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Aircraft Lightning-Induced Voltage Test Technique Developments

K.E. Crouch

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Aircraft Lightning-Induced Voltage Test Technique Developments

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INTRODUCTION

The increasing use of solid state electronics to perform flight control and other critical functions in aircraft has led to increased concern about the reliability of such electronics under adverse environments. The potentially hazardous environments include surge voltages induced in aircraft electrical wiring by lightning strikes. Solid state circuits operate at low levels and cannot tolerate the transients which may be induced by lightning.

To learn more about lightning-induced voltages, a series of NASA-sponsored programs was conducted. This research led to a better understanding of how lightning interacts with aircraft electrical circuits and the development of a test, known as the lightning transients analysis (LTA) test for determining lightning induced voltages in electrical circuits (Ref. 1, 2, and 3).

Since the aircraft must be available before the susceptibility of its electrical circuits can be determined by the LTA test, a need exists for analytical techniques with which to predict this susceptibility during the design phase. Contractual efforts to develop such tools have been underway since 1972 (Ref. 4). The difficulty of solving this problem analytically is recognized, and proven techniques are not close at hand.

In response to a concern about fly-by-wire system vulnerability, an LTA test was performed on the NASA-Dryden Flight Research Center (DFRC) F-8 digital fly-by-wire (DFBW) aircraft in 1974 (Ref. 5). The aircraft was subjected to electric currents which were similar in waveform to lightning strokes but greatly reduced in amplitude. The test data were then extrapolated to correspond with severe lightning strike currents. The F-8 data was widely studied and prompted positive efforts to design lightning protection into fly-by-wire control systems, including the USAF/General Dynamics F-16 (Ref. 6) and the NASA space shuttle (Ref. 7). The magnitude of the voltages measured in the F-8 and the apparent absence of a logical relationship to the injected test current has caused some skepticism regarding the validity of the basic LTA test and the authenticity of the lightning strike amplitude and waveform simulated in the test. Questions were also raised about the validity of linear extrapolation of test data to predict induced voltages under full-scale lightning stroke conditions, and about whether the test current being driven through the aircraft was in fact the primary cause of most induced voltages.

The occurence of return strokes, such as the one represented by the 2 x 50 microsecond waveform (time to reach crest x time to fall to ½ crest) used in the LTA test has been confirmed (Ref. 8).

Much less is known about the nature of streamer and leader currents occurring in the airframe, and no attempt was made during the LTA test development to simulate these currents. Whereas their amplitudes are almost certain to be less than return strokes, their rise and decay times may be considerably shorter, producing substantial rates of rise.

Flight research programs (Ref. 9, 10 and 11) are under way to learn more about these currents and other characteristics of lightning by flying instrumented aircraft in or near thunderstorms, but a number of years will be required to accumulate a meaningful data base.

The basic test concept involves subjecting the aircraft to an environment substantially representative of what it will encounter in flight and observing the electrical/electronic system responses.

The test can be divided into two major parts, (1) simulation of the lightning environment, and (2) observation of the response. If a full scale simulation can be made, then the electrical/electronic systems can be energized and provide their own response (failure, upset, etc.). Full scale simulation is not presently possible, and even if it were, it is doubtful if anyone would be willing to risk an aircraft system. Consequently, the applied test levels must be "non-destructive". This generally translates to injected peak current levels of less than 1000 amps.

These restrictions impose considerable burden on the observation of the electrical/electronic system response. Now, instead of observing system performance, system measurements must be taken, analysis of system circuits made, and extrapolated predictions of system response made. Most of the induced voltage test programs completed to date have been performed at reduced levels.

In response to these questions, NASA sponsored further work aimed specifically at investigating the relationships between variations in the simulation circuits and responses of the aircraft wiring induced voltages. The results of that work was reported in 1980. The present effort is an extension of that effort and attempts to resolve some of the additional questions raised during that effort. The program used the NASA F-8 aircraft as a test bed to be able to compare present results with prior tests. Contemplated changes in simulation techniques were made at Lightning Technologies, Inc. using a one tenth geometric scale model of the F-8. The results of this work was applied to full scale (geometric) tests conducted on the F-8 at Dryden. Assistance in analyzing instrumentation requirements was provided by The Charles Stark Draper Laboratories under separate NASA funding. The program was conducted during the period November 1981 to September 1982.

OBJECTIVES

The implementation of lightning protection on aerospace vehicles affects both the electronic and structural system designs. At the present time, lightning test techniques for evaluation of structural damage and fuel system hazards are available (Ref. 12) and in wide use. Test techniques for the evaluation of lightning indirect effects on aircraft electrical/electronic systems are not accepted or widely used. This program is one in a continuing effort to improving the understanding of this phenomena and to develop induced voltage test techniques that will be widely accepted and used.

The present program focuses on two areas of concern. The first continues work toward understanding the cause/effect relationship between the applied test waves and the resulting induced voltages. The second addresses the problems associated with obtaining accurate and reliable induced voltage measurements under two major constraints: 1) allowing the aircraft to be several 10's of kilovolts relative to the hangar and 2) shrinking the instrumentation to a size compatible with the space available inside a modern aircraft.

The overall program goal is to develop a test technique for nondestructively measuring the induced voltage levels in an aircraft. The technique must have widespread acceptance and the equipment required must be safe, reliable and relatively low cost. As the program continues, developments and concepts are evaluated by performing tests on the NASA/DFRC F-8 DFBW aircraft. Data obtained can be compared and evaluated in terms of past work carried out on the F-8 at Dryden.

The specific objectives of the effort reported here were to:

- Understand transverse electromagnetic (TEM) travelling waves between the aircraft under test and its various current return paths and resolve the apparent slow transit times noted in the previous effort.
- Extend the development of the inductor capacitor (LC) ladder network generator for longer pulses and include a cloud simulation.
- Investigate repetitive pulse test techniques.
- Determine the optimum number and placement of return conductors around the test aircraft.
- Investigate the upper frequency response of aircraft wiring to establish instrumentation bandwidth limits.

THE LIGHTNING INDUCED VOLTAGE TEST TECHNIQUE

Due to the number of investigations that have been carried out and the changes proposed to the basic test procedures, it does seem appropriate at this time to summarize the present concensus of what would be the most appropriate way to conduct a test. It is recognized that all of the votes, so to speak, are not in and further changes will be forthcoming. However, the last report of technique procedures was published in 1974 (Ref. 3) and a current revision is certainly appropriate.

SAFETY

Aircraft operations always have and probably always will be subject to some risk. Consequently, safety has always had a high priority around aircraft operations. The same is true for induced voltage or any other lightning simulation testing conducted on an aircraft system. The following paragraphs establish guidelines for conducting safe tests. Only those aspects of safety related to the high voltage testing are covered. Other hazards normally encountered in the facility are covered by the established safety rules of the facility.

Simulated lightning testing, even though applied at reduced levels, involves the use and operation of high voltage equipment including capacitors and arcing switches. The electrical energies involved and the manner in which they are used far exceed the levels necessary to cause human fatalities. Consequently, precautions must be taken and test procedures followed which insure that during the test applications, personnel cannot come in contact with any electrically energized parts of the test circuit.

A secondary concern is the inherent danger of passing substantial currents through an aircrft fuselage containing fuel. This concern includes the problems associated with electrical arcing taking place in an area where fuel vapors may be present.

The following paragraphs give the specific details concerning practices to be followed during tests.

High Voltage Safety

Personnel Familiarization. - Prior to the start of active testing all personnel working in the area, those assigned to the test as well as those normally working in adjacent areas, should be assembled for a safety briefing and familiarization with the project. At that time each person should be given a copy of the write-up "Personal Safety - High Voltage, High Current Test Area Operations", copy of which is contained in Appendix 1.

Test Area. - The aircraft, test generators, waveshaping circuits, HV power supply, and capacitors will all, from time to time, be energized to potentially dangerous levels. Therefore, these items will be contained within a perimeter defining the test area. This area shall be fenced or roped off in such a manner as to preclude any person standing outside of the rope, to come in contact with any of the above listed items or any other point. No one shall enter the test area without the permission of the test operator.

A safety ground point must be established to which the facility ground, test circuit power supplies and grounding stick can be connected. This point may also serve as an instrumentation ground reference point. The grounding stick which is used for personnel protection, shall be constructed of a metal shepherd's hook connected to a wire braid which runs to the grounding point. The handle shall be made of non-conducting material (i.e., plastic pipe or rod).

Test Procedures. - High voltage test equipment shall be operated only by qualified and previously designated personnel. Prior to commencing a test, the operator and one observer shall be stationed at points outside of the test area. From their observation points, the two will verify that no one is inside the test area. If the two of them do not have an unobstructed view of the entire test area, a third observer shall be stationed on the test area perimeter as required.

Once the test area has been cleared of personnel, the test operator shall enter, remove the grounding stick, return to his station and carry out the test. At the completion of a test or a series of tests, the operator will shut down the HV power supplies, enter the area and ground all potentially energized points before allowing any others to enter. The ground stick shall be hung on the aircraft pitot boom or other current injection points between tests.

Fuels Safety

Fuel Tanks. - Since the aircraft will usually be an operational aircraft, residual fuels will be present in the tanks, lines and vents. Since a fuel-air mixture is required to support combustion, it is recommended that the tanks be completely filled with fuel to eliminate as many fuel air areas as possible. In addition, the remaining air spaces should be purged and maintained under dry nitrogen pressure during the test period.

Open Arcs. - An attempt should be made to insure that all switching arcs around the aircraft, including the switching gap, be restricted or enclosed. However, some tests may require or result in an open arc. Consequently, it will be very important for all personnel to be aware of and on the watch for fuel spills or fuel vapors in the test area. No test shall be conducted with fuel leaks or spills in the area. Testing can resume only after the spills or leaks have been repaired and/or cleaned up. The source of any fuel vapors in the area must be identified and dealt with prior to proceeding with the tests.

SIMULATION

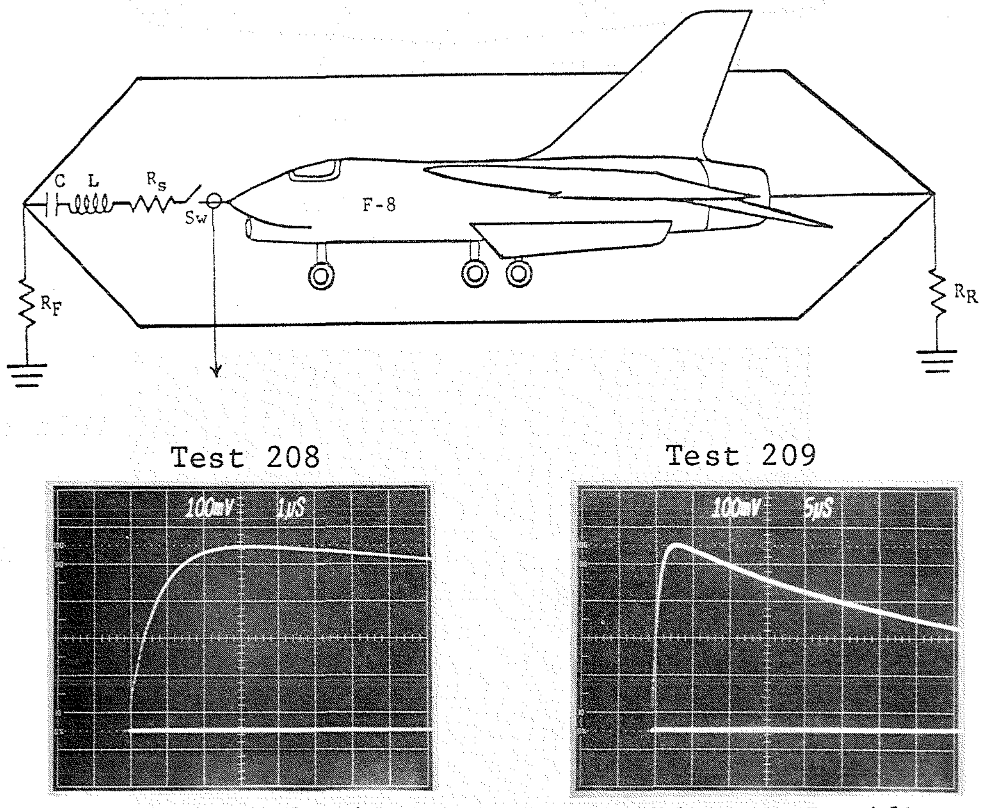
At the present time, there is much discussion surrounding the simulation aspects of lightning induced voltage testing. Some investigators, recognizing the complicated interactions of the electromagnetic fields surrounding an aircraft in flight during a lightning strike, refer to ground tests as stimulations rather than simulations. An aircraft sitting on a hangar floor is vastly different from one in flight. It is not the intent here to resolve these differences. The following paragraphs describe methods of obtaining an electromagnetic environment that is the most representative and repeatable between test sites when established in a readily available facility.

The electromagnetic test environment is established and controlled by the following components: Pulse Generator, Aircraft Termination and Return Circuit. Although these components are discussed separately, they are interconnected and interact to produce the final result.

Pulse Generator

Although several physical configurations can be used, the basic and fundamental pulse generator used in lightning induced voltage tests consists of a capacitor(s) charged to a preset voltage, a switch (mechanical, electrical or in the case of a Marx capacitor configuration, a set of spheres), and some waveshaping resistors and inductors. This type of generator is usually configured to establish a relatively smooth, double exponential current pulse through the aircraft with current magnitudes of 100 to 1000A and crest times of several microseconds. During this type of testing, the aircraft is normally directly connected to the return lines. Figure 1 shows a typical test configuration and test current waveshapes.

As this type of circuit is configured to obtain faster and faster current risetimes, the current waveshape begins to distort due to transmission line effects. The aircraft and the return circuit form a short transmission line. The surge impedance of this line varies as the aircraft geometry changes over its length but it probably ranges from 75 to 125 ohms. When the switch is closed and a voltage is applied to the system, the input to the aircraft appears to be approximately 100 ohms. A voltage wave whose magnitude is determined by the ratio of series impedance and aircraft system surge impedance travels along the aircraft length. Associated with the voltage wave is a current wave equal to the voltage wave divided by the surge impedance. At the termination, the system is shorted so the voltage wave reverses and the current doubles as the reflected wave returns to the input. At the front, the impedances again cause a reflection, the current again increases and another wave travels along the airframe. The actual process is complicated by the existence of the wings, tail, etc. The process continues until the current builds up to its final value as shown in Figure 2.

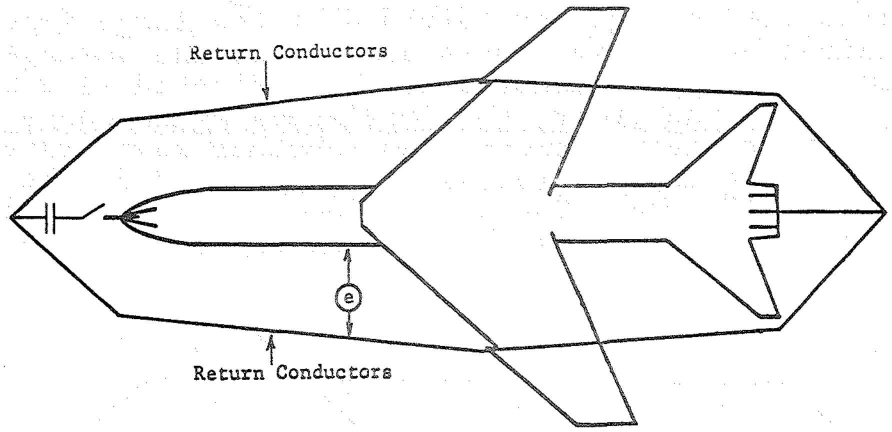


Test 208 — 100A/div 1µs/div

Test 209 — 100A/div 5µs/div

$L = 18\ \mu H$
$C = 1.5\ \mu F$
$R_s = 45\ \Omega$
$E_s = 25\ kV$
$R_f = 120\ \Omega$
$R_R = 130\ \Omega$

Figure 1 - 2 x 50 µs Return Stroke into Aircraft Terminated with Short Circuit.



