TABLE 1 - TYPICAL TEST CURRENT ATTACHMENT CONFIGURATIONS

Current Generator Attachment Point	Return Conductor Attachment Point
Aircraft	
Nose	Tail
Windshield Post	Tail
Nose	Wing Tip
Nose	Engine
Nose	Landing Gear
Nose	Vertical Tail
Wing Tip	Tail
Wing Tip	Wing Tip
Engine Inlet	Engine Exhaust
Engine Inlet	Tail
Helicopter	
Main Rotor Blade	Tail Rotor Blade
Main Rotor Blade	Landing Skid
Main Rotor Blade	Nose
Tail Rotor Blade	Landing Skid
Tail Rotor Blade	Nose

The number of current generator and return conductor configurations may be reduced by using analysis to show that the selected current generator and return conductor configurations achieve the most severe lightning transients for the aircraft test points. The analysis and models used in the analysis should be validated by comparison with lightning test results.

The return conductors and current generator attachments should be configured to simulate the important characteristics of the lightning and aircraft interaction. The current distribution on the test aircraft should simulate as much as possible the current distribution that would exist on the aircraft during an in-flight lightning strike.

The return conductor arrangement will be dependent on the aircraft shape. The aircraft and return conductors cannot be considered uniform transmission lines, such as a coaxial transmission line, except in the crudest approximation. So the aircraft and return conductor arrangement should be configured to provide repeatable test results, with a representative current distribution on the airframe.

This may be achieved using the aircraft on the ground and an assembly of return conductors. The preferred installation would be to use return conductors about the aircraft fuselage, wings and tail boom, which would encourage a representative current distribution in the aircraft. As a minimum, the return wires should be arranged as a ground plane under the aircraft fuselage, wings, and tail boom. This may be the most practical return conductor configuration for large transport aircraft. This will exaggerate the current density on the lower part of the aircraft nearest the ground plane. This is typically satisfactory for wing-mounted wiring and systems, and for aircraft where the critical wiring, systems, and key coupling points (such as doors and hatches) are on the lower part of the aircraft. But this configuration produces lower current density on the higher parts of the aircraft, such as the top of the fuselage and near the cockpit windows.

Practical aircraft and return conductor configurations form a non-uniform transmission line. The characteristic impedance of this complex non-uniform transmission line typically ranges from 70 to 150 Ω. The aircraft and return conductors are driven at one lightning attachment point by the test current generator. The aircraft and return conductors are typically shorted together at the other lightning attachment point for that test configuration. This aircraft and return conductor arrangement will produce a drive point impedance that has low resistance at low frequencies, is inductive in the range of 10 kHz up to a high-Q quarter-wavelength resonance frequency of the aircraft/return conductor transmission line, and then with multiple transmission line resonances at higher frequencies.

This differs from the characteristics of natural lightning attachment to aircraft. Lightning return stroke characteristic impedance or surge impedance have been estimated to range from 1000 to 6000 Ω, with some longitudinal resistance in the lightning channel. Therefore, the aircraft during a natural lightning strike will not exhibit a high-Q quarter-wavelength resonance, but will exhibit a lower-Q half-wavelength resonance related to the lightning current path length through the aircraft.

The aircraft and return conductor arrangement may be terminated with matching resistors instead of shorting the aircraft and return conductors. Matching the transmission line may eliminate the quarter-wavelength transmission line resonant response that is test configuration dependent. However, for most lightning attachment configurations, the aircraft and return conductor are much too complex to be represented as a uniform transmission line. Even if the aircraft and return conductor transmission line can be terminated in a matched impedance, the matching load resistance is generally so high that it reduces the amplitude of the input current that can be injected into the aircraft with a given current generator. This results in an unacceptable signal-to-noise ratio and hampers the ability to measure induced transients in wiring. It also reduces the normal half-wavelength resonance typical for a natural lightning strike to an aircraft.

With the aircraft and return conductor shorted at one attachment point, the quarter-wavelength transmission line resonance provides conservative induced transient measurements at the resonant frequency. The quarter-wavelength resonance occurs at a frequency that is lower by half compared to the half-wavelength resonance. The defined lightning environment spectra decrease 40 dB per decade or 12 dB per octave as frequency increases in the airframe resonance frequency range. So the induced transient response due to the quarter wavelength resonance may be higher than an induced transient response due to a half wavelength resonance.

