at the highest levels possible, and then test cables that did not experience the full level individually at the full level.

The first approach is illustrated in Figure 8.

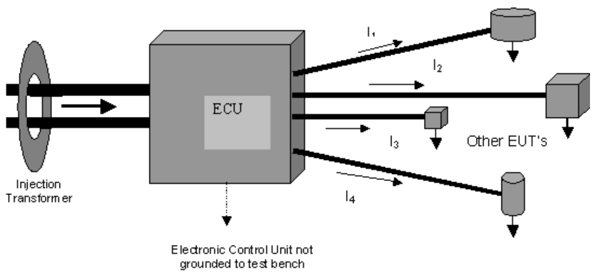

Figure 8. Test Current through Ungrounded EUT

In Figure 8, the test current is injected into two cables on the left side of the Electronic Control Unit (ECU) and is allowed to flow through the ECU case into four other cables between the ECU and other EUTs since the ECU is not grounded. In this figure, the sum of $I_1 + I_2 + I_3 + I_4$ is the injected current.

In an electronic engine control system, the cables on the left side of Figure 8 would go to the aircraft interfaces, and the cables on the right side of Figure 8 go to engine-mounted accessories. The ECU receives electric power via one of the aircraft cables or an engine-mounted generator that is one of the "other EUTs" in the figure. The ECU does not have to be grounded to the test bench to function. These tests are also sometimes conducted with the bulkhead connector brackets (normally grounded to the airframe or engine) ungrounded, so that the injected test currents flow continuously through the system.

The second approach is a combination of simultaneous application of currents in all branches of the system of sufficient amplitude to induce 'readable' signals in interconnecting circuit conductors followed by application of full threat currents in those cables/branches where the specified currents were not reached during the simultaneous injections. This is not a perfect solution since it leaves, untested, the condition where all cables receive the specified currents simultaneously. Systems tested in this manner have not experienced functional upsets during in-flight lightning strikes.

Relationships among Test Currents and Voltages. When a V_L is applicable, as when the tested cables contain unshielded as well as shielded circuits, care should be taken to assure that the similar relationships exist between test current and limit voltage as exists in the aircraft installation. This requires some knowledge of the coupling mechanism(s) that give rise to the transients being applied. References 2 and 3 give little guidance in this area. Table 2 gives the proper relationships between the voltage and current waveshapes that are induced by lightning in aircraft circuits.

Table 2. Relationships Between Test Voltages and Currents

Voltage Waveshape	Current Waveshape	Coupling Mechanism
Due to Lightning Current Component A		
2	1	$d\Phi/dt$
3	3	$d\Phi/dt$, travelling waves
4	5A	IR
4	5B	IR + Redistribution
5A*	5B	Shield IR
Due to Lightning Current Component H		
3_H	3_H	$d\Phi/dt$, travelling waves
Not defined	6_H	$d\Phi/dt$
* Here 5A is the voltage inside a shield due to 5A current in the shield		

The waveshapes noted in Table 2 are defined in References 2 and 3. The relationships among voltage and current waveshapes listed in Table 2 are approximate and depend on the impedances of specific cables and other factors. Thus, for example:

- When applying I_T as Waveform 1, V_L should look like Waveform 2.
- When applying V_T as Waveform 4, I_L should look like Waveform 5A. To stop the test, when the I_L current amplitude is reached by a current waveform of shorter time duration (i.e. a short duration ‘spike’), may not sufficiently stress the system.

Existing test standards provide only minimal guidance in this area.

Travelling Wave Effects. Characteristic impedances relate the voltage and current amplitudes of travelling waves that are represented by Waveform 3. When performing tests with Waveform 3 on unshielded or hybrid cable bundles, the assigned current levels should usually be related by a minimum of 25 ohms to establish the corresponding voltage level. The 5-ohm relationship that is implied in Table 6 of Reference 2 is not realistic, except in rare circumstances where the Waveform 3 transients are the result of tank circuit oscillations among lumped L and C elements at circuit terminations. Even the 25-ohm characteristic impedance is unlikely. A more typical relationship is the cable–airframe transmission line characteristic impedance of approximately 100 ohms.

Calibration Waveforms. The ability of the transient generator to circulate specified test currents in the system cables should be verified prior to test. “Calibration” of the transient generator by having it inject the specified current into a short circuit (as in a calibration jig) is not sufficient for tests of a system with long cables. Ability of the generator and intended injection method to produce current waveforms similar to those specified (i.e. Waveform 1, 5A, 5B or 6_H) in the system cables should be verified. This can usually be done by trying out the generator and injection method on the system cables themselves, at low levels.