Idealized Test Circuit

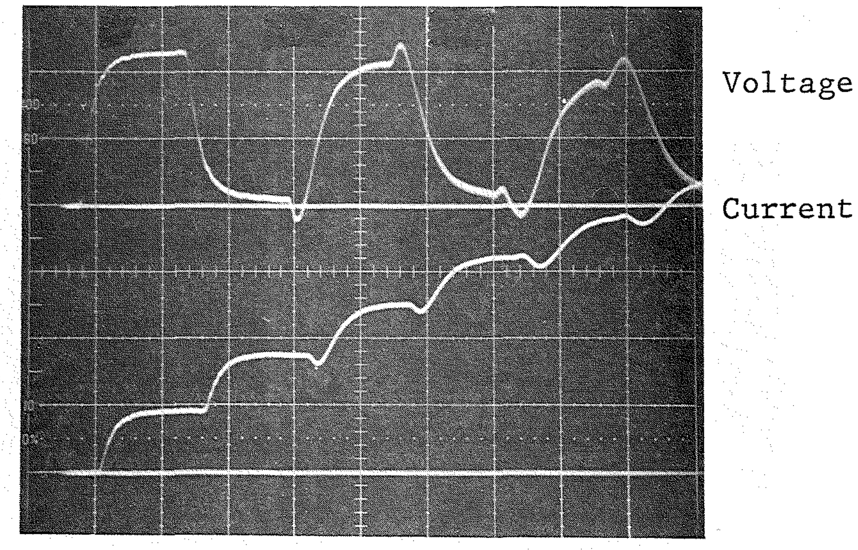


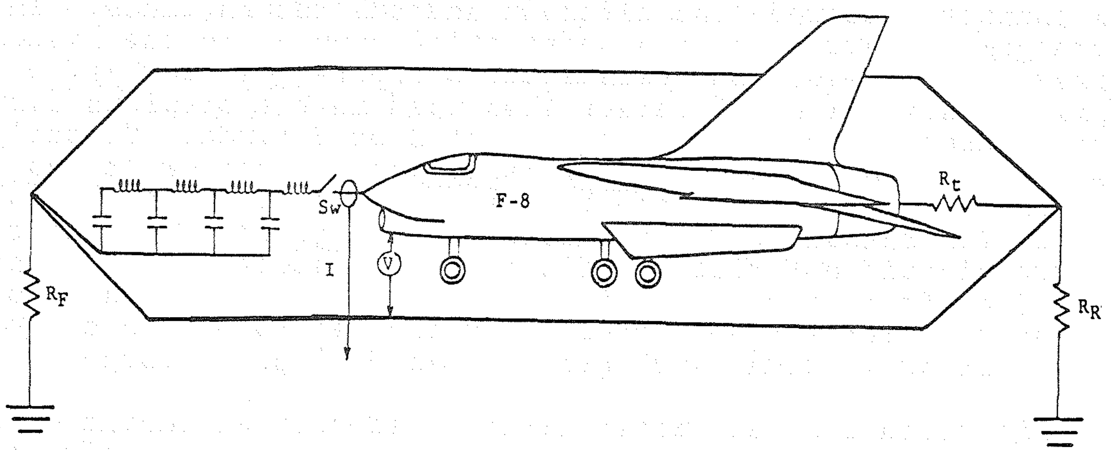
Figure 2 - Voltage and Current Travelling Waves on an Idealized Test Circuit; as Observed at the Center of the Fuselage

To control this phenomena and obtain a current wavefront with a relatively smooth double exponetial, an aircraft termination resistor, approximately equal to the system surge impedance is connected between the aircraft and the return lines. This arrangement introduces two substantial changes in the system. First, the termination resistance, which ranges from 75 to 125 ohms, is significantly larger than used in the previous circuit and reduces the current magnitude by 2 or 3 times. Secondly, since the termination resistor is between the aircraft and its return circuit, the voltage between the two rises considerably. Since, for reasons discussed later, it is preferable that the return circuit not rise in voltage with respect to the hangar, the aircraft must rise and insulation under the wheels becomes necessary. Terminated circuits can be used to obtain current pulses of 50 to 300A, with crest times of 1 μs or longer.

Although the terminated circuit reduces the amount of reflections and hence the variations on the current wavefront, they are still present due to impedance divisions between the series inductance and the aircraft surge impedance. Also as faster rising pulses are applied, reflections from wings, etc. begin to perturb the current waveshape even more. To deal with these problems as well as to attempt to simulate the lightning channel return stroke, the LC ladder network generator was developed. The network is designed to have a surge impedance equal to the aircraft system surge impedance. Now the source impedance will equal the transmission line and termination impedance giving current pulses that crest in 130 ns. An example of an LC ladder network generator is given in Figure 3. Unfortunately, at these times, the non-uniform nature of the aircraft transmission line system begins to appear. The pitot boom has one surge impedance changing to another at the forward fuselage and cockpit area. The wings add a major change in surge impedance as well as other aircraft parts. Reflections and refractions from these areas are responsible for the various amplitude changes that follow the pulse application. Ideally, the current pulse from an LC ladder network generator would be a square wave pulse. As can be seen in the oscillograms of Figure 3, the pulse deviates considerably from the ideal.

In order to introduce higher voltages into the system, tests have also been conducted (Ref. 13) at much higher voltages by using a Marx type impulse circuit.

The type of switch used to initiate the circuit is not critical for slow risetime pulses but appears to be very important for fast rising pulses. A discussion of the phenomena is covered later in this report.

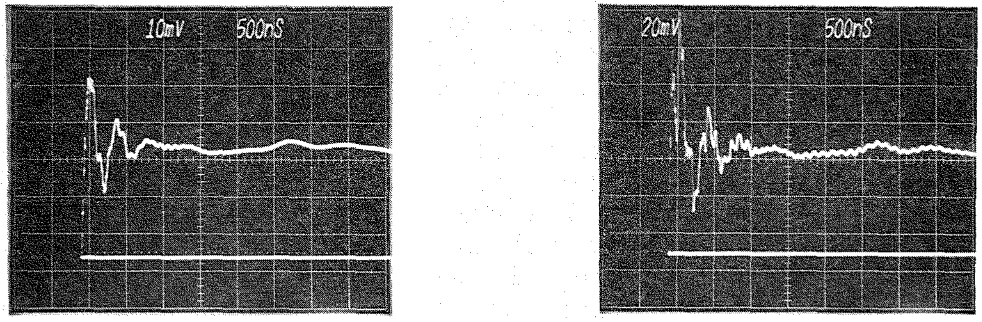


Current

Voltage

Test 230

Test 230



0.2A/div 0.5µs/div

22.4V/div 0.5µs/div

Figure 3 - LC Ladder Network Schematic and Typical Voltage and Current Oscillograms.

Aircraft/Return Line System

As stated in the previous paragraphs, the aircraft and the return lines form a transmission line system. Unless the aircraft is completely enclosed by a cylindrical return conductor, magnetic and electric fields will couple to other conductors outside of the system such as steel in the hangar floor, metal walls, etc. Energy coupled to these systems will cause transmission line travelling waves to propagate on these systems as well as the primary system. Reflections and refractions in the external systems will show up in the measurements made in the primary circuit. The number of return conductors used, their spacings with respect to the aircraft and the floor and the proximity of other conductors will govern the external transmission line interference problem. Usually, the aircraft geometry, the need for access to the aircraft, hangar configuration and other physical factors will have as much to do with return circuit configuration as the electrical requirements.

As shown later in this report, 4 to 6 wires strung under and along side the aircraft with an equal number above the aircraft are about the optimum number. Wires must also follow the wings out to the tips, both above and below the surfaces.

To reduce the interference due to reflections and refractions on the external transmission lines, both ends of the return conductors should be connected through resistors to building ground/steel. Values of 100 to 150 ohms are usually sufficient. These resistors will absorb the energy coupled from the primary test circuit to the external circuits. To determine how much energy is involved, make two measurements of the oscillatory voltage at the input point of the aircraft with the aircraft open circuited. Compare oscillograms of this voltage with and without the return circuits resistively connected to the building. The rate of decay is a measure of energy loss. If the circuit oscillations die out in 1 to 2 cycles with resistors in place but last much longer without them, then more return conductors are needed. The best attainable is probably 4 to 6 cycles. Further discussions on this problem is given later in this report.

Terminations

The main concern for the termination resistance is to be sure that it is a low inductance component and has sufficient energy capability to absorb the energy stored in the generator. If repetitive pulses are being applied, power handling capability may also be a concern. Series parallel combinations of carbon composition 2-watt resistors have been used effectively. In pulse applications each resistor can safely dissipate 10-watt-seconds or joules of energy. A 0.5 μF capacitor charged to 50 kV stores 625 joules, so 63 resistors are needed to terminate the circuit.

RESPONSE/MEASUREMENT TECHNIQUES

To accurately assess the results of an induced voltage test, two sets of measurements are required. The external electromagnetic environment must be recorded as well as the internal wiring response. In the majority of cases, the same or similar types of instruments are involved in both measurements. The main difference between the two measurements will be magnitude with the external measurements in 100's and 1000's of amperes and volts and the internal measurements in amperes and volts.

Sensors

Probes for measuring voltage and current both outside and inside the aircraft require careful selection or fabrication. Input currents to the aircraft are usually measured using current transformers at the attachment/entry point or the exit point. For slow rising current waves, the point of measurement is not important as the current entering will equal the current exiting. At risetimes of less than 2 μs, the input current will differ substantially from the exit current. At the higher frequencies, the aircraft return line transmission line tends to act as a low pass filter due to the shunt capacitance. Also, reflection and/or refraction currents may not be evident at the rear of the aircraft. It is always prudent to measure and compare input and output currents; and fast risetime pulses must always be measured at both ends.

Current transformers with adequate magnitude range and frequency response are commercially available from several sources. Shielding and insulation are necessary with the configuration depending on the type of data link used.

It is not possible to make total aircraft current measurements at points along the fuselage. It is possible to make surface current density measurements. Probes are commercially available or can be constructed (Ref. 14 and 15) to measure the magnetic fields at the skin surface. The summation of these fields equals the current. Measurements of the waveshape of current on the wing, for example, may be necessary in order to accurately understand the response of circuits in those areas.

In addition to the information concerning currents on the aircraft skins, voltages surrounding the aircraft are also useful in describing the electromagnetic environment. Probes for this purpose are usually most effective if they are constructed for the specific measurement. Resistive probes with values 10 times the surge impedance will not appreciably affect the system simulation. However, the physical configuration of the probe can be important. During the testing, the electric and magnetic fields will exist in the space between the aircraft skin and the return circuit and/or the building ground. If the length of the resistive probe used to measure the electric field is significantly smaller than this distance, it will alter the field configurations at the point of measurement. If a measurement of the electric field (voltage) between the fuselage and a return conductor is required, the probe must be in that physical location. Using wire leads to transfer that voltage to a probe physically located at another point will also compromise the measurement.

An effective method of making a voltage probe for such measurements is to string a series of 2-watt carbon composition resistors across the gap to be measured. Strings of one hundred 47 ohm resistors have been used quite effectively for distances of approximately one meter. The number of resistors and the values used will depend on the circumstances at the point of measurement. The string is used as a voltage divider by differentially measuring the voltage across one or more elements in the resistor string.

Measurements can also be made using commercially available capacitive field probes. These must be positioned properly to insure that the resulting data really represents the fields of interest. If possible, the surface field at the aircraft as well as the field at the return line should be measured.

In general, current transformers or resistive shunts and voltage dividers give direct data (currents and voltages) while field probes give derivatives of the measured quantity. Depending on the sophistication of the instrumentation system, this may or may not be a problem.

Internal or system response sensors are, in general, the same as the external sensors except that the magnitudes to be measured are lower and the physical space available for the sensor is smaller. Many times, the circuit under the observation will be powered. In those cases, the power and/or operating voltage levels will have to be filtered or blocked out of the measurement since the typical induced voltage will be 1-10 volts, while the operating voltages may be 10's or 100's of volts. Internal electric and magnetic fields may also be measured using field probes of appropriate range.

Data Links

The first LTA tests used twin coaxial cables to transmit the induced voltage signals from the aircraft to an oscilloscope. Current measurements were also carried in coaxial cables. To obtain good frequency response characteristics, these coaxial systems must be operated at 50 ohm (surge impedance) levels. Since the induced signals were low, the cables were connected directly to the circuit under test. Consequently, all circuit data reported were taken with 50 ohm loads on the circuit. If this impedance level does not affect the circuit response, and if the aircraft is essentially operated at ground potential, the use of coaxial, direct connected cables can provide a simple, reliable means of transmitting the data during slow front tests.

For tests where the airframe is elevated substantially in voltage, the direct connection systems will not work. Two alternatives then exist - placing the recording instrumentation in the aircraft or transmitting the data out on a non-conducting medium. Most researchers use analog light pipe (fiber optic) systems for this function. Commercial systems are available with various capabilities. A system with appropriate bandwidth characteristics for the particular test conditions must also be selected. Care in use involves monitoring of dynamic range. Most systems operate over approximately -1.0 V to +1.0 V. Signals exceeding these levels will be distorted. With appropriate attenuators and sufficient care taken, this limitation can be tolerated.

Other data links, such as on site, flash analog to digital (A/D) conversion with digital light pipe link, frequency modulation (F/M) telemetry and repetitive pulse equivalent time sampled data systems, have been discussed but no practical hardware exists at this time.

Recording/Analysis Instrumentation

Much of the existing lightning induced voltage data has been obtained using photographic recording of oscilloscope traces. High speed flash A/D converters have also been employed with the data analyzed immediately on digital computers. The degree of sophistication attainable in this area is probably limited only by the funds available for the effort.

Measurement Techniques

The two primary lightning parameters, voltage and current, as well as the response parameters, must be monitored during tests. Voltages are primarily measured using voltage dividers, and currents are measured using pulse current transformers or resistive shunts. The output of these devices as well as other sensors, are usually low-level analog voltage signals which are transmitted to oscilloscopes on coaxial cables. In some laboratories, the sensor outputs are transmitted over fiber optic links to digitizing electronics for computer processing. The common objective of all systems is an accurate and complete record of sensor outputs during the performance of a test. Two measurement-system parameters are important; signal-to-noise (S/N) ratio and bandwidth.

At the final measurement-system recording point, the signal is very low (1-10 V across 50 Ω) compared to the generator test voltages and currents. Consequently, shielding is very important.

For example, oscilloscopes and other data acquisition equipment are usually placed inside a metallic shielded room and coaxial cables are routed inside of metallic conduits. The use of fiber optic links reduces the need for cable shielding, but optic transmitter and receiver shielding must be carefully designed. No matter what means are used, a noise check is required where the sensor inputs are shorted together and a simulated lightning test is applied to measure the resulting noise. Such a noise measurement will establish the S/N ratio for a particular configuration. Since all relevant transfer functions are linear, the S/N ratio cannot be improved by increasing the simulated lightning test level, unless the noise level is inherent in the measuring system (e.g., white noise in a fiber optic receiver).

Measurement system bandwidth or response time is the other important paramter. Oscilloscopes and data acquisition equipment with bandwidths of 100-400 MHz are not uncommon. The total measurement system bandwidth is a function of all the elements in the system: sensors, transmission system, and recording equipment. A measurement-system response time measurement is, therefore, normally made to check the response, especially if the data are expected to contain high frequency components (>20 MHz)

Data Interpretation

One of the most crucial and controversial parts of the lightning induced voltage test is the interpretation or scaling process. The assumption basic to the test is that the electromagnetic coupling responsible for the measured data is a linear phenomena. The external and internal magnetic fields are contained within or propagating in a non-saturable medium. Therefore, the coupling or transfer function for electromagnetic energy is linear. Consequently, if the driving function parameter is increased by a certain factor, then the response will increase in a like fashion-provided that increase does not drive the circuit into a nonlinear region. A zener clamped circuit will not rise to 10 times the zener diode voltage because the dynamic impedance of the diode drops, redistributing the voltage distribution in the circuit. In general, induced voltage measurements are reported and scaled by the test laboratory to some appropriate factor without regard to the impact of circuit non-linearities. The equipment design engineers must then evaluate the data in light of their knowledge of the circuit performance and determine what will actually happen in the circuit and predict the upset, failure or degradation response.

Lightning induced voltage data is normally scaled to "average" and "severe" lightning strike models. An average stroke has a peak of 30 kA and a 22 kA/µs rate of rise. A severe stroke has been defined to have a 200 kA peak and a 100 kA/µs rate of rise. The maximum rate of rise for a double exponential waveshape theoretically occurs at time zero and will be equal to the charge voltage divided by the total circuit inductance. In practice, parasitic capacitance and the distributed nature of the circuit inductance, shift the maximum di/dt point to a slightly later time and reduce it a few percent. The rate of rise drops exponentially as the crest value is approached, so an approximate average rate of rise can be obtained by dividing the peak current by 75% of the crest time (94% of the rise time).

Crest times are determined in IEEE Standard No. 4 as rise-times (10-90%) multiplied by 1.25. A current pulse with a 1 μs crest time can be extrapolated to 30 kA and 22 kA/μs to represent an "average" lightning stroke and a 2 μs pulse extrapolates to a severe stroke of 200 kA and 100 kA/μs. In both of these cases, the same extrapolation factor can be used for peak current effects and rate of rise effects.

When using the LC ladder network generators, the rate of rise will usually not be in the same proportion as the peak current. In most tests, the rate of rise will be quite fast compared to the peak current. For example, a 400 amp, 125 ns (crest time) LC ladder network current pulse will have a 500:1 peak current extrapolating to a "severe" stroke.

If different extrapolation factors do exist, then an analysis of the data obtained must be made to determine if the response obtained is related to current peak or rate-of-rise. Sometimes measurements must be made with different waveshapes to identify the driving function. Once that assessment has been made, then the appropriate scale factor can be applied.

In most instances, the double exponential wave will be the easiest to apply since a common scale factor can be used. This will only be true as long as the standard "average" and "severe" stroke definitions are used. Recent data (Ref. 16 & 17) has been published by several lightning investigators indicating that lightning current risetimes may be many times faster than the current "severe" stroke. Tests representative of these risetimes can probably only be performed using the LC ladder network generator.