For helicopters with avionics in the nose area, the highest lightning transients tend to result from the nose to tail rotor blade current generator and return conductor configuration, as shown in Figure 20. Current generator attachment to main rotor blades may result in the highest lightning transients for wiring and systems installed on the engine and gearbox. With the main rotor blade current generator and return conductor configuration, a coaxial return may be impractical and a simplified configuration may be used. However, additional analysis may be required to account for differences between transients measured in the test configuration and expected transients in flight.

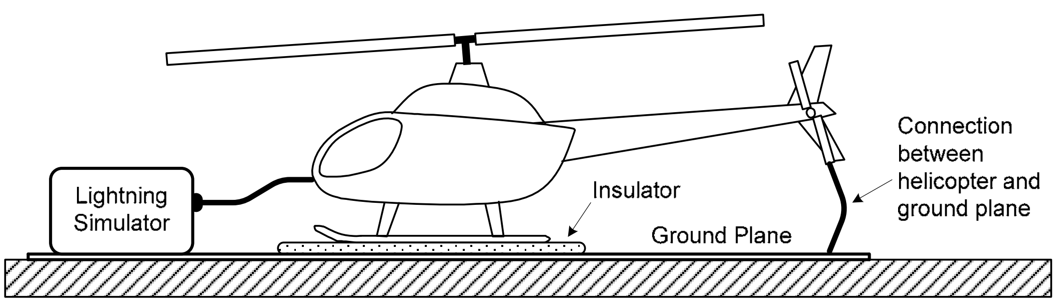

FIGURE 20 - HELICOPTER GROUND PLANE ARRANGEMENT

For small aircraft, conductors surrounding the aircraft uniformly spaced from its surface may be the most effective return conductor arrangement. This arrangement, shown in Figure 21, provides reasonably representative current distribution between the top and bottom surfaces of the aircraft. Additional analysis to represent the in-flight current distribution should not be necessary in this arrangement, except to consider the resonance of a short circuit return connection compared to the expected impedance of the lightning channel for an in-flight lightning attachment.

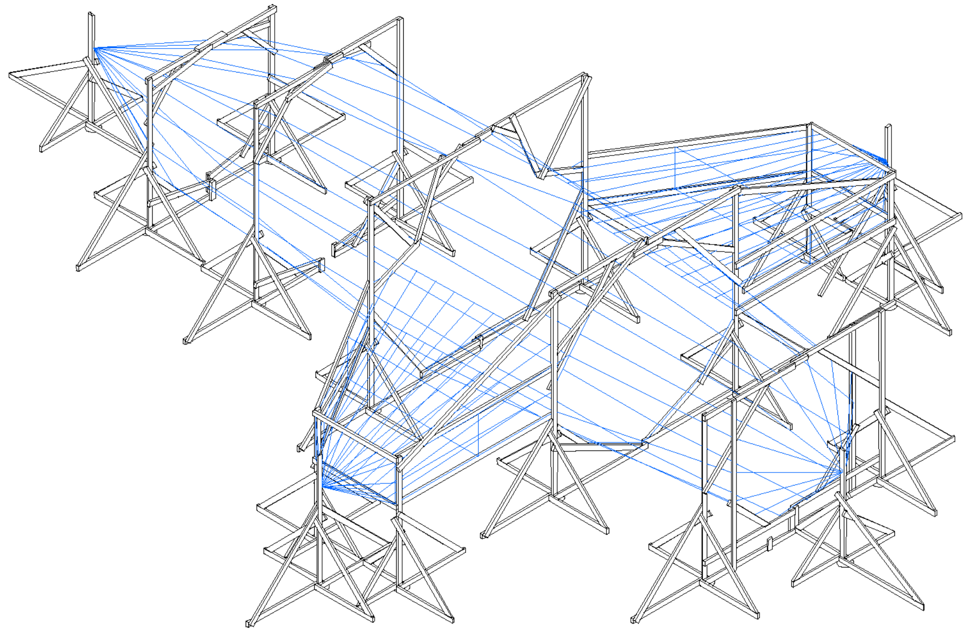

FIGURE 21 - SMALL AIRCRAFT RETURN CONDUCTOR ARRANGEMENT

For large aircraft, the return conductor arrangement may be more complex, and it may not be practical to have conductors above the aircraft. Therefore, additional analysis may be necessary to assess the aircraft current distributions in the test configuration and in the normal in-flight lightning attachment. The analysis should determine the effect of the test return conductors, and the effect of the return conductor termination on the aircraft surface current distribution. Analysis should determine the differences between test current distribution and the expected surface current distribution for an aircraft in-flight lightning attachment. Method of moments, finite-difference time domain, and finite element models are all effective tools for assessing the lightning surface current distribution on large aircraft.