Waveforms in Tested Cables. It is not necessary to reproduce the specified current waveforms in the system cables exactly, but it is necessary to inject waveforms that are able to couple realistic transients into the cable circuits. Such coupling usually depends on rate of rise ($d\Phi/dt$) as well as amplitude of the injected shield current. If the injected currents are deficient in rates of rise, amplitudes, or time duration, an alternate test current generator should be utilized or the shield transfer impedances determined and corresponding conductor transients injected directly into the cables with shields disconnected.

The calibration methods described in Reference 3 for cable bundle tests are usually adequate for the short (3.3 m) cables usually used in cable bundle tests of individual EUTs, but not for systems employing longer cables.

MS and MB Transient Levels. The 60% relationship between induced voltages, due to the Component A and Waveform H environments that is inherent in the standard Multiple Burst levels of Table 7 in Reference 2, are utilized to assign the Waveform 3 Multiple Burst voltage level of 900 volts, but since the 28 Vdc circuits are single wires, a lower current level of 9 A has been assigned which reflects a typical characteristic impedance of 100 ohms. Standard current Waveform 6_H is only a current, so no associated voltage waveform is assigned. The amplitude is set at 7.5 A reflecting the 5% relationship to the assigned pin injection test current of 150 A due to Component A.

The MS waveform set is defined as one transient induced by Component D of the external environment followed by thirteen transients induced by Component D/2, as shown in Figure 9.

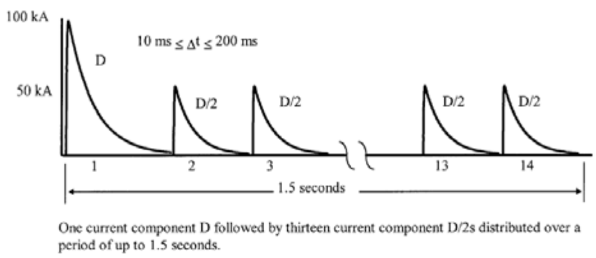

Figure 9. Multiple Stroke Waveform Set

In the MS application, Component D represents a severe first stroke in a negative flash to earth since only the negative flashes contain multiple strokes. Since systems also have to tolerate the induced effects of one positive stroke, most MS waveform sets begin with a transient induced by Component A instead of Component D.

Multiple Burst Tests

Most of the examples in the foregoing sections have referred to MS tests. MB tests are usually applied prior to the MS tests since the chances of damage to the tested system from the MB transients are usually less than from the higher amplitude and longer duration transients induced by the MS environment. The same considerations regarding simultaneous applications and transient amplitudes apply to MB tests. The transient amplitudes are lower than those applied for the MS tests, as shown in Table 4 of Reference 2 reproduced earlier. A typical MB waveform set comprised of Waveform 3_H transients is shown in Figure 9.

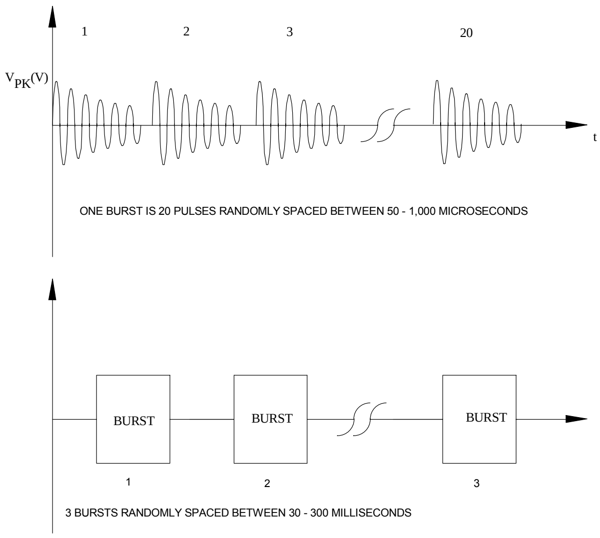

Figure 9. Multiple Burst Transient Waveform Set

For systems such as engine controls that are interconnected with short cables exposed to strong lightning magnetic fields, Waveform 6_H currents are applicable. A typical cable bundle current induced by current Component H in an aircraft is shown in Figure 10.

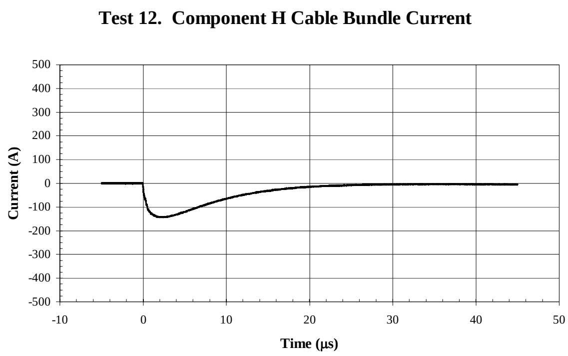

Figure 10. Typical Cable Bundle Current Induced by Component H

Current Waveform 6_H is a good simulation of both the fast rate-of-rise and time duration aspects of the induced current shown in Figure 10.