SUMMARY OF THE TEST TECHNIQUE

The preceding paragraphs give several options for the conduct of a lightning induced voltage test based on the requirements of the project. The rationale for various concerns and procedures are also included. The following paragraphs are a set of functional guidelines intended to tie all of the discussions together.

- A lightning induced voltage test will most likely be performed for one of two reasons: to check a design or to obtain data to determine a protection design. Based on the test objectives, a decision as to what type of test waveform is most appropriate and what extrapolation level to use must be made.

- The next step will be to prepare a safety plan and test plan for the effort. The information to be gathered and the circuit locations to be tested will be contained in this plan. Some time must be allowed for changes or additional data points to reinforce questionable data obtained during the test.

- The aircraft must be positioned and insulated as required in an appropriate test area. Fuel systems must be protected by the purging and inerting procedures. Electro-explosive devices must be pinned and protected.

- Return circuit conductor holding fixtures must be constructed and the return circuit conductors attached. Install pulse generator switch, and terminations. Position safety fence and warning systems. Position instrumentation, data links, sensor-both external and internal. Establish safety ground point and ground stick. Connect, but do not energize the power supplies.

- Hold the safety briefing and assign operator and safety personnel positions. Familiarize everyone with system and safety precautions. Establish the order of the operating procedures and be sure that all are familiar with the sequence of test events.

- Begin the testing with sensor and waveshape checks, noise verifications and system response as necessary.

TECHNIQUE INVESTIGATIONS

The following paragraphs report the results of the work carried out under this contract effort. The program is basically an extension of the work started under contract NAS4-2613 and reported in NASA CR 3329 "Improved Test Methods for Determining Lightning-Induced Voltages in Aircraft", September 1980. The experimental work conducted here used essentially the same basic equipment configurations as reported earlier and the reader is referred to that report for a complete description of the aircraft and its associated test circuits. Specific changes in the circuits will be elaborated here.

The work carried out during the current effort falls into both the simulation and the response area. The results are reported under those headings. The majority of the work was carried out in the simulation area.

SIMULATION STUDIES

The following efforts were carried out to obtain a better understanding of the interactions between the aircraft and its external environment. The goal of a simulation is to faithfully reproduce an external environment which will result in an internal response which is representative of that obtained where the aircraft is subjected to the natural environment.

Travelling Wave Transit Times

During the previous work, it was noted that the transit time/oscillation frequency of the aircraft system did not correspond with the aircraft length in terms of the speed of light. If the electromagnetic waves around the airframe are essentially propagating in the air, Maxwell's equations state that their velocity must be that of the speed of light. Several other investigators also noted the same observation without a good explanation. Consequently, a literature review and an experiment was formulated to investigate the phenomena further.

Transit Time Theories. - Conversations concerning probable explanations of the slower travelling wave velocities observed during the F-8 full and reduced scale tests, were held with Dr. Clifford Skouby, McDonnell Douglas, St. Louis, Missouri, Professor Thomas Trost, Texas Technological University, Lubbock, Texas, K.P. Zaepfel, NASA Langley Research Center, Hampton, Virginia, Preston W. Geren, Boeing, Seattle, Washington and William W. Cooley, Boeing, Seattle, Washington. Each of these individuals concurred with or supplied part of the following discussions.

In general, an aircraft fuselage and its return conductors, along with the hangar environment, form several coupled transmission line systems. The primary transmission line and the one of interest consists of the aircraft fuselage and the return conductors. A second set of systems consist of the fuselage and conductors such as rebar in hangar floors, concrete or earth, the steel and/or metal sheeting used to construct the hangar or test lab. Another system consists of the return conductors and all of the aforementioned conductors. In the primary transmission line, as long as the conductors are relatively parallel and of low resistance, the primary mode of wave propagation will be TEM. This implies that the electric and magnetic field vectors are perpendicular and have no components in the direction of travel. Waves travelling on other transmission lines may or may not be TEM waves due to high resistance conductors and lossy dielectrics involved. The voltage and current surges that are observed on the primary transmission line will be made up of all propagating waves. If the observed wave could be resolved into its component parts, as postulated by Bewley (Ref. 18), then the effects due to waves travelling on the non-primary transmission lines could be more easily seen. These waves, since they are propagating in regions containing substances other than air, will propagate at lower velocities governed by the respective values of permittivity and permeability.

Depending on the relative proportions of the primary wave versus the induced secondary waves, the velocity of the composite wave will be reduced from that of free space. However, the toe or beginning of the surge will travel at the highest speed of the system. As suggested by Bewley, the current and voltage waves of the system may not be in phase, with one leading the other. This may have been observed experimentally during the F-8 tests at NASA Dryden. Measurements of the time of arrival (Figure 42 and 43 in Ref. 19) indicate that the voltage wave moved faster than the current wave.

Since the overall observed surge velocities were 50% lower than the speed of light, it would appear that the wave component travelling on the primary transmission line is not more than 50% of the total wave or the resultant velocity would be higher. It can be postulated from the results of the tests that the relationship between the primary waves and secondary waves is related to the shunt capacitances of the system. When a complete cylinder surrounds the fuselage, no secondary waves will exist, but when the fuselage is surrounded by thin wires, the secondary shunt capacitance will be large and therefore the secondary waves will comprise a significant part of the observed wave.

Considering the geometry of the system and the dielectric materials involved, it is hard to believe that the secondary waves could in fact comprise 50% of the total wave and that their velocity of propagation is reduced that significantly. A more likely situation would be 10-20% contribution from secondary waves with their velocities being 20-30% slower. The combinations of these waves would not give the observed result. Consequently, a further explanation must be found.

Transit Time Experiments. - Using the test fixture shown schematically in Figure 4 and pictorially in Figure 5, controlled tests were conducted to determine the reasons for the apparent lower velocities. The fixture, which is 6.15 m (20 ft.) long, was initially configured with bare, thin wires at the center and positioned on 1.11 m (4 ft.) diameter circle around the edge. The first tests involved only two wires. Later, more edge return wires were added as well as a 12.5 cm center conductor. For each of these configurations: two thin wires, multiple returns, and large tubular center with various return wires, measurements were made of the transit times in the system.

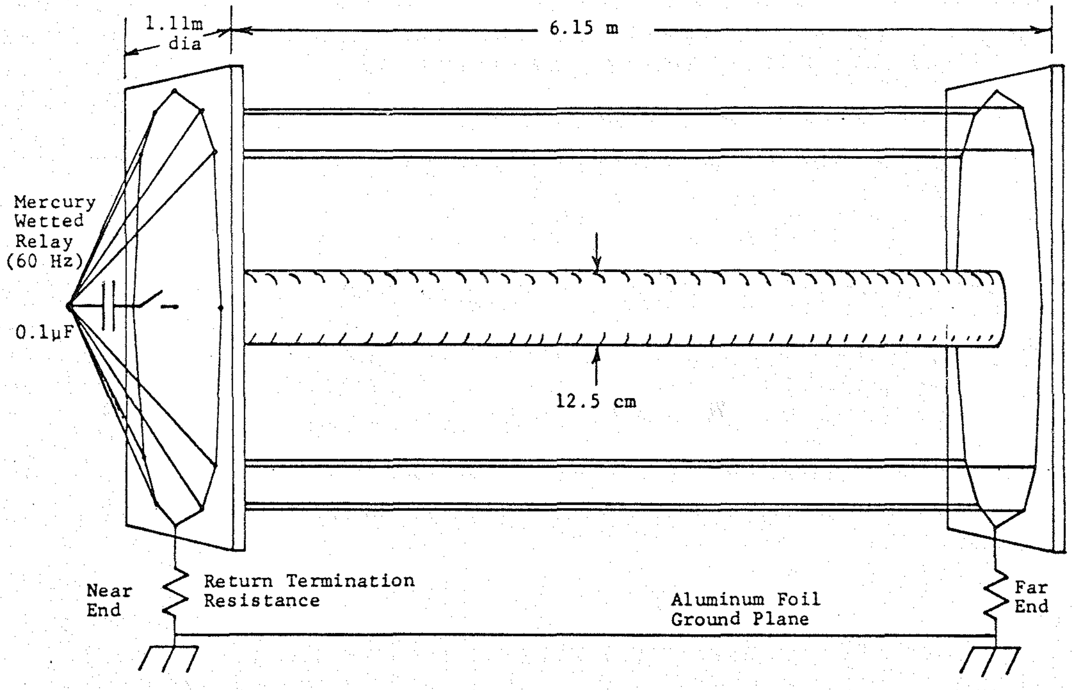


Figure 4 - Diagram of Transit Time Test Fixture.

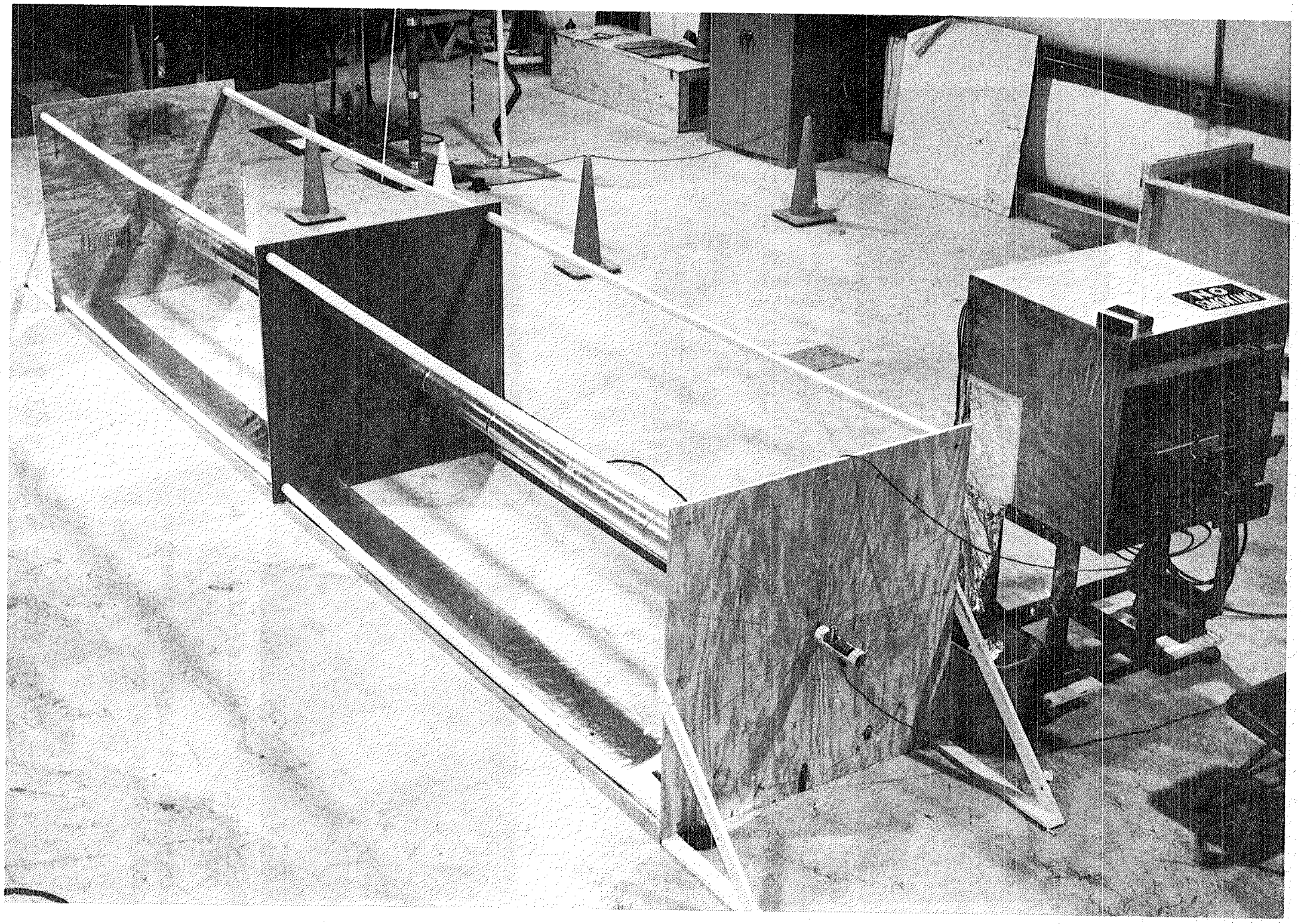
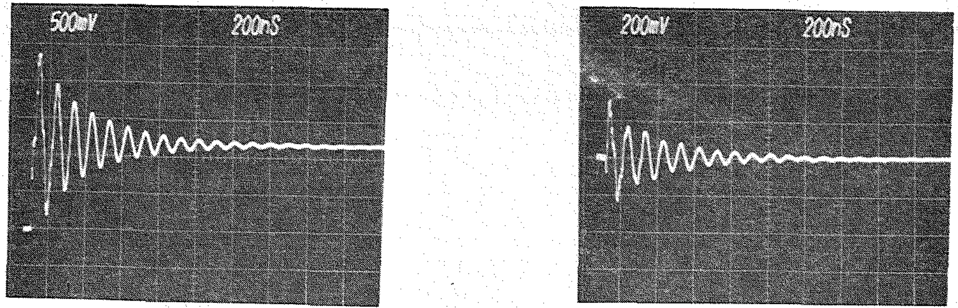


Figure 5 - Transit Time Test Arrangement

Figure 6 shows the open circuit response when two thin wires were installed in the fixture. Figure 7 shows the response with pairs of wires at 45°, 135°, 225° and 315° around the fixture. This condition is similar to the return configuration used for the previous aircraft tests.

Test 68 Test 69



Voltage 200ns/div
50V/div

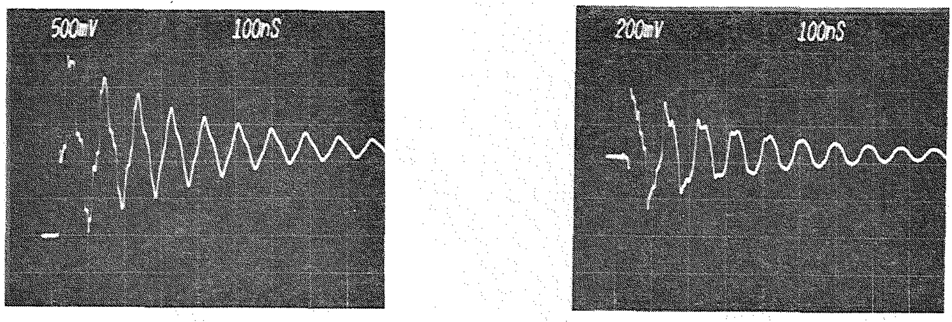
Voltage Between Wires

Current 200ns/div
4A/div

Current in Center Wire

Figure 6 - Two Wire Transmission Line-Open Circuited Measured at the Center of the Line.

Test 79 Test 80



Voltage 100ns/div
50V/div

Voltage Between Center and return wires

Current 100ns/div
4A/div

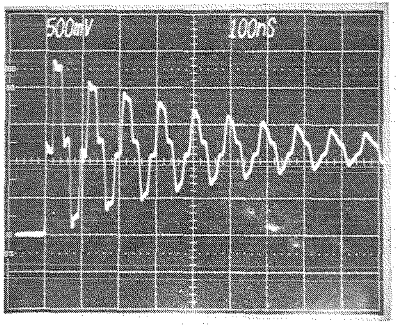
Current in Center Wire

Figure 7 - Thin Center Wire and 8 Returns-Open Circuited Measured at the Center of the Line.

Figure 8 gives the voltage measured at the center of the test fixture with the four sets of wires as before but with the 12.5 cm tube in the center.

Test 101

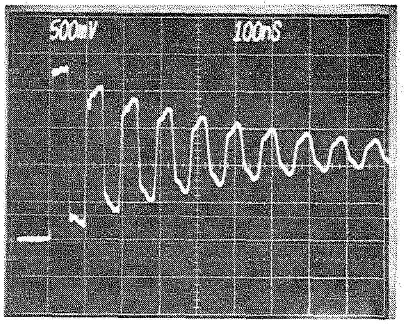
Measured at
Center of
Fixture



Voltage
50V/div
100ns/div

Test 105

Measured at
the Far End
of Fixture



Voltage
50V/div
100ns/div

Figure 8 - 12.5 cm Center Conductor and 8 Returns-Open Circuit Measured at Center and Far End of the Line.

Table II gives a summary of the transit times determined from these tests.