Localized return conductors may also be used for lightning induced transient response for wiring in specific areas of the aircraft, such as the stabilizers or engines. Figure 22 shows localized return conductors for measurements associated with wiring in the vertical stabilizer.

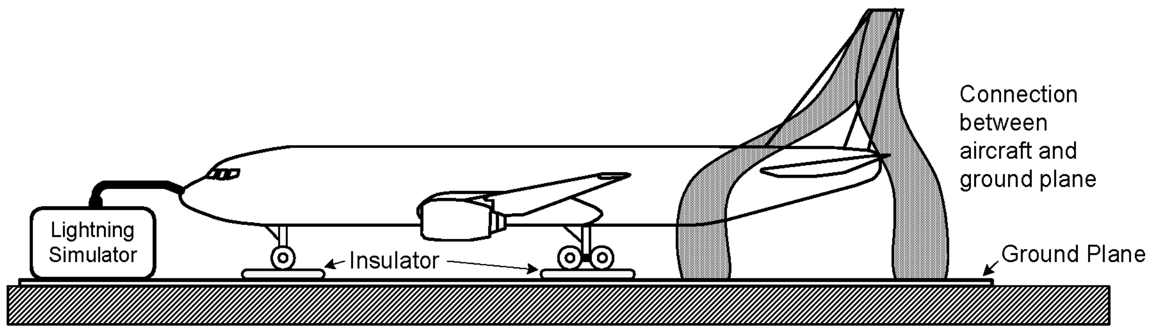

FIGURE 22 - LARGE TRANSPORT AIRCRAFT RETURN WIRE ARRANGEMENT

The test aircraft must be isolated from the return conductors except at the current generator and return conductor attachment points. The tires or helicopter skids must be isolated from the ground plane return conductors using insulating pads or stands. The insulating pads or stands must withstand the voltages developed between the aircraft and return conductor, particularly during high current pulse tests.

The ground plane should preferably be single point grounded to facility ground near the test generator ground point to meet health and safety requirements. Care should be taken to minimize traveling wave effects or spurious oscillations between the return arrangement and the facility (i.e., hangar). This might be accomplished by careful selection of the ground point, or by grounding the return arrangement to the facility via resistors to damp out such resonances, or by grounding the arrangement via a low DC resistance connection which has a high impedance at high frequencies.

6.1.4 Measurements

The aircraft tests provide induced transient responses that may be used to determine the ATLs that can be compared to the TCLs and ETDLs. Therefore, the aircraft lightning measurements should be chosen to match the method by which the aircraft TCLs and the equipment or system ETDLs are defined. For example, if the TCLs are defined as individual wire open circuit voltages and individual wire short circuit currents, then aircraft measurements should include individual wire open circuit voltages and wire short circuit currents. Or, if the TCLs are defined as overall wire bundle currents, then the aircraft measurements should include overall wire bundle currents.

Also, the aircraft lightning measurements should provide data that can be directly compared to the ETDLs and corresponding equipment qualification tests. For example, if the ETDLs and corresponding equipment qualification tests are based on the DO-160/ED-14, Section 22 wire bundle injection tests, the wire bundle injection tests levels are based on open circuit loop voltages and/or wire bundle currents. Therefore, the full aircraft lightning measurements should include open circuit loop voltages and short circuit currents.

Several types of measurements can be made. These include:

a. Open circuit voltages (V_{oc}), which are induced voltages measured between an individual open-ended wire and adjacent aircraft ground, with the other end of the wire grounded at the remote equipment location using a low-impedance ground termination. Equipment at either end of the measurement wire is disconnected from the wire bundle, but shields of the measured wire, (if present) and any other shields in the same wire bundle should be grounded in the normal fashion, either locally or to equipment connectors, if such shields are normally grounded at each end in the installation.

b. Short circuit currents (I_{sc}), which are induced currents measured on individual wires with both ends of the wire grounded using low-impedance ground terminations. Other conditions are as described in paragraph a.

c. Wire bundle currents (I_{bc}), which are induced currents measured in a wire bundle, with the aircraft equipment that use the wire bundle installed in their normal manner and the wire bundles connected to the equipment at each end, in the normal manner.

d. Loaded circuit voltages (V_l), which are induced voltages measured between a wire and adjacent aircraft ground, with both ends of the wire terminated normally, and with the aircraft equipment installed in their normal manner.

e. Loaded circuit currents (I_l), which are induced currents measured on individual wires with both ends of the wire terminated normally, and with the aircraft equipment installed in their normal manner.