A typical burst pattern of twenty Waveform 3 transients is shown in Figure 11 and a pattern of four bursts is shown in Figure 12. The transients in a burst have to be applied randomly at time spacings between 50 and 1000 μs. The start of each burst is to be between 30 and 300 ms from the previous burst, and there are to be a minimum of three bursts applied in each waveform set. Since a finite time period is usually needed to monitor system performance and the MB transients are usually not damaging to system components, the MB waveform sets are often run continuously for a period of several minutes.

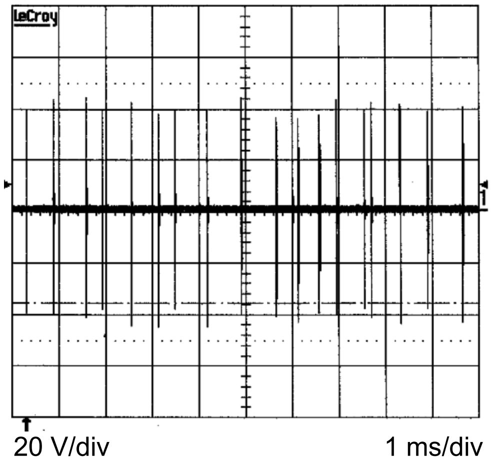

Figure 11. Typical Burst of Twenty Waveform 3 Transients

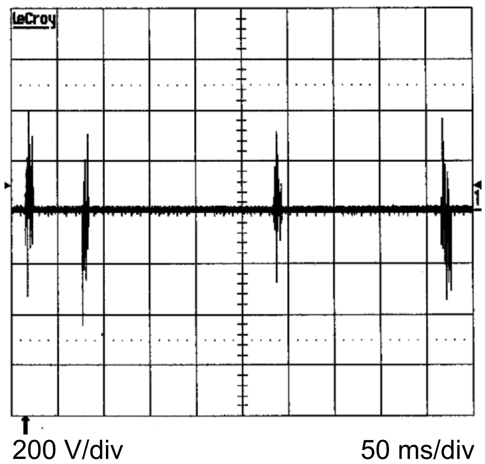

Figure 12. Typical Multiple Burst Waveform Set

MB Waveform 3 transients at amplitudes up to 15 A (Level 4) can usually be produced by a signal generator and amplifier with pulse power capability of 10 kW or so. The Waveform 6_H transients above Level 2 usually have to be generated by capacitor discharge circuits.

Experience With System Tests

Tests have been conducted on many types of systems at Lightning Technologies, Inc. since the MS and MB environments were first defined in the early 1980's. In some cases, the system has not been affected but in others, the system has experienced some type of response during the tests, and occasionally some component damage is experienced, usually as a result of an MS test being applied to power inputs.

Tested systems have included engine and flight controls, and a wide variety of cockpit displays. Responses have included:

- Changes in fuel flow and engine thrust
- Changes in control surface position
- Momentary loss of a display, with automatic recovery
- Loss of display with pilot input necessary for recovery
- Changes in color of a display

These effects have sometimes occurred upon application of the first pulse in a waveform set, but more often they have occurred after some later transient has been applied within a waveform set. These responses have prompted changes in system hardware or software and retest to verify that the problem has been corrected.

Subsequent flight experience of systems certified by system tests that have applied the MS and MB environments, together with damage tolerance tests of the individual system components, has been very good. These systems do not appear to have been upset or damaged by the in-flight lightning environment.

System tests have also enabled protection designs to be evaluated under intentionally degraded conditions, such as increases in cable shield termination resistance by insertion of resistive gaskets between connectors and cases or by interruption of cable shield continuity.

Control systems have been tested in "closed loop" as well as "open loop" configurations. The closed loop configuration usually means that the system receives feedback from control positions and environmental inputs and responds to them in accordance with control laws. Systems tested in an open loop mode process inputs but do not receive system outputs and correct for them. In the latter case, perturbations in system outputs (i.e. command signals) must be assessed to establish whether they are acceptable (i.e. benign) or not. Certifying authorities have accepted test plans based on both configurations of the tested system. The closed loop arrangement usually requires a more elaborate test setup, but the open loop arrangement usually requires that more parameters be recorded during the tests, and a more painstaking assessment of data following the tests.

References

1) SAE ARP 5413/EUROCAE ED 81*"Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning"*

2) SAE ARP 5412 *"Aircraft Lightning Environment and Related Test Waveforms"* 1999

3) RTCA DO-160D/EUROCAE ED 14 *"Environmental Conditions and Test Procedures for Airborne Equipment" Section 22 "Lightning Induced Transients"*

4) Fisher, F.A., Perala, R.A., and Plumer, J.A. *"Lightning Protection of Aircraft"* Lightning Technologies, Inc. 1990