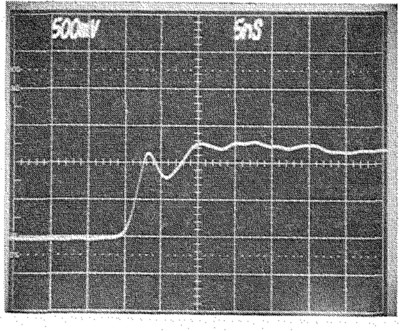
TABLE II - SUMMARY OF TRANSIT TIMES DETERMINED FROM OPEN CIRCUIT RINGING FREQUENCIES

Test No.	Description	Frequency MHz	Transit Times ns
69	Two Wire	10.3	24.2
80	8 Wires & Center Wire	10.8	23.2
105	12.5 cm & 8 wires	10.8	23.2
-	6.15 m	calc. from speed of light	20.5
-	6.9 m		23.0

From Table II, the two wire transit time is 18% longer than that calculated from a 6.9 m line, while the others are 13% longer. However, the travelling wave actually begins its propagation as soon as the switch is closed. Therefore, it starts at the switch, propagating radially out to the edge of the fixture, and distance must be measured along the entire path. In the transit time test fixture, the switch is at the center. The travelling wave must go down the face of the fixture prior to reaching the return wire. This is a distance of about 0.63 m (25 in.) which requires about 2.1 ns to transverse. Adding this distance to the 6.15 m yields 6.8, which corresponds to the 23 ns transit time. This analysis yields errors of 5% and 0.9% respectively. It appears that the transit times measured, correspond with the speed of light well within the accuracy of the ability to measure them in this experiment.

As the travelling wave reaches the edge of the fixture starting at the center, it must experience a significant change in the transmission line impedance, i.e., going from a radial propagation to a two wire propgation. A reflection, therefore, should exist as a result of this transition. Figure 9 shows the voltage as measured at the start of the fixture and there is definitely a reflection occurring in the 5 ns time frame. The reflection reduces the initial voltage indicating a negative reflection which would correspond to a reduction in the transmission line impedance.

Test 27



Measured
at the
Near End
of Fixture

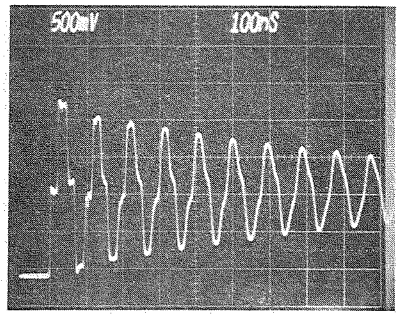
Voltage
50V/div
5ns/div

Figure 9 - Two Wire Transmission Line, Voltage Reflections at the Start of the Line.

In the previous section, it was postulated that the transmission lines formed by the center conductor and other return lines in the area would carry a portion of the travelling wave and, if higher dielectric constants and/or resistive media were present, the waves would travel at lower velocities. The present tests do not show any evidence of the slower velocities. However, this does not mean that the waves are contained between the center conductor and the return wires. Figure 10 shows the results of a test conducted specifically to test this hypothesis. The transmission line was set up with the 12.5 cm tube in the center with four pair of thin wire returns around the fixture. Strips of 30 cm wide aluminum foil were taped to the floor at the side of the test fixture and across the ends to establish a ground reference as well as provide shielding for the measurement cables. Voltage measurements were made at the center of the fixture with the return wires resistively terminated to the ground foils, disconnected from the ground foils and shorted directly to the ground foils. The ringing frequency remains the same for open circuit and terminated, but drops slightly (longer return path) for the shorted condition. Both the shorted and especially the open conditions, result in longer lasting oscillations, less decay in amplitude with time. The decay rate corresponds to the loss of energy from the circuit. The basic circuit, center tube and four pair of return wires, is where the energy is injected. When the transmission line between the return lines and ground foils contain resistance, the energy coupled to that line will quickly be absorbed (1 cycle or less). The change in the rate of decay between terminated return lines and open return lines, reflects the portion of the travelling wave energy which is coupling out of the primary transmission line (tube to return lines). This phenomena was also observed in other configurations. With the 12.5 cm tube and a single return wire above and below, termination resistors between the return lines and foils caused the oscillations to die out in less than two cycles. However, the exhibited frequencies still corresponded to transit times at the speed of light.

If the travelling waves, as observed and measured during this experiment, always propagate at the speed of light, then what can explain the lower frequencies observed during the earlier F-8 tests? To investigate this occurrence, aluminum foil strips representing wing and vertical fin were added to the transit test fixture. Measurements of the reflected waves were made before and after each addition. The complete simulation is shown in Figure 11. The dimensions of the simulated wing and tail were chosen to be proportional to that of the F-8 aircraft. The frequency of the oscillations shown in the final oscillogram of Figure 12 has dropped about 45% from the initial condition, tube only. This corresponds very favorably with the 50% difference noted in the earlier test work.

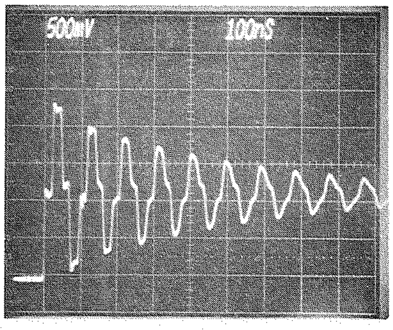
Test 117



$R_{Return} = \infty$

Voltage
50V/div
100ns/div

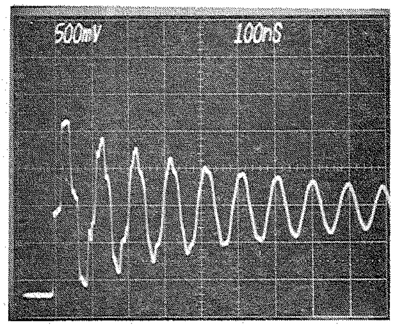
Test 116



$R_{Return} = 330\Omega$

Voltage
50V/div
100ns/div

Test 118



$R_{Return} = 0$

Voltage
50V/div
100ns/div

Note: All Measurements Made at the Center of the Fixture.

Figure 10- Comparison of Return Line Termination Configurations.

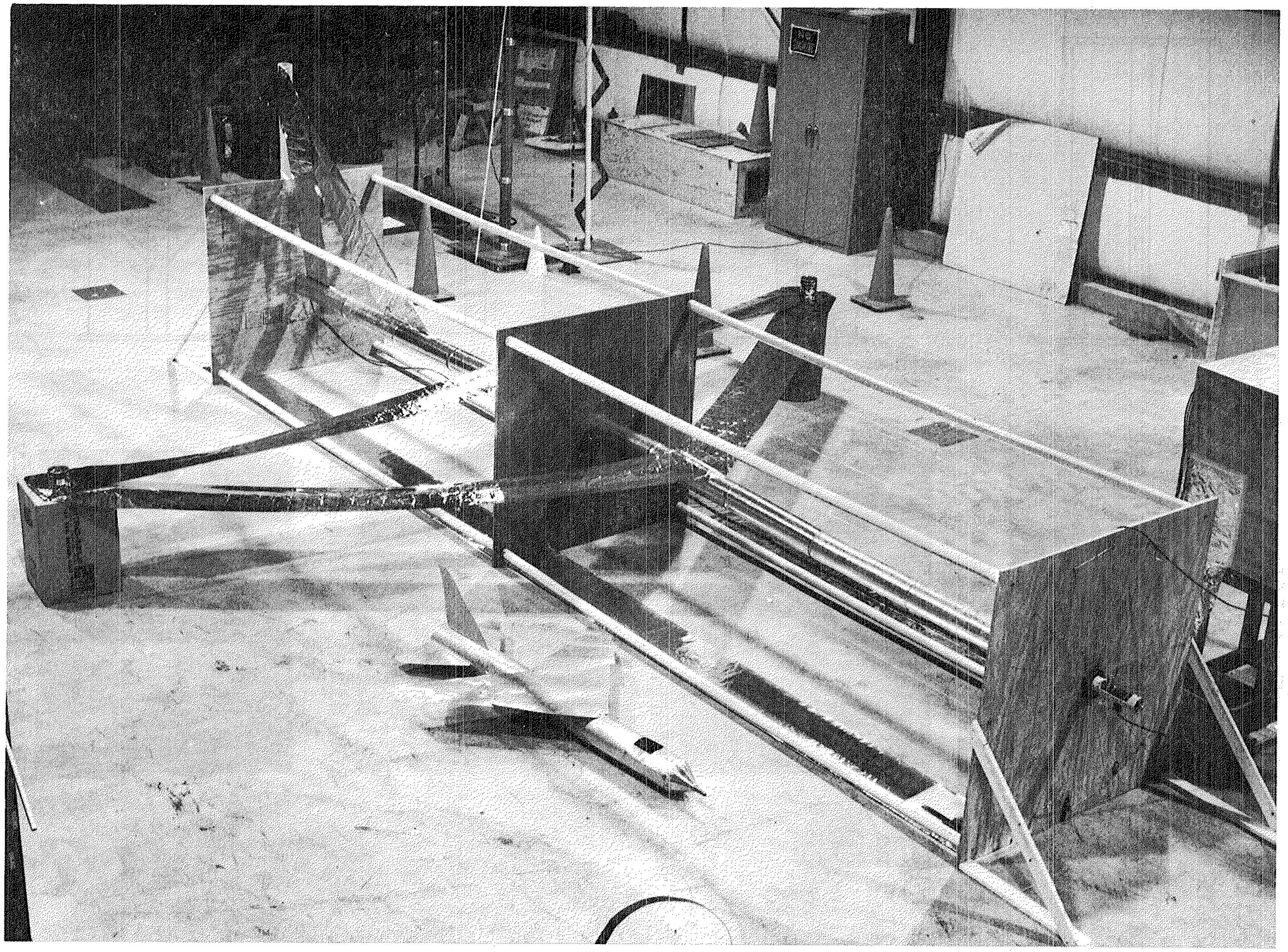
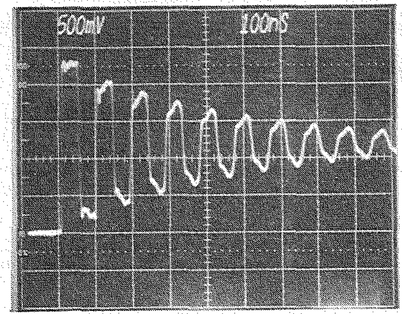


Figure 11 - Transit Time Test Fixture With Simulated Aircraft Wings & Tail.

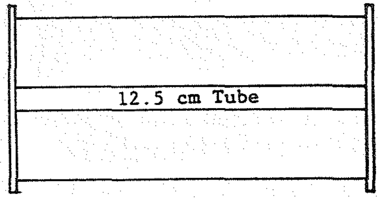
Tube & Returns

t = 23.3 ns

Test 105



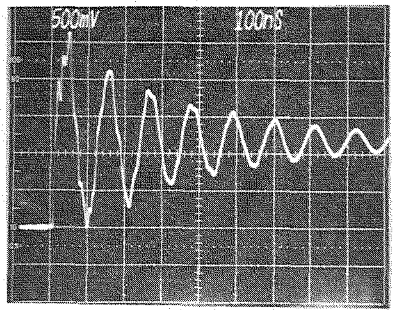
50V/div 100ns/div



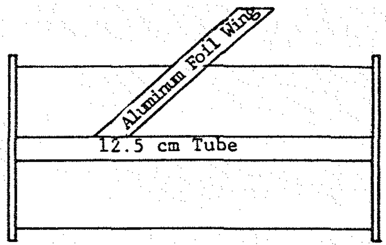
Add 1 Wing

t = 27.9 ns

Test 104



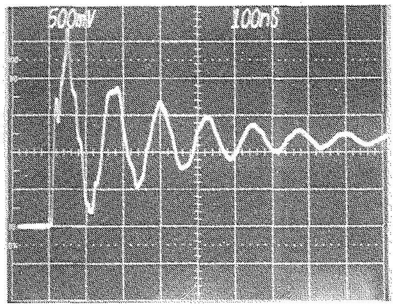
50V/div 100ns/div



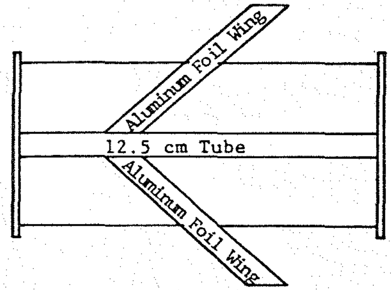
Add 2nd Wing

t = 31.9 ns

Test 106



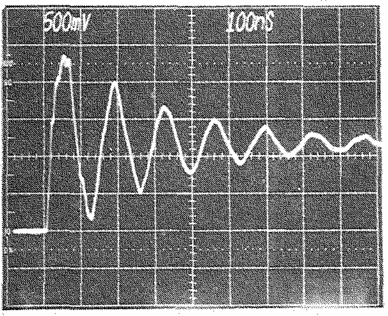
50V/div 100ns/div



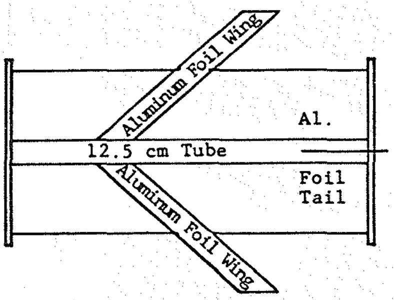
Add Tail

t = 32.8 ns

Test 108



50V/div 100ns/div



Note: All measurements at Rear of Fixture

Figure 12 - Comparison of Ringing Frequencies as a Function of Added Parts.

The travelling wave starts at the front of the fixture and propagates down the tube. When it reaches the point where the wings are attached, it experiences a substantial transmission line impedance change. Part of the wave reflects back, part refracts on down the line and part (most) propagates out along the wing(s). At the end of the wings, the wave again reflects and starts back to the fuselage. At the fuselage, the wave again refracts and reflects and proceeds on to the tail. At the tail, more refractions and reflections take place. The effect of all of these reflections is to cause the bulk of the travelling wave energy to follow a much longer path between the nose of the aircraft and the tail than would be normally suspected. Hence, it takes longer for the bulk of the wave to traverse down and back along the aircraft fuselage.

Figure 13 shows oscillograms of the voltage at the front of the fixture and the rear of the fixture. The oscilloscope was independently triggered and the same voltage probe and cables were used in both oscillograms allowing a time of arrival measurement of the voltage wave to be made. The start of the voltage waveform at the rear of the fixture is almost exactly 20.5 ns after its appearance at the front of the fixture. Also, test 110 shows a negative reflection at the front of the fixture at about 18-20 ns. This corresponds very closely to twice the distance from the switch to the leading edge of the simulated wing. The fact that the reflection is negative substantiates the assumption that the impedance drops at the point the wings attach to the fuselage. A negative reflection as produced by a lower impedance/short circuit transmission line termination will result in a ringing frequency which is related to two transit times instead of four as is the case with a positive reflection which is produced by a higher impedance/open circuit transmission line termination. The reflections also appear in the oscillogram of test 109 but are not nearly as pronounced.

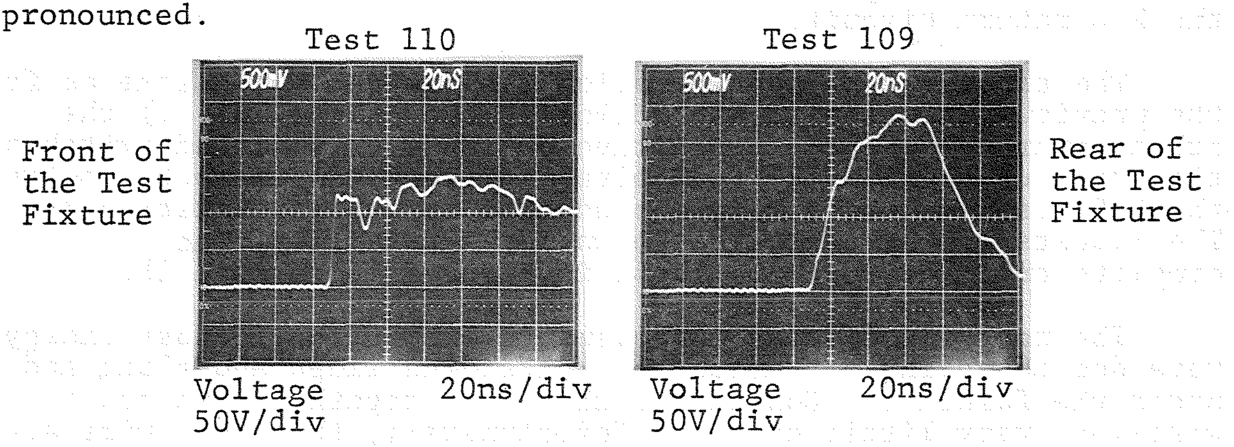
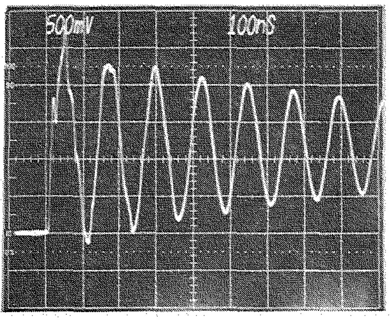


Figure 13 - Comparison of Travelling Wave Voltages at the Front and Rear of the Fixture with Simulated Wings.

It can be observed in Figure 12 that as more simulated parts are added to the tube, the Q of the circuit is reduced. This means that more of the energy is being coupled outside of the primary tube/return lines transmission line. Figure 14 verifies that indeed the travelling wave energy is being absorbed by the return line to ground foil termination resistors. The oscillogram of test 107 is taken of the same configuration as oscillogram 106 in Figure 12, except that the return line termination resistors are removed. This shows clearly that a significant coupling is occurring to transmission line systems outside of the primary system.

Test 107



Rear of the
Test Fixture

Voltage
55V/div
100ns/div

Note: Much less damping than in Test 106 (Fig. 12) where return lines are resistively terminated.