The measurement configurations described in a. through e. are shown in Figure 23. The loaded wire measurements described in d. and e. above are usually made only in special cases, such as navigation light and window heater circuits, and power distribution buses, since such measurements would otherwise require elaborate breakout boxes whose presence could affect the measured transients. Also, loaded circuit measurements would probably have to be conducted with the system powered up, to account for non-linear load impedances. Surge protection devices installed in aircraft wiring should be considered. Surge protection devices would be in the conducting state from induced voltage due to natural lightning strikes, but would not conduct during tests with lower test currents.

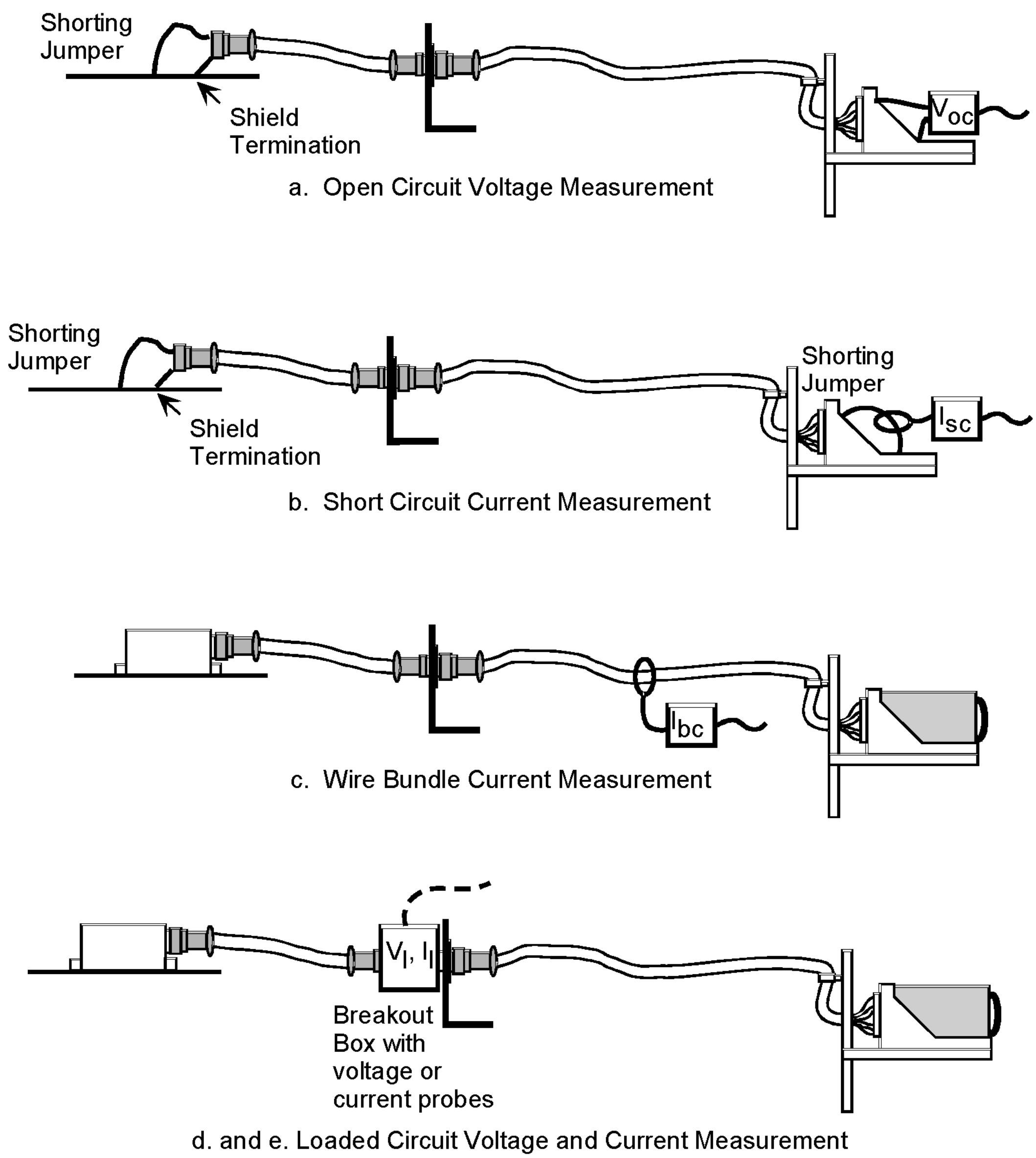

FIGURE 23 - SCHEMATIC REPRESENTATION OF MEASUREMENT TYPES

Figure 23 gives a schematic representation of these measurement types. The first three measurement types are most commonly used, because they can be easily related to the ETDLs verified with DO-160/ED-14, Section 22 tests, and because the measurement can be performed using relatively simple circuit shorting devices. With the first two measurements a. and b., a Thevenin equivalent circuit can be derived for each measured aircraft circuit, from which the ATLs can be determined. The last two methods d. and e. typically require more complex breakout boxes to install the voltage and current probes without affecting circuit and wire bundle shield characteristics.

For open circuit voltage and short circuit current measurements, the aircraft wiring of interest is disconnected from the LRU at both the measurement and remote ends. The remote ends are grounded to nearby airframe structure by using jumper wires. The jumper wires length should be minimized to prevent magnetic coupling from influencing test results. Grounding the aircraft wire at one end allows all of the voltage induced in the wire to be measured at the other end. High input impedance voltage probes should be used for these open circuit measurements. Short circuit current measurements are made by installing an additional grounding jumper at the measurement end, so that both ends of the wire being measured are shorted to the aircraft structure. Currents flowing in the wire are then measured using a current transformer placed around the grounding jumper at the measurement end.

Additional measurements may include voltages induced by magnetic fields passing through apertures, lightning currents flowing through structural resistances, and surface current density. Both magnetically induced and structural voltages may be measured by installing a test wire in the aircraft where the particular voltage measurements are desired. For both magnetically induced and structural voltage measurements the test wire is electrically bonded to aircraft structure at one end and the open circuit voltage is measured at the other end of this wire. This is similar to measurement a. above. For magnetically induced voltage, the wire is positioned so as to enclose magnetic fields penetrating through apertures. For structural voltage, the wire is routed near the structure of interest. The space between the wire and structure should be minimized to reduce magnetic field coupling to the test wire. Surface current density may be measured by installing surface current density probes at selected locations on the aircraft external surfaces. These measurements are helpful to characterize the current distribution around the aircraft. The results may be used to correct differences between the aircraft and return conductor current distribution and predicted aircraft current distribution during a natural lightning strike. These measurements are also helpful to characterize the induced transient coupling mechanisms in particular areas of the aircraft. This is especially important when determining the appropriate scale factors to use for pulse test measurements if the standard test waveform(s) (component A and H) are not applied.

Locations of LRUs and associated interconnecting wiring should be identified using aircraft system installation drawings and aircraft installation inspection. The wire shielding status should also be determined from the drawings. Any shield at the measurement end, which is normally grounded either by the connector backshell or through one of the connector pins to a ground within the LRU, should be grounded to the airframe. A convenient location should be selected close to the disconnected LRU for grounding the shield during the induced voltage measurements.

Instruments used to record and measure specified test voltages and currents, such as network analyzers, oscilloscopes and probes, should be calibrated to standards traceable to the appropriate national standards body, such as the U.S. National Institute of Standards and Technology (NIST), using procedures and processes approved by the appropriate national standards body.

6.1.5 Swept Frequency Aircraft Tests

Swept frequency aircraft tests are used to measure transfer functions of induced transient voltage or current relative to the current injected into the aircraft. The frequency-domain transfer functions are multiplied by the appropriate lightning environment spectrum, and Inverse-Fourier transformed to produce the resulting time-domain lightning response. Swept frequency aircraft tests typically use low amplitude injection current, and the transfer functions, including amplitude and phase, are measured using vector network analyzers.