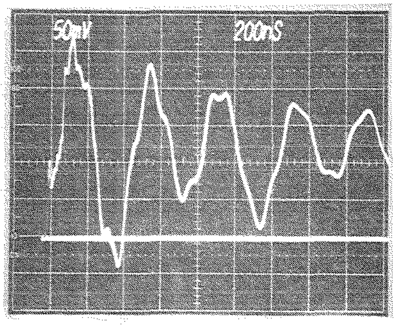
Figure 14 - Ringing Frequency Oscillogram With Return Line Terminations Removed, Simulated Wings on the Tube.

Return Circuit Conductor Configurations

As noted above and in the report from the previous effort, (Ref. 19), the return circuit conductor termination to the building ground can have a marked affect on the system performance. As a result of these findings, it was decided to experimentally evaluate the energy loss as additional conductors were added to the F-8 return circuit.

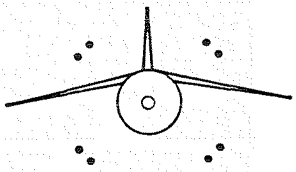
The circuit test configuration was basically the same as for the previous effort with the following two exceptions: 1) the pulse generator was the repetitive pulse mercury wetted switch of the previous section, 2) the voltage divider was connected between the F-8 fuselage and a return conductor at fuselage station 375. The results of the tests are shown in Figures 15. The complete array of wires is shown in Figures 16 through 21.

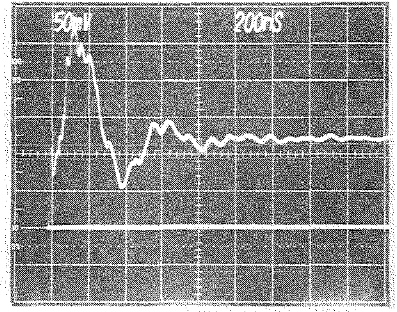
The most significant improvements (reduction in lost energy) were due to adding conductors out under the wings and along and under the fuselage. Connecting the wires together with cross wires had very little effect. Unfortunately, the final wire arrangement, shown in Figures 18 through 21 is not practical since walking to and from the aircraft for operations is hazardous due to the potential for tripping over wires.



Test 255
55V/div
200ns/div

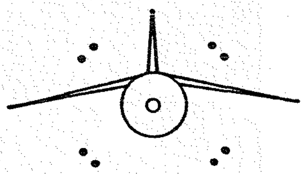
Return conductors
open at rear
shorted at front
8 lengthwise wires

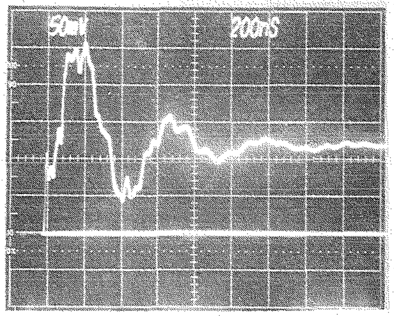




Test 254
55V/div
200ns/div

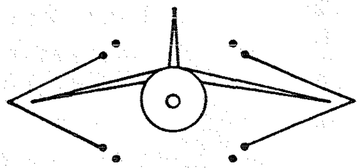
As above with
return conductors
terminated 140Ω front
150Ω rear

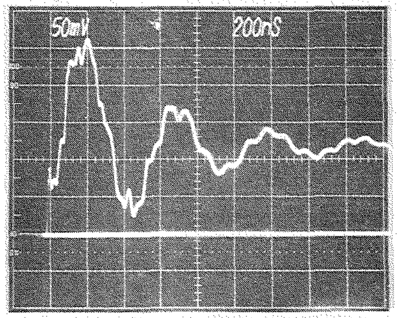




Test 256
55V/div
200ns/div

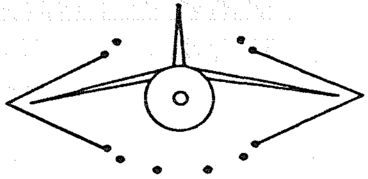
As above, with 2
wires added under
and over both wings
See Fig. 18

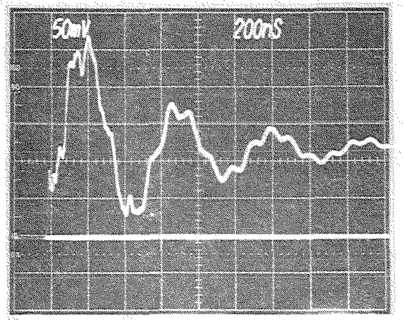




Test 257
55V/div
200ns/div

As above, with 2
additional wires added
under the fuselage





Test 258
55V/div
200ns/div

As above, with all
wires connected at
each stancion

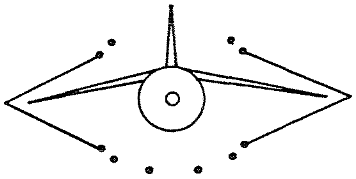
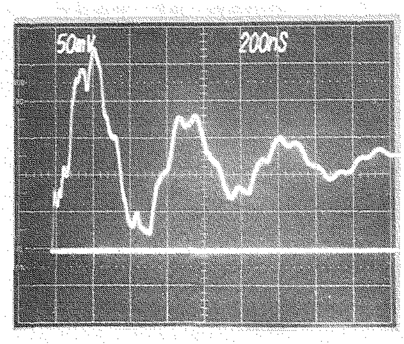
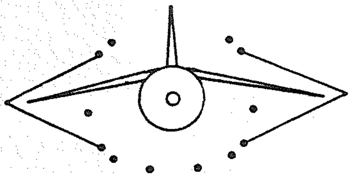


Figure 15 - Return Circuit Conductor Evaluations.

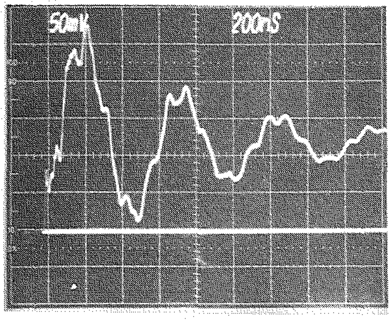


Test 259
55V/div
200ns/div

As above, with 2 more wires, 1 on each side of the fuselage

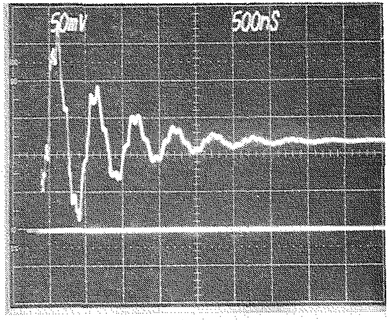


Test 260



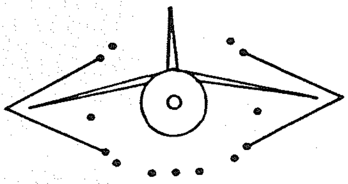
55V/div 200ns/div

Test 260

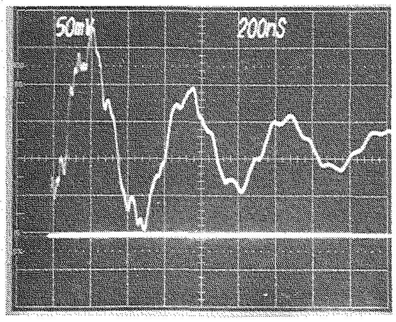


55V/div 500ns/div

As above, with 1 wire added under fuselage

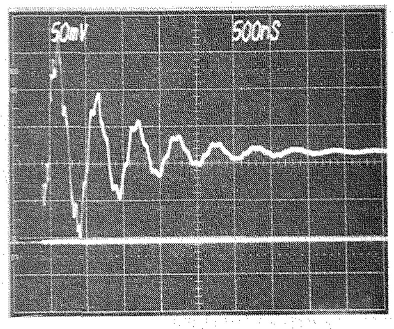


Test 261



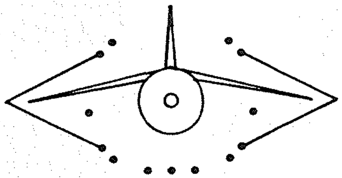
55V/div 200ns/div

Test 261

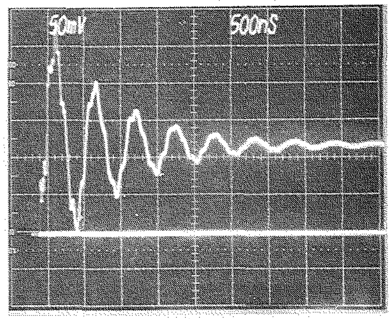


55V/div 500ns/div

As above, with 3rd wire added over and under each wing



Test 262
55V/div
500ns/div



As above, with 2 more wires added above the aircraft, resulting in 15 wires around the aircraft. See Fig. 19-22.

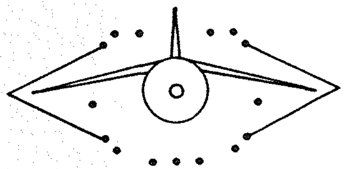


Figure 15 (cont'd) - Return Circuit Conductor Evaluations.

Figure 16 - Photograph of the NASA F-8 Test Arrangement.

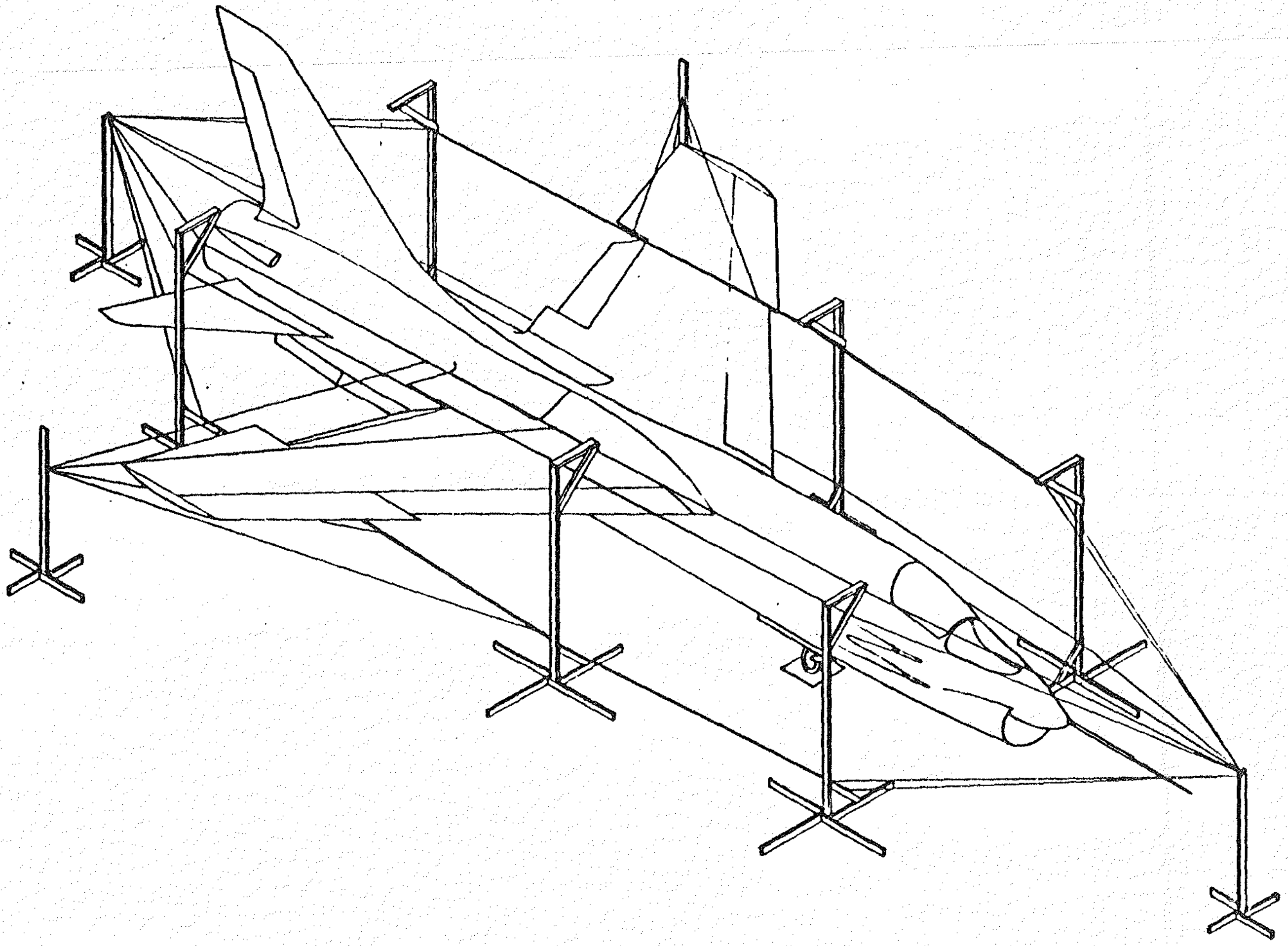


Figure 17 - Drawing Showing the NASA F-8 and Four Pairs of Return Wires.

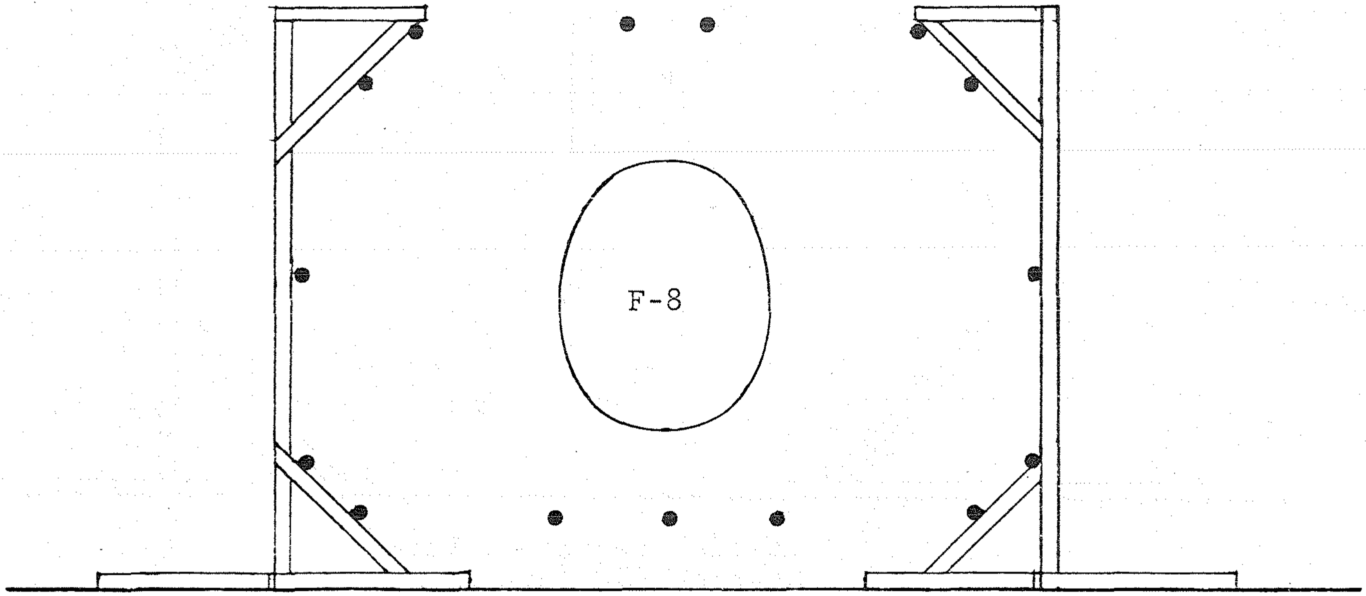


Figure 18 - Partial Sectional View at Fuselage Station 181 (1st support stanchion).

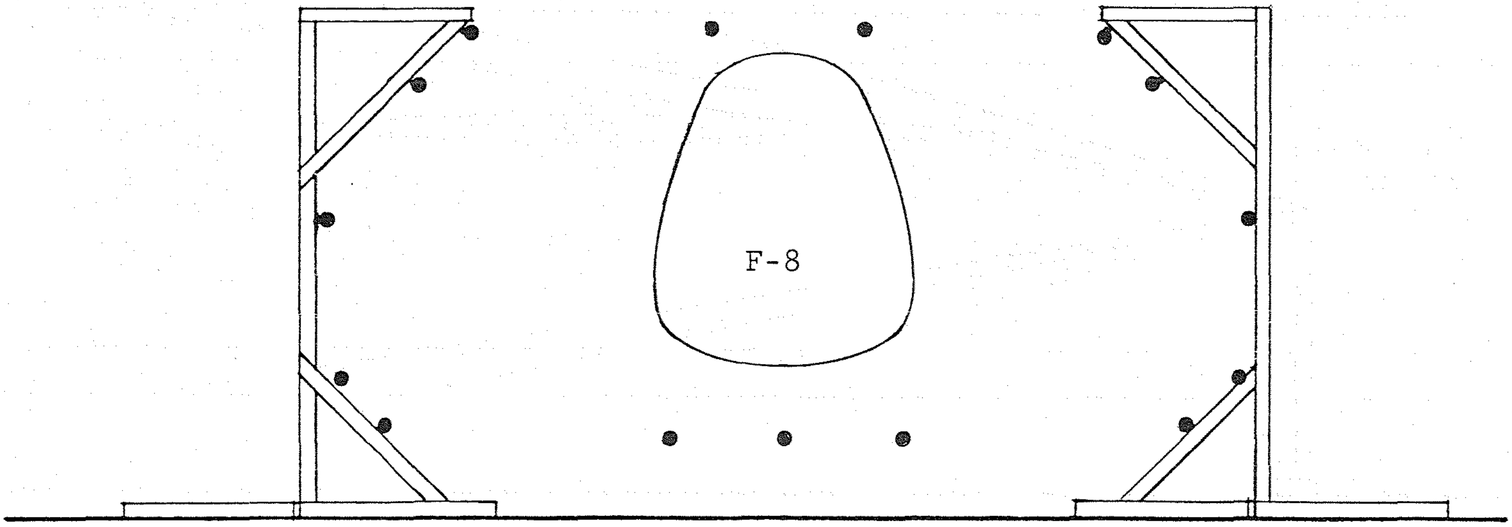


Figure 19 - Partial Sectional View at Fuselage Station 375 (2nd support stanchion).

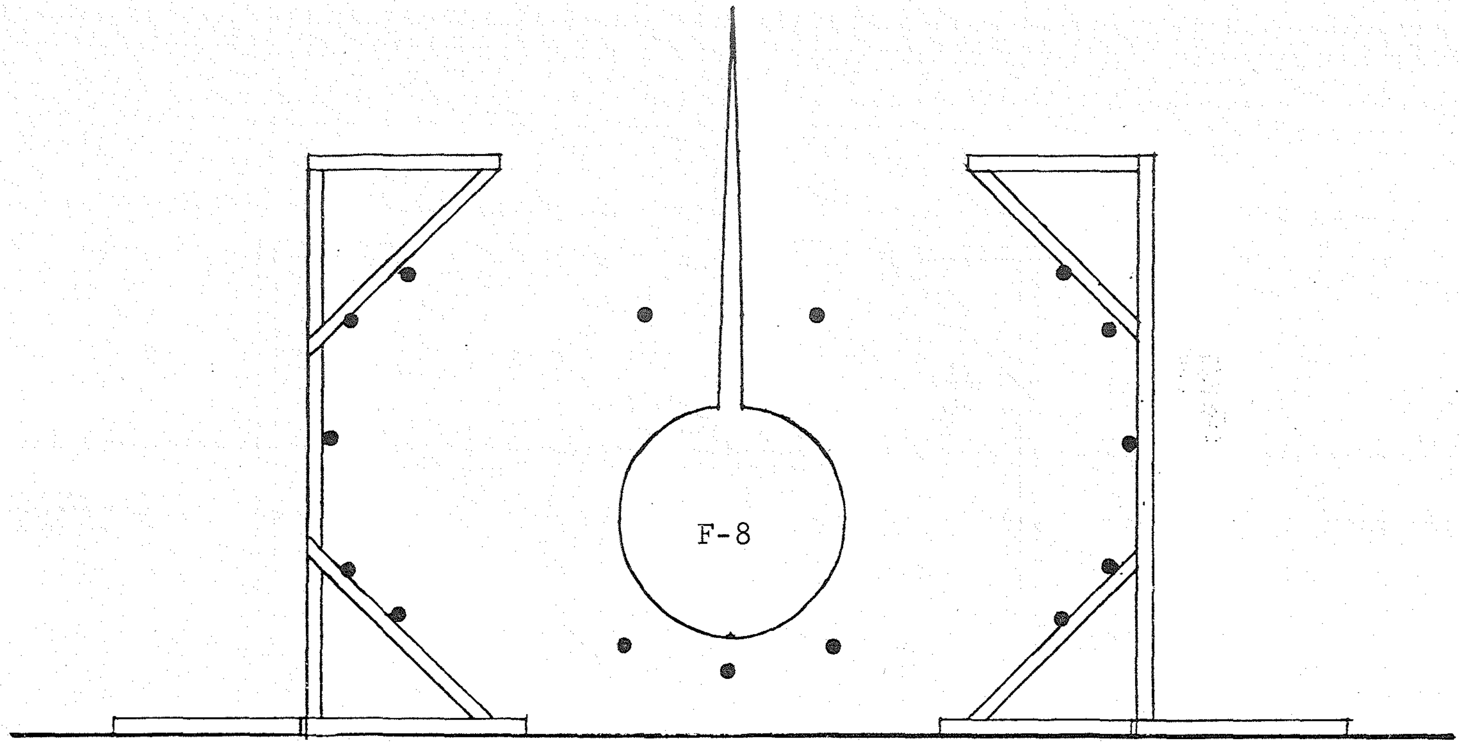


Figure 20 - Partial Sectional View at Fuselage Station 670 (3rd support stanchion).

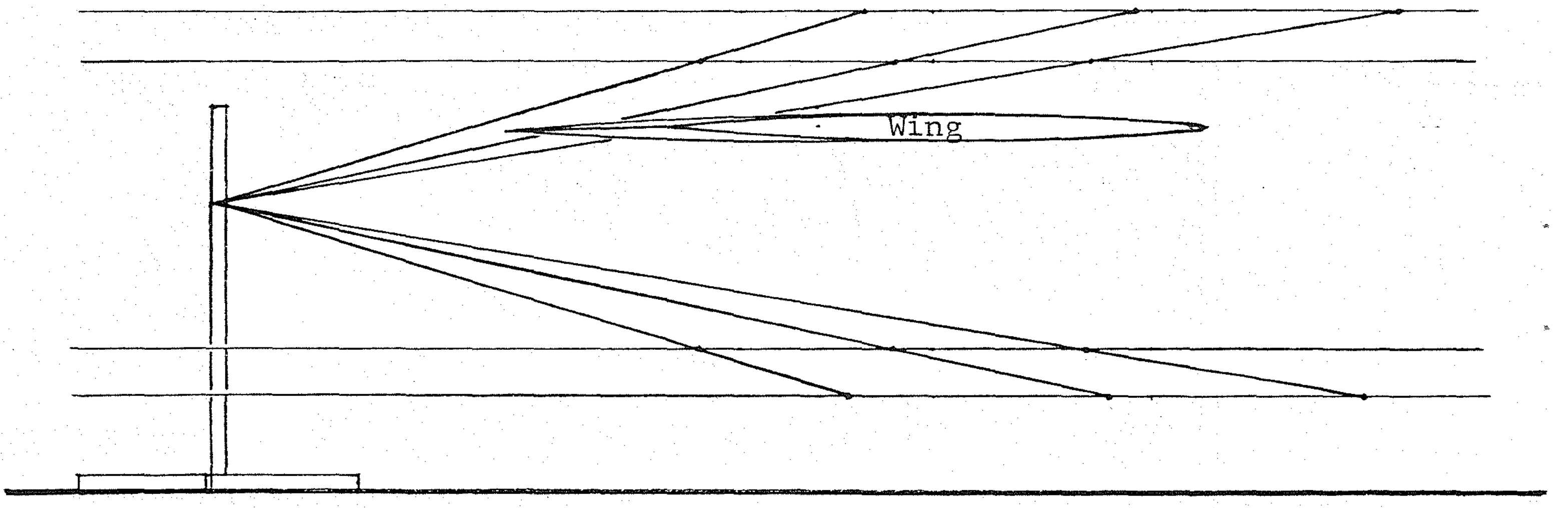
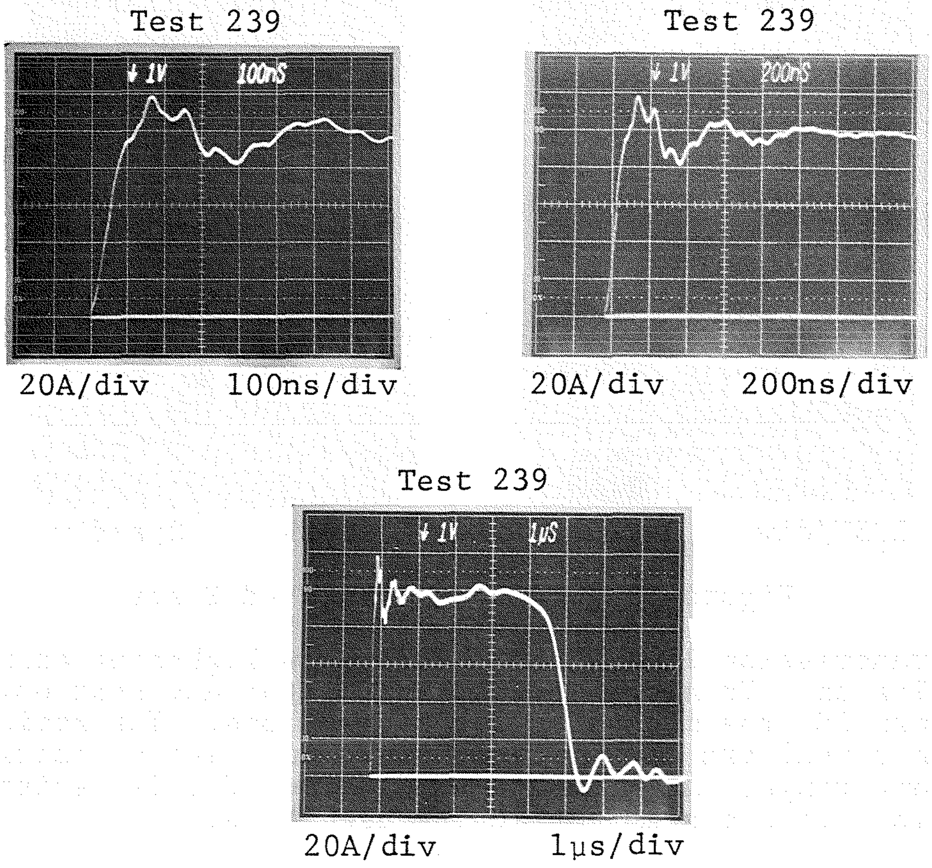


Figure 21 - Partial Section View at Wing Station 96 Looking Outboard.

LC Ladder Network

Continuing with the work started in CR 3329, further modifications were carried out on the LC ladder network (LCLN) generator. Three specific variations in generator operating mode were made: 1) the number of elements was increased and the electrical length was also increased, 2) lumped capacitor representing a "cloud" was installed, and 3) resistance in the circuit was investigated.

In the previous effort, the LCLN generator was composed of six 2.5 nF capacitors and seven inductors and represented 120 m of stroke channel. In the present effort, 24 capacitors 1 nF each with 25 inductors were assembled to represent 240 m of arc channel. The first circuit produced a current pulse lasting about 3 μs. The latter circuit, when injected into a 100 ohm terminated F-8, produced a pulse of about 5 μs. Typical current waveshapes are given in Figure 22.



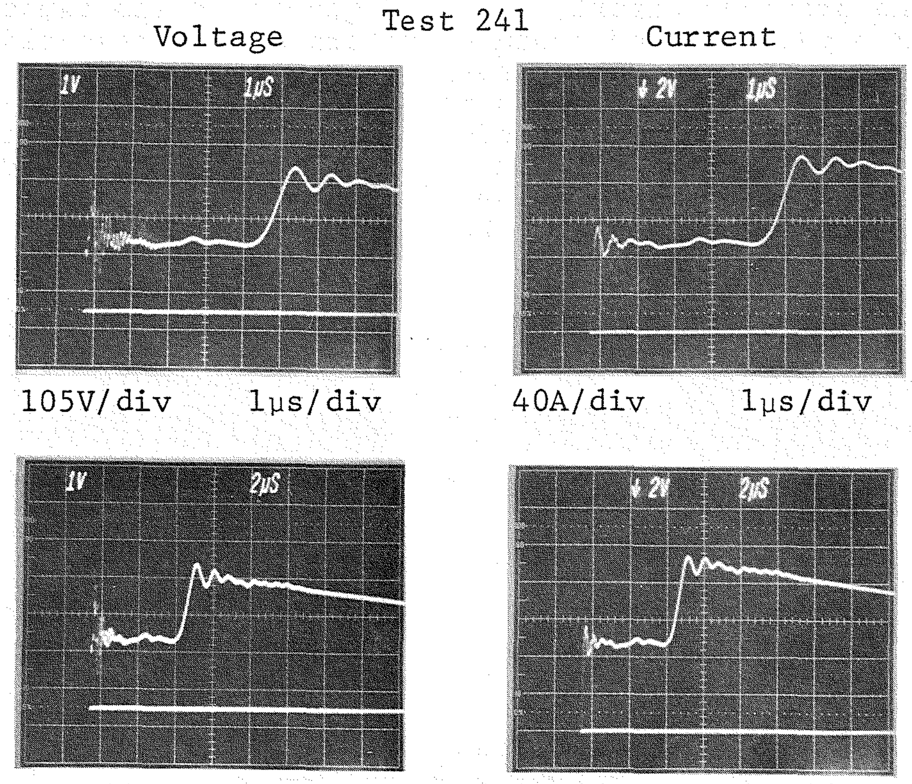
Test 239 — 20A/div 100ns/div

Test 239 — 20A/div 200ns/div

Test 239 — 20A/div 1μs/div

Figure 22 - LCLN Typical Current Pulse Waveshape.

To represent a cloud or capacitive contribution to the system a 0.5 μF capacitor was connected at the beginning of the LCLN generator. Oscillograms of these tests are given in Figure 23. The line and the 0.5 μF capacitor were both charged to 20 kV but the LCLN generator looks like a 100 ohm source impedance, so it drops one-half the voltage in the generator and the other half on the aircraft surge impedance. At the time the LCLN line pulse ends, the 0.5 μF capacitor takes over and it only sees the 100 ohms at the end of the aircraft, so the current and voltage double. To eliminate this jump, a series resistor of 100 or more ohms would have to be inserted between the 0.5 μF capacitor and the line.


Test 241

Voltage Current

105V/div 1μs/div 40A/div 1μs/div

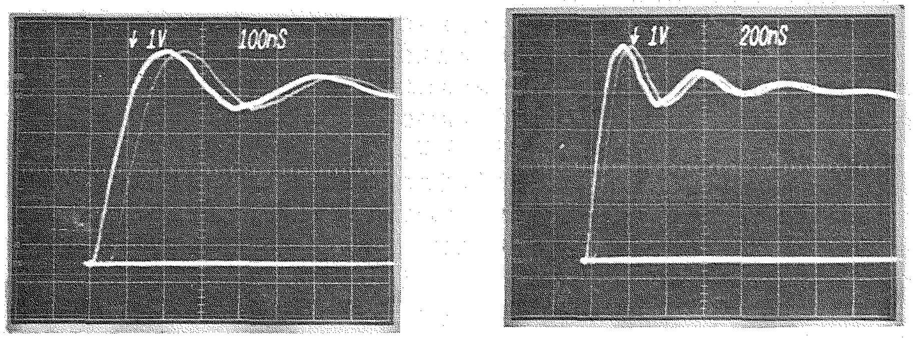
105V/div 2μs/div 40A/div 2μs/div

Figure 23 - "Cloud" Simulated Tests

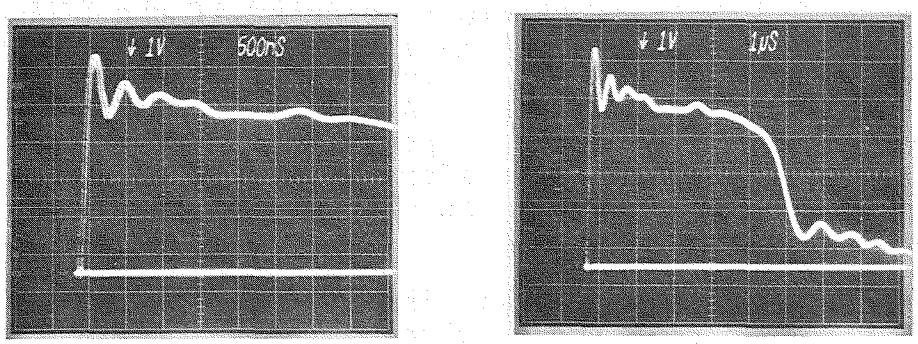
A transmission line which simulates a lightning channel must contain losses. In a real stroke, the light and heat emitted from the arc provide the mechanism for energy loss. The resistive component in a real arc is very non-linear and varies greatly over the current range. An accurate simulation of this resistance is not possible in the simple circuits used here.

During the tests conducted in the present effort, 2.8 ohms was inserted in each stage of the LCLN generator. The results of these tests are given in Figure 24. Trigger jitter on the oscilloscope is responsible for the displaced traces on the oscillograms. The current pulse waveshapes for the resistive (RLCLN) generator are similar to the other generator except for two areas. The RLCLN generator wavefront is smoother and more uniform than the LCLN generator. The risetimes for both are very nearly the same (100 ns). The RLCLN generator output amplitude is about 10% lower than the LCLN generator and droops with time. The droop and tail off (it does not return to zero at the end of the pulse) are probably due to the fact that the propagating wave is no longer TEM. There will be a component of the wave in longitudinal direction as well as in the perpendicular direction.