6.1.5.1 Test Setup

The aircraft and return conductor arrangement is set up as described in 6.1.3. Since the swept frequency aircraft tests do not generate high voltage between the aircraft and return conductors, the separation distance between the aircraft and return conductors should be chosen for current distribution uniformity, not voltage standoff requirements. Preferably, the impedance of the generator should be matched by terminations of similar impedances at each end on the aircraft. If it is not possible with this arrangement to drive sufficient current through the aircraft to obtain suitable measurements at low frequencies (i.e., below 1 MHz) the remote extremity of the aircraft may be terminated in a short circuit to the return conductor arrangement. A sketch of a general test setup is shown in Figure 24.

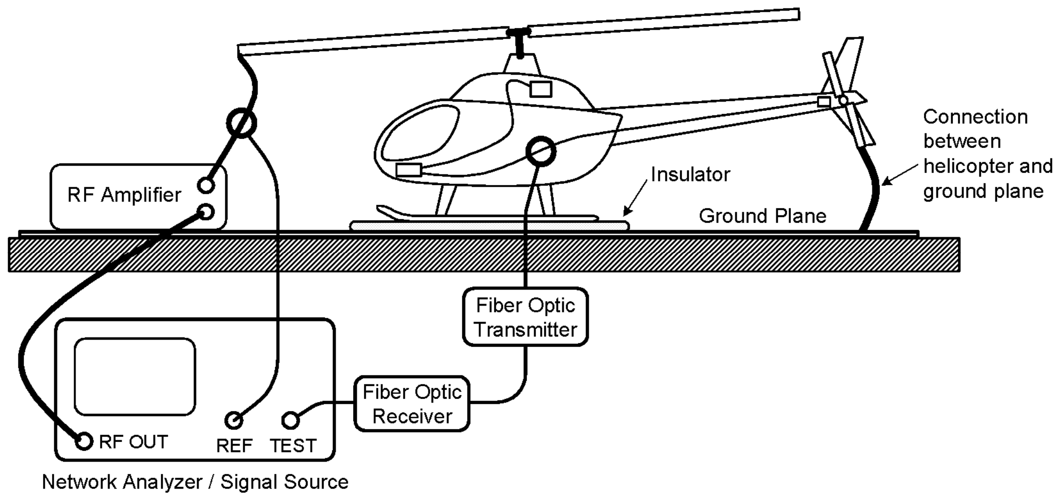

FIGURE 24 - SWEPT FREQUENCY TEST SETUP

Swept frequency tests use relatively low current, which develop relatively low voltages across joints or other interfaces that could potentially arc during natural lightning strikes. Because of this, it may be necessary to use low-impedance jumpers across joints and interfaces to simulate the expected lightning current paths. For example, control surface actuators may be nonconductive at low amplitude test currents but may conduct during full threat lightning strikes. If the actuator control or position sensor system transients are being measured, one test configuration may incorporate jumpers across the actuator.

6.1.5.2 Test Waveforms

Swept frequency tests use low amplitude sinusoidal current that is injected at an aircraft attachment point. The current is frequency-swept or frequency-stepped in a defined frequency range. The frequency range needed to characterize lightning induced transients depends somewhat on the aircraft, the coupling mechanisms between the airframe injected current and the internal areas of the aircraft, and the interaction with wires in the aircraft. But in general, the lowest frequency of the range should be of the order of 100 Hz to determine the diffusion and structural voltage characteristics. The highest frequency should be on the order of 50 MHz, to determine aircraft and wire bundle resonance effects. Coupling and resonant effects above this frequency are not significant for lightning because the lightning environment spectra are decreasing at 40 dB per decade at these frequencies.

The injected current amplitude should be high enough to measure transfer functions with adequate signal to noise ratio. The injected current with a given RF power amplifier output power rating will vary with frequency. The injected current will be high at low frequencies where the aircraft and return conductors have low resistance. At higher frequencies, the injected current will decrease as the inductive impedance of the aircraft and return conductor circuit increases. Through the aircraft resonances the injected current will vary widely.

6.1.5.3 Instrumentation

A swept- or stepped-frequency signal generator is the current source. The signal generator output is typically amplified by a wide-band RF power amplifier to produce the current injected into the aircraft at one attachment point. The RF power amplifier must operate into a highly mismatched load, since the impedance of the aircraft and return conductors typically is low-resistance and inductive at lower frequencies, but then varies widely through the airframe resonances.

A current transformer is installed on the conductor that connects the output of the RF power amplifier and the aircraft. This current transformer is connected to the reference channel of the network analyzer, which measures the injected current. In some cases more than one current transformer may be used, to provide adequate operating bandwidth for the frequency span of approximately 100 Hz to 50 MHz.