Test 242



20A/div 100ns/div 20A/div 200ns/div



20A/div 500ns/div 20A/div 1μs/div

NOTE: Oscilloscope trigger jitter caused trace separation

Figure 24 - Current Pulse Waveshapes for a Resistive LCLN Generator

Repetitive Pulse Techniques

In all of the induced voltage test work done previously, the applied stimulation/simulation was single pulse. When working with fast rising, short duration pulses, measurements on conventional oscilloscopes are difficult to observe. It is almost impossible to make a visual assessment of the data. Alternatively, storage scopes or digital storage systems can be used to record the data. Each of these steps requires more sophisticated and more expensive instrumentation. Some of these problems may be overcome by using a repetitive pulse generator to refresh the oscilloscope trace. Such a generator would require changes in previous operating modes. Obviously, a mechanical switch would not be sufficient. Working in the range of 50 kV (most tests have been conducted between 20 and 50 kV) an electronically triggered sparkgap system can be used to switch the system. Due to the way the trigger systems operate, most triggered sparkgaps operate best when one electrode is connected to ground. This may require some relocation of generator components but doesn't materially change the system function.

It is not certain exactly what the best simulation circuit will be, however, it is possible to estimate the limits of energy needed. A 2 x 50 μs wave injected into a circuit which has the aircraft terminated in its apparent transmission line impedance, with peak currents of 200-300 amps should be the upper limit. Using a 0.5 μF capacitor at 50 kV, 625 joules will be stored for each pulse. At a 30 Hz repetition rate, approximately 19 kVA will be dissipated in the aircraft termination resistor. A 100 ohm, 19 kW resistor is a big resistor. To get the storage capacitor completely charged in two cycles (30 Hz rep. rate), a full wave, 3 phase power supply will provide the most efficient use of equipment kVA rating.

The power requirements can be reduced if the LCLN generator is used. With 24 stages at 1 nF each, the stored energy at 50 kV is 30 joules. At 30 Hz, 900 VA (watts) will be required. At 60 Hz, 1000 watts would be dissipated. A 50 kV, 50 mA (2.5 kVA) DC power supply can supply the necessary power to charge these capacitors every 16.7 milliseconds. As before, the termination resistors and other circuit components will have to be designed to handle whatever power levels are selected.

To understand the problems involved and to investigate possible advantages of repetitive pulse operation, tests were conducted on the F-8 aircraft. Most of the work during the present effort was done using the LCLN generator in the repetitive mode. Some tests were carried out with other generator circuits. Figure 25 shows a schematic representation of the aircraft/generator configuration for these tests. All of the data presented except for the "cloud" simulation work was done using repetitive generator techniques. In general, the technique was quite successful and, except for some triggering jitter, the oscillograms were clear and sharp.

One area of concern noted was the switch operating characteristics at fast pulse risetimes. Figure 26 shows current and voltage oscillograms of the first attempt to introduce fast rising pulses into the F-8. The voltage oscillogram shows more variance in waveshape than the current oscillogram and the sweep for both was triggered from the voltage trace. The distortion in the oscillogram is not due to trigger jitter since jitter will displace the entire trace causing a smear such as shown in Figure 24.

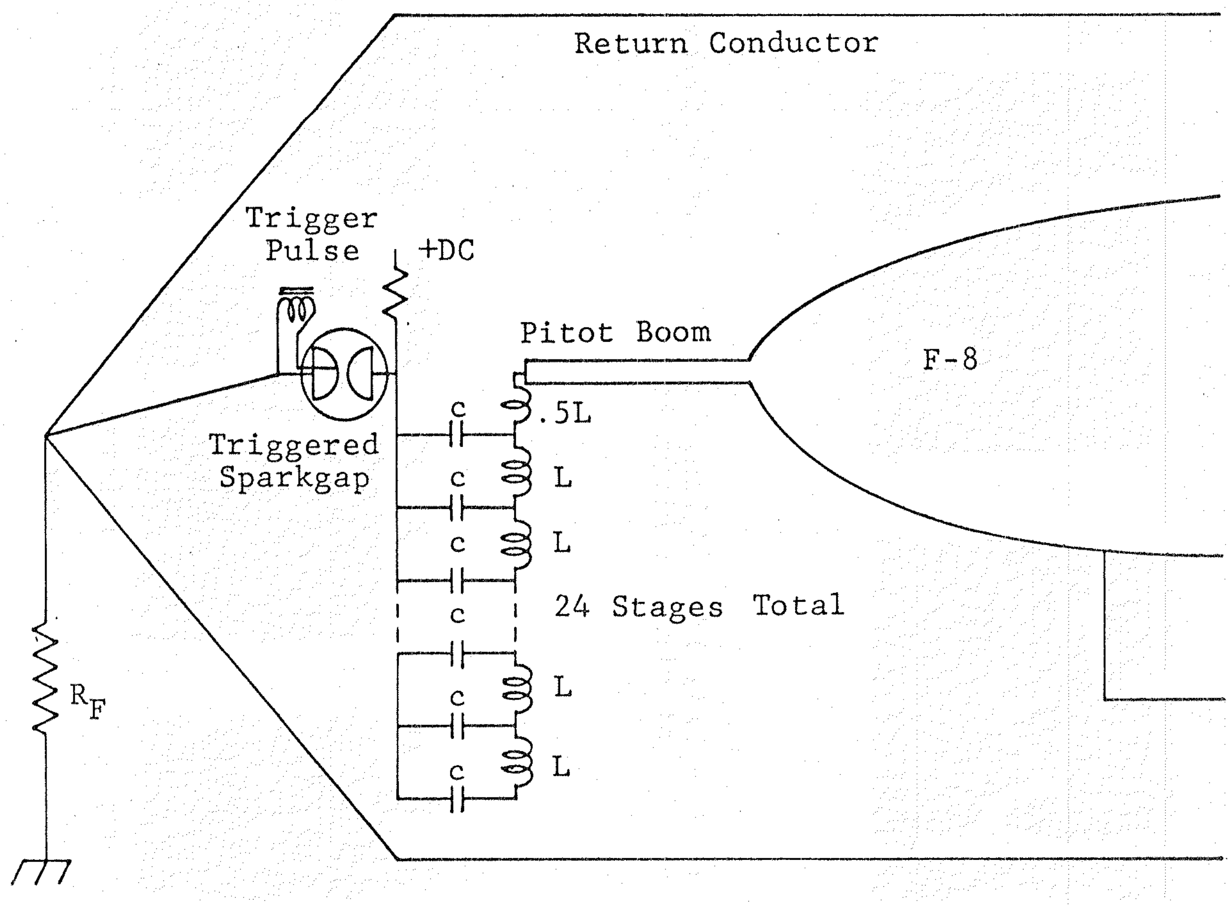
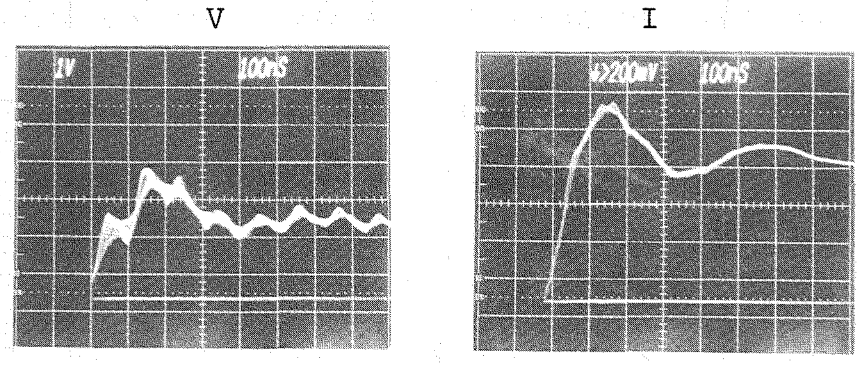


Figure 25 - Schematic Diagram of the LCLN Repetitive Pulse Generator Configuration.

To investigate the problem further, tests were conducted by opening and closing the triggered sparkgap spacing. The results of this test are shown in Figure 27. The voltage waveshape shows a change for both increasing or decreasing the gap spacing and both seem to be better in terms of varying waveshape.

Test 216



V

I

4900V/div
100ns/div

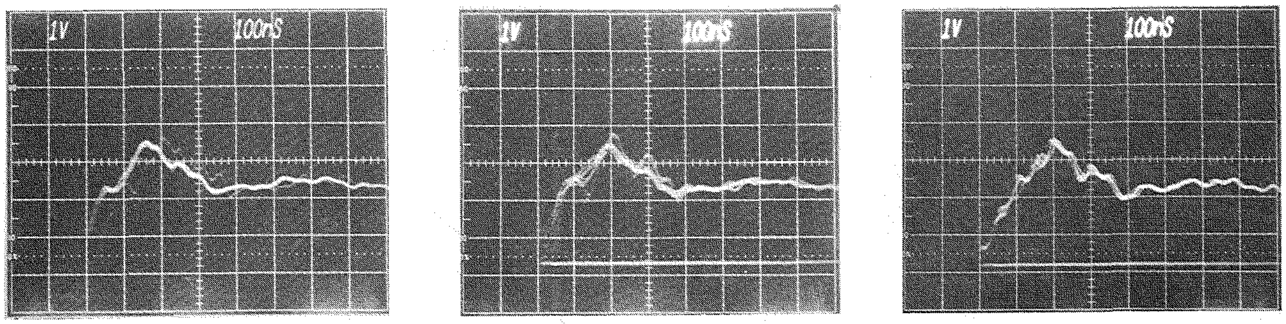
>200A/div
100ns/div

Figure 26 - Fast Rise Voltage and Current Oscillograms at the F-8 Pitot Boom.

Test 218

Test 217

Test 219



opened 2.4mm

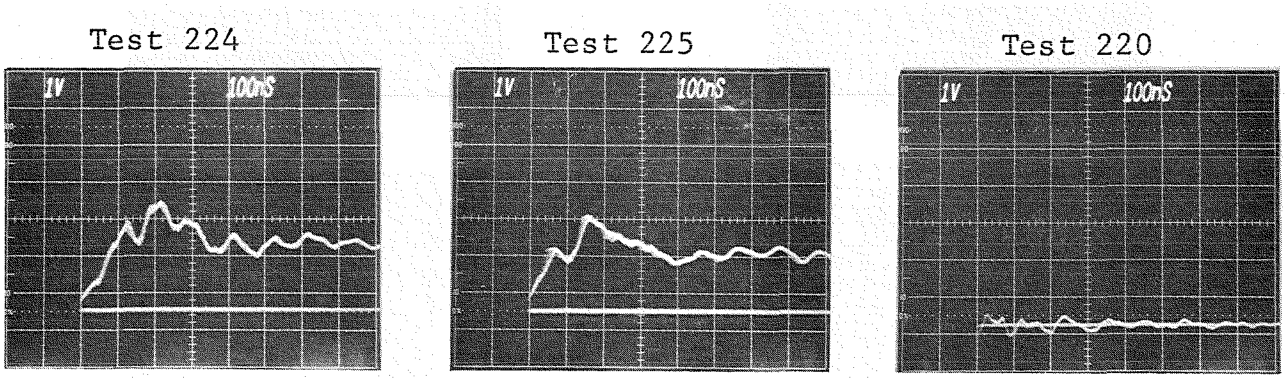
reference

closed 2.4mm

4900V/div

Figure 27 - Effect of Opening and Closing the Trigger Sparkgap Spacings at the Pitot Boom.

Another waveshape comparison was made by increasing the power supply voltage and letting the gap self fire. The voltage was then reduced about 10% and the gap triggered. The results of these tests are shown in Figure 28. Also shown is a voltage measurement made with no charge voltage on the generator. The voltage obtained is that due to coupling from the sparkgap triggering pulse.



Test 224 Self Fired

Test 225 Triggered

Test 220 Trigger Noise

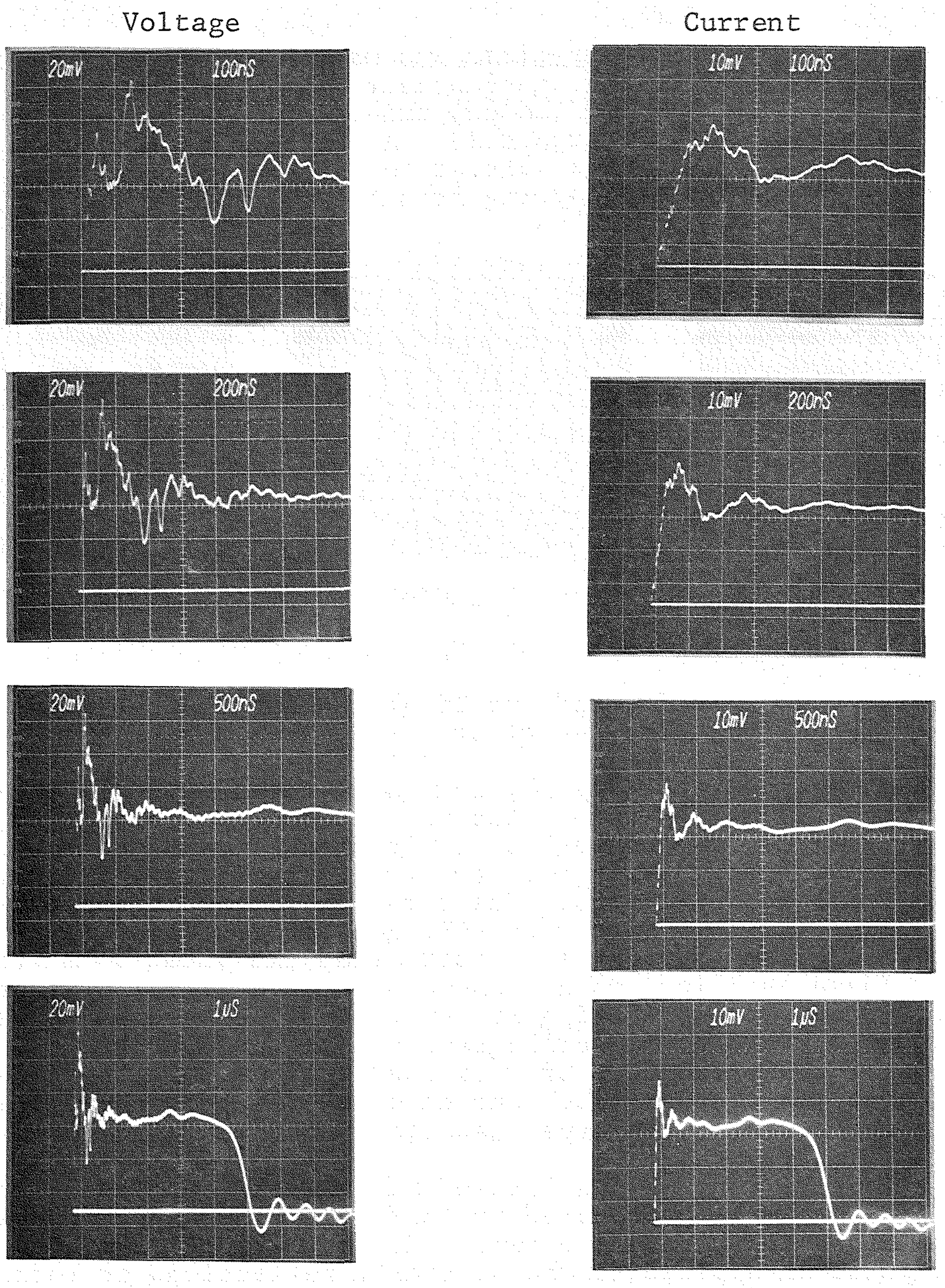
4900V/div

Figure 28 - Self Fired and Triggered Switch Operations at the F-8 Pitot Boom.

It does appear the the physical arc processes involved with closing the switch can affect the way the voltage is applied to the test system. To complete an evaluation of this phenomenon, tests were conducted using the same 24 section LCLN generator with two different switches. The first was a low voltage, mercury wetted relay switch. With the LCLN generator charged to 110V, a set of voltage and current oscillograms at the pitot boom were taken. These oscillograms are shown in Figure 29. The other test was performed using the triggered sparkgap with the LCLN generator charged to 20 kV. These oscillograms are shown in Figure 30. Comparisons of these two sets of oscillograms show that the closing characteristics of the switch can have an effect on the applied voltage and current waveshape, especially the leading edge.