The test probe is installed to measure shield current, wire current or wire voltage, depending on the desired transfer function. The test probe may be a current transformer or voltage probe, and once again, more than one probe may be used for a single test point to provide adequate operating bandwidth and sensitivity over the entire frequency range.

The measurement instrument is typically a vector network analyzer that measures the amplitude and phase of the test probe relative to the reference current injection probe. Most vector network analyzers use phase-locked detectors, narrow measurement bandwidth, and repetitive sampling to assure adequate signal to noise and dynamic range. In the case where a current transformer probe is used, care must be taken that the measurement not be influenced by the insertion impedance, especially at the low frequency part of the spectrum.

Wide-band analog fiber optic links are often used to connect the current or voltage test probe to the network analyzer. A short coax cable is then used between the test probe and the analog fiber optic transmitter. The output of the fiber optic receiver then drives the network analyzer input. The fiber optic link eliminates unwanted current on the test probe wires between the aircraft and the instrumentation. These currents can be a significant source of measurement noise. The analog fiber optic link must have operating bandwidth the same as the desired transfer function bandwidth.

6.1.5.4 Measurement and Data Recording

The induced transient responses are measured as transfer functions relative to the input current at the attachment point of the aircraft. As such, the transfer function is independent of the lightning current component. It can be used to determine the induced transient response on aircraft wiring by multiplication by the A, D, D/2, or H frequency spectrum and inverse-Fourier transforming the product. It is very important that data is taken at enough frequency points to accurately characterize the frequency-domain transfer function. That is, the data must be well sampled in frequency to capture the transfer function. This generally requires fewer data points at low frequency (20 to 50 points per decade) where the transfer function does not change rapidly, and requires many more data points at high frequency (100 to 200 points per decade) in the transfer function resonance frequency region. The division between high and low frequency is approximately 1 MHz.

An important part of swept frequency measurements is the instrumentation system calibration. This is not the individual test equipment calibration, but an end to end measurement of the probes, interconnecting coax cables, and amplifiers. This calibration characterizes the frequency dependent responses of the probes, wires, network analyzer, and amplifiers. The calibration transfer function $H_C(f)$ should be repeated for each probe and measurement configuration, and the results stored so that these responses can be extracted from the desired test point responses. Both amplitude and phase data should be measured for the calibration transfer function, so that loss (or gain) and line length effects can be compensated for in the aircraft transient transfer functions.

The test point response transfer function $H_T(f)$ is the ratio of the test point response X(f) to the injection current I(f) so that:

$$H_T(f) = \frac{X(f)}{I(f)} \qquad \text{(Eq. 1)}$$

where:

$H_T(f)$ = the test point response transfer function

X(f) = the test point response

I(f) = the injection current

This test point response transfer function must be corrected to remove the amplitude and phase characteristics of the probes, wires, network analyzer, and amplifiers. The corrected transfer function $H_{TC}(f)$ is:

$$H_{TC}(f) = \frac{H_T(f)}{H_C(f)} \qquad \text{(Eq. 2)}$$

where:

$H_{TC}(f)$ = the corrected test point response transfer function

$H_T(f)$ = the test point response transfer function

$H_C(f)$ = the correction factor

The data set for a swept frequency test point consists of transfer function data recorded as frequency, magnitude, and phase. The data set may be plotted as magnitude (usually in dB) versus frequency on a logarithmic frequency scale. Phase versus frequency can also be plotted. Modern network analyzer allow the number of frequency data points to be specified in frequency ranges such that the entire transfer function measurement will be well sampled.

System noise transfer functions should be measured for each type of lightning transfer function measured, in each general measurement location of the aircraft. Noise transfer functions for shield or wire currents are typically measured with the current transformer removed from the shield or wires, and placed adjacent to the wires in that aircraft location. The current transformer should be isolated from the aircraft structure.

Noise transfer functions for wire voltages are typically measured with the voltage probe disconnected from the aircraft test point and grounded to the voltage probe shield. For unbalanced, common-mode voltage probes, the voltage probe shield should be connected to the same aircraft reference point, such as structure, that was used during the test point transfer function measurement.

6.1.5.5 Measured Data

Typical measurement types consist of the following:

(1) Measurement system calibration transfer functions $H_C(f)$

(2) Wire bundle shield current transfer functions

(3) Individual wire voltage transfer functions

(4) Individual wire current transfer functions

(5) Voltage noise measurement transfer functions

(6) Current noise measurement transfer functions

(7) Input Impedance for each attachment configuration

(8) Aperture or structural voltage transfer functions

(9) Surface current density transfer functions.

A current amplitude transfer function is shown in Figure 25, along with the related noise amplitude transfer function.

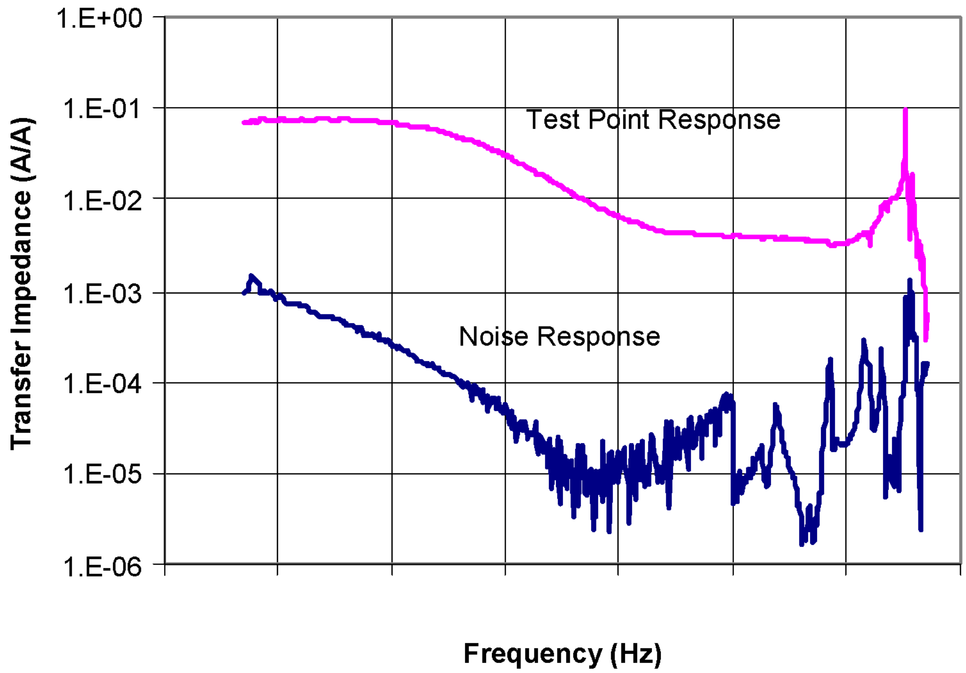

FIGURE 25 - TRANSFER FUNCTION EXAMPLE

6.1.5.6 Data Processing

The transfer function data must be processed to determine the time-domain pulse response transients for each test point. Each transfer function is multiplied by the lightning current component frequency spectrum. This product is then inverse-Fourier transformed to determine the pulse response. The lightning current frequency spectra generated at the same frequencies as the measured transfer functions simplify the multiplication.

The inverse Fourier transform must have high fidelity to deal with the wide frequency bandwidth (over five decades), and large dynamic range of the transfer functions. Typically, this means that the inverse Fourier transform must have high numerical precision, and must handle unequally spaced frequency samples in the transfer function. Many commercially available Inverse Fourier transform computational routines are based on Fast Fourier Transforms (FFT) geared to repetitive signals, with uniformly spaced frequency samples. These may be less suitable for transforming the transfer functions than special purpose integral Fourier transform routines. The selected inverse Fourier transform routine should be validated with analytical transfer functions that have similar characteristics, including frequency sample spacing, as the transfer functions that will be measured.

Additional processing may be performed to correct the data for aircraft current distribution effects caused by the return conductor configuration, or for aircraft termination impedance mismatches. Corrections are usually made by combining the measured transfer function with an analytically generated transfer function.

6.1.5.7 Data Assessment

Interpretation of the transient waveforms derived from swept frequency transfer functions is done by comparing these ATLs to the ETDLs and determining whether the requirements are being met considering margins and uncertainties. The data may also be processed to account for any differences between the test return conductor/aircraft current distribution and in-flight current distribution.

The measured transient waveforms are commonly more complex than the standardized waveforms, and may need to be approximated by a combination of two or more standardized waveforms. Figure 26 shows an example of the appropriate peak levels that would be recorded relative to the standardized waveforms.