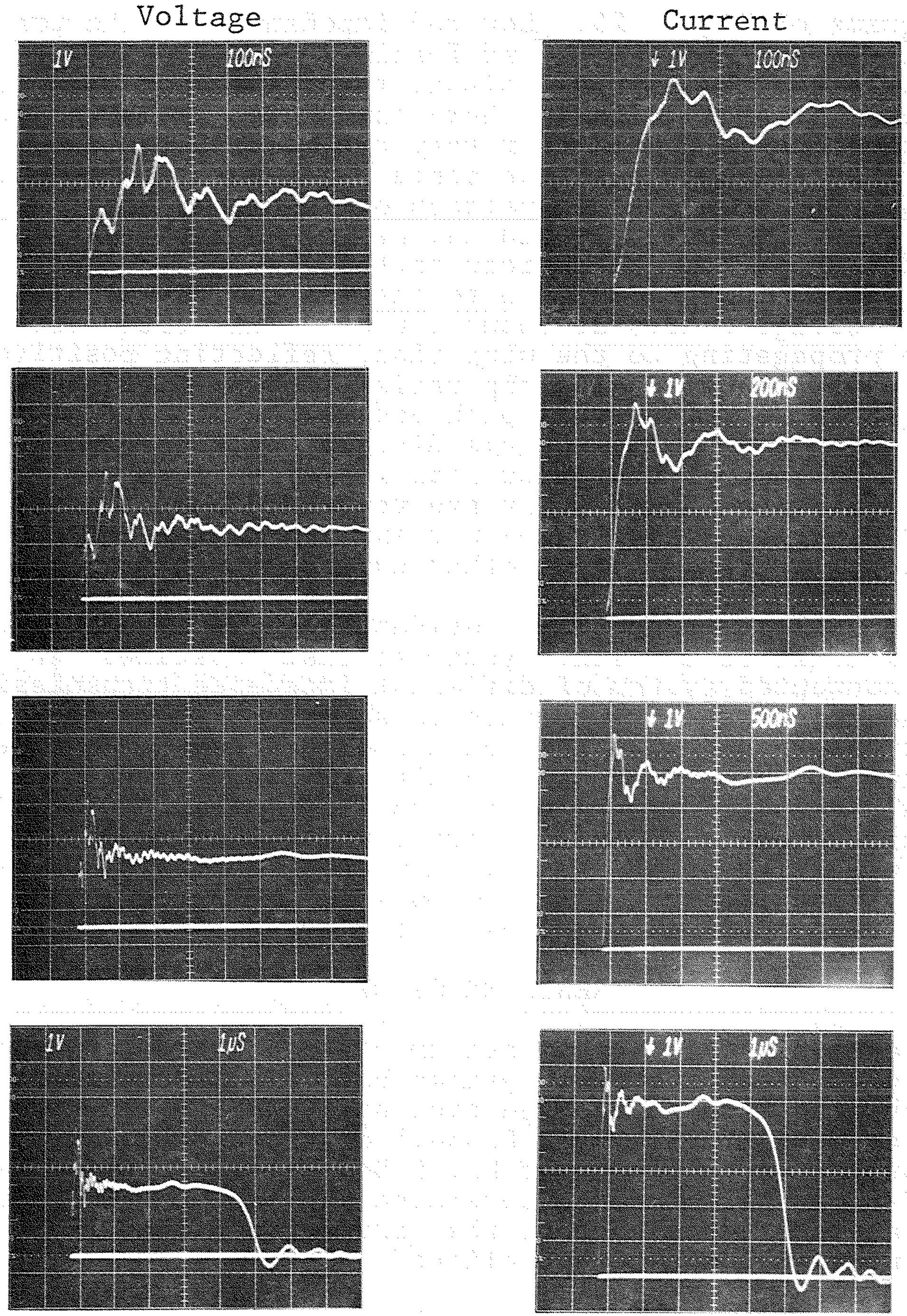
It appears that as the rate-of-rise of the applied pulse increases, the more pronounced the effect of the surge impedance changes along the aircraft become. If for example, a 200 ns rising pulse is applied to the aircraft, reflections or refractions from points that are less than 10 to 15 m away will not be evident because the reflections can get back (two transit times) before the applied wave changes much. When waves rising in 20 ns or so are applied to the system, changes in surge impedance as close as 2-5 m away will show up. If the change in impedance is downward then the current wave will reflect increased and the voltage will reflect reduced. This phenomena appears in the

Test 229



Voltage Oscillograms are 22.5V/div
Current Oscillograms are 0.2A/div

Figure 29 - Low Voltage Mercury-Wetted Switch LCLN Generator Oscillograms.



Voltage Oscillograms are 5190V/div
Current Oscillograms are 20A/div

Note: Leading edge waveshape differences

Figure 30 - High Voltage Triggered Sparkgap Switch LCLN Generator Oscillograms.

oscillograms of Figure 29. Lowered impedances at the transition from pitot boom to fuselage and fuselage to wings are probably responsible for the initial voltage reversals, but the nose wheel response is probably also in there somewhere. As these reflections reach the LCLN generator they are mostly absorbed, but may be reflected slightly positive since the generator is lower impedance than the boom. An inspection of Figure 29 shows positive voltage peaks at the 40 ns and 140 ns. The first peak corresponds to the distance from the divider to the leading edge of the wing and the second is the distance to the back of the wing. The first negative voltage starts at about 300 ns. This could correspond to the wave propagating to the wing tips, reflecting positive, propagating to the opposite wing tip reflecting negative and coming back to the nose. The exact path and reason for all of the reflections is not clear. The voltage divider was connected to the aircraft at the base of the pitot boom so reflections taking place at that impedance change point are very hard to determine. The simple reflection analysis doesn't explain all of the reflections and their polarities, but no other explanation can come close.

Two conclusions do become evident when viewing this data. 1) The aircraft return line system at fast risetimes behaves as an interconnected system of different impedance transmission lines. Thus, the injected current pulse is shaped by the reflection/refraction phenomena and obtaining a smooth exponential rise of less than 100 ns may not be possible. 2) The switch closing time has a very definite effect on the applied pulse. High voltage switching systems may contain jitter which will greatly affect the repeatability of the tests. Repeated tests will be required to verify that indeed the applied pulses are not changing enough to cause data invalidation from test to test.

RESPONSE STUDIES

An analysis of several instrumentation system concepts was performed to determine what systems held the best promise for use with lightning-induced voltage testing. The effort in this area was assisted by Mr. Robert O'Donnell of the Charles Stark Draper Laboratories. As a result of Mr. O'Donnell's analysis, testing on the F-8 was performed to determine the maximum frequency content in an induced voltage so that proper bandwidth limits on instrumentation could be established.

Candidate Systems

Five different methods of making induced voltage measurements during reduced magnitude, simulated lightning tests were considered. They are:

1. Differential Conductive Coaxial Cable

   A pair of conductors, properly shielded, connect the aircraft measurement point with the external recording system. Historically, this was accomplished using a twinaxial cable (RG-22/U) and a differential input oscilloscope.

2. Analog Fiber Optic Line

   The measurement is converted to an optical signal by a transmitter; carried on a fiber optic cable, reconverted to an electrical signal, and delivered to a recording system.

3. Repetitive Pulse Sampling System

   Stretched pulse samples are transmitted optically to a sampling data system which records the samples.

4. Flash A/D Optic Link System

   A high speed, miniaturized flash A/D converter takes the measurement in the aircraft and the data is digitally transmitted over the optic link to the recording system.

5. FM Telemetry

   The analog signal is used to modulate an FM transmitter to an outside receiver which is connected to the recording equipment.

The objective of this phase of the program was to analyze the several instrumentation systems. Two were chosen for further evaluation. Instrumentation system characteristics considered for these analyses were as follows:

1. Bandwidth - 0 to 50 MHz nominal
2. Signal Length - $\sim$100 cycles
3. Signal Range - must have attenuation capable of accepting from 100 to 0.1 volt inputs
4. Isolation - sensor must be capable of operating at a considerable voltage above the recording system.
5. Sensor Size - aircraft space is at a premium, so small size is imperative.
6. Cost - to be useful to general aviation manufacturers, the cost must be reasonable.

7. Operational Requirements - logistics power, support and time factors must always enter the picture.

Differential Conductive Coaxial Cable. - This system may not be a candidate for future "LTA" tests because the aircraft must be grounded. Also, measurement cable impedance from each line to ground is 50 ohms which, when connected to a circuit under measurement, will load that circuit. A blocking capacitor must be used when the circuit under observation contains power. Higher input measurement impedances can be attained by inserting series resistance at the measurement point but since the cable impedance remains 50 ohms, the transmitted signal is reduced. For a 50 kilohm input impedance, the signal will be reduced 1000:1. From past experience, a typical induced voltage was from 0.5 to 5 volts. A 1000:1 attenuation would reduce this to the measurement system noise level (1-5 mV).

Much of the data taken previously has been generated using the differential coaxial cable data transmission system, therefore, it will be useful as a data base.

Analog Fiber Optic Link. - The electrical measurement signal is converted from electrical levels to light levels which are then carried from the sensor/transmitter to a receiver which converts back to electrical signals. The transmitter must be a well shielded module containing the appropriate attenuation components, batteries, and electrical-to-light solid state converter. The receiver, usually incorporated into the recording/viewing equipment, must also be well shielded and may contain any number of signal processing elements in addition to the light to electrical level converter. The major concerns that have been expressed in regard to light pipe systems are bandwidth limitations (most available systems have 20 MHz upper limits), range sensitivity (work best with ± 0.5 V range signals), and drift. Admittedly these limitations are tolerable if no other feasible method of achieving the required electrical isolation exists.

Repetitive Pulse Sampled Data Instrumentation System. - For each of the other induced voltage measurement systems, a single simulated lightning pulse is introduced at the airframe and an electronic/electrical system response measurement is made. These measurement systems have various limitations including impedance, isolation, bandwidth, etc. Using a repetitively applied pulse allows the use of sampling techniques where a very narrow sample (10^{-9}s. or less) is taken for each succeeding pulse. These samples are stretched and reconstructed on slower bandwidth equipment. Examples of this type of equipment are the Tektronix 1S1 preamplifier which allowed measurements to 1 GHz on a 30 MHz oscilloscope and the 7S11/7T11 sampling preamplifiers which permit 1 GHz measurements on a 100 MHz scope.

For the sampled data system to operate properly it is necessary to have a stable, jitter free trigger pulse. Unless the trigger signal is available at almost exactly the same time for each succeeding applied pulse, it will not be possible to reconstruct the sampled wave. In some applications, it is possible to obtain the trigger from the measured signal. That would be difficult in this situation for two reasons: the aircraft electrical/electronic system response to the reduced magnitude, simulated lightning pulse is usually quite low in amplitude and, in some cases, may even be zero. Secondly, the objective of this system is to obtain high frequency data and transmit it on a lower bandwidth system. The trigger pulse, of course, will have to be a full frequency signal, especially since it will have to arrive at the sampling control equipment at or before the start of the induced signal. If the trigger signal is too late, the initial portion, if not the entire signal, will be missed. In view of these considerations, it would appear that the logical source of the trigger pulse would be from the simulation generator. Detection of the switch closing would be the ideal point. This signal would precede or coincide with the application of the simulated lightning pulse to the airframe and should precede any electrical activity in the electrical/electronic system. Detection of the application of the switching command to the triggered sparkgap will not be useful due to the statistical jitter associated with the switch firing. Possibilities include detection of light emitted from the switch or a capacitive voltage divider at the output of the switch.

The measurement and recording components of the repetitive sampled data equipment are commercially available from several vendors. For this evaluation, the systems offered by Tektronix were evaluated. Review of the pertinent literature from Tektronix indicated that it may be possible, with some modification, to install an optic link to transmit the data between the S-1 sampling head and the 7S11 sampling unit. The 7T11 time base would require no modification.

The size of the sampling heads (S-1, S-2, etc.) for these systems are very attractive for this application since they are quite small (8cm x 8cm x 8cm). This should allow for them to be installed easily within the confines of a modern aircraft without undue stress.

Flash A/D Optic Link System. - In an analog optic link system, varying levels of light are transmitted on a fiber optic light pipe and then reconverted into electrical signals. If the light pipe is used to transmit digital data, then the resolution can be theoretically improved. The basic concept of the flash A/D optic system is to digitize the induced voltage using a flash A/D converter, storing the digital data at the sensor; and to transmit the digital data over a light pipe to the recording equipment. Since the data has been generated in a digital format, the most logical recording equipment would consist of a minicomputer system. The data can then be analyzed and presented in several different formats with relative ease.

Even though the computer interface and light pipe transmission systems are quite readily available, the flash A/D sensor/memory system is a special purpose item and will have to be developed. Nominal system characteristics, based on the previously stated instrumentation system characteristics, would include but not be limited to the following:

Sampling Rate - to attain 50 MHz bandwidth, sampling rates of 150 to 200 MHz will be required. Lower rates must also be available.

Resolution - six bits would be sufficient but eight may be attainable. One hundred words (samples) at 200 MHz gives 0.5 μs of data. One thousand words would cover 5 μs which corresponds to the length of typical high frequency induced voltage signals.

Memory - using an eight bit word, and 1000 words requires an 8 k FIFO (first in, first out) memory.

Control - external command signal (light pipe) controls.

Size - as small as possible, hopefully 8cm x 8cm x 8cm.

Power - internal batteries or if space is not available, feed from aircraft power.

A basic operating scenario would be as follows. The flash A/D is in a standby mode (some chips dissipate several watts during operation). A few seconds prior to the application of the simulation pulse, the A/D converter is activated. A trigger signal is extracted from the applied pulse and transmitted to the minicomputer. After a predetermined delay, the computer signals the flash A/D to stop. The computer then reads out the 8 k memory and reconstructs the induced voltage signal. If the signal is not complete or out of range, adjustments are made in the sensor attenuators and the trigger delay and the test repeated. With proper delays in stopping the flash A/D, it should be possible to capture the leading edge of the signal. If the signal length exceeds that captured, then a slower sampling rate would be used and the test repeated.

The attraction for this type of system is its inherent compatibility with computer analysis of the data. Microcomputers are now readily available and competitively priced. It also has the advantage of a trigger signal to stop rather than a trigger signal to start collection of data allowing a greater chance of obtaining the leading edge of the data.

FM Telemetry System. - The analog signal, properly attenuated, is used to modulate a carrier which is transmitted to the recording equipment. In general, the bandwidth of modulated carrier (AM or FM) is twice the highest frequency of the modulating signal. Theoretically, with 50% modulation it would be possible to transmit a carrier with twice the frequency of the modulating signal. Practical limitations in the design of discriminators/detectors dictate that the carrier be three times that of the modulating signal. To transmit a 50 MHz signal, a 150 MHz carrier would be required. However, at the present time no equipment is commercially available for such use. Some work for handling such bandwidths has been done using microwave links but the size of the equipment and its associated antennas do not make it attractive for the present application.

Instrumentation System Evaluations

Discussion with industry experts indicated the best candidates for further work were the analog and flash A/D fiber optic link systems. The repetitive sampled data system is also attractive due to its inherently higher bandwidth capability (up to 1 GHz).

These three candidates were evaluated by Mr. O'Donnell and the results are documented in his report (Ref. 20). The evaluation concludes that higher frequency data can be obtained using a repetitive pulse sampled data system but present hardware cannot be adapted as hoped. Therefore, new sophisticated hardware would have to be developed. Prior to developing such hardware, a need for the frequencies should be established (200 MHz and greater).

For ground based measurements (standard lightning induced voltage tests) analog fiber optic (light pipe) systems are commercially available with bandwidths of up to 100 MHz. If a need for airborne data storage is established, the flash A/D converter system would be a useful system but specific hardware may have to be developed due to the special nature of the task. If frequency requirements are 25 MHz or less, then commercially available flash A/D converters and buffer memories are available today in sizes near what is required.

The analysis provided by Mr. O'Donnel pointed out that the need for further development work on instrumentation is dependent on establishment of a reliable estimate of the upper frequency bandwidth in the induced voltage signal measurement.

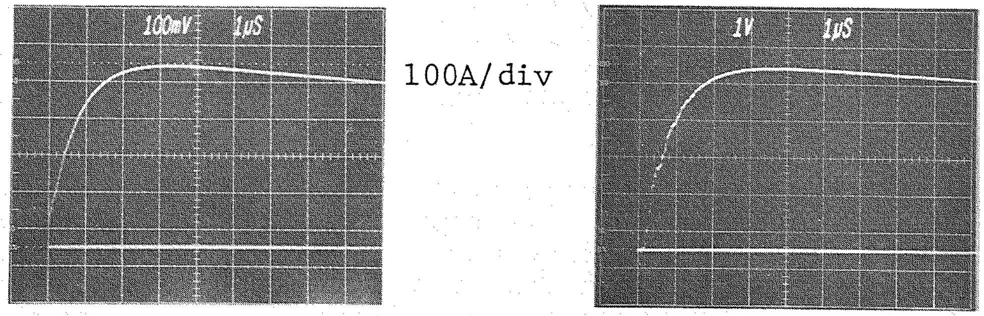
Induced Voltage Upper Frequency Tests

As a result of Mr. O'Donnell's findings, measurements of lightning induced voltages in the same aircraft wiring circuit as during the previous effort were made with various input current pulses. Examination of these data points was carried out to determine the upper frequency content that might be present in the measurement.

To verify that indeed the present system duplicated the previous effort configuration, measurements of induced-voltages were made using a 2 x 50 µs wave with the aircraft shorted to its return lines. The results of that test are given in Figure 31. Measurements of induced voltage were made using 50 ohm terminations at the scope as well as high impedance (1 megohm). These measurements compare favorably with Figures 29 and 30 of NASA CR 3329. The waveshape is very similar but the amplitude is 20% higher. Two identifiable frequencies are evident of the oscillograms, one at 750-800 kHz and a very low level oscillation at 10-11 MHz.

Applied Current

Test 210 Test 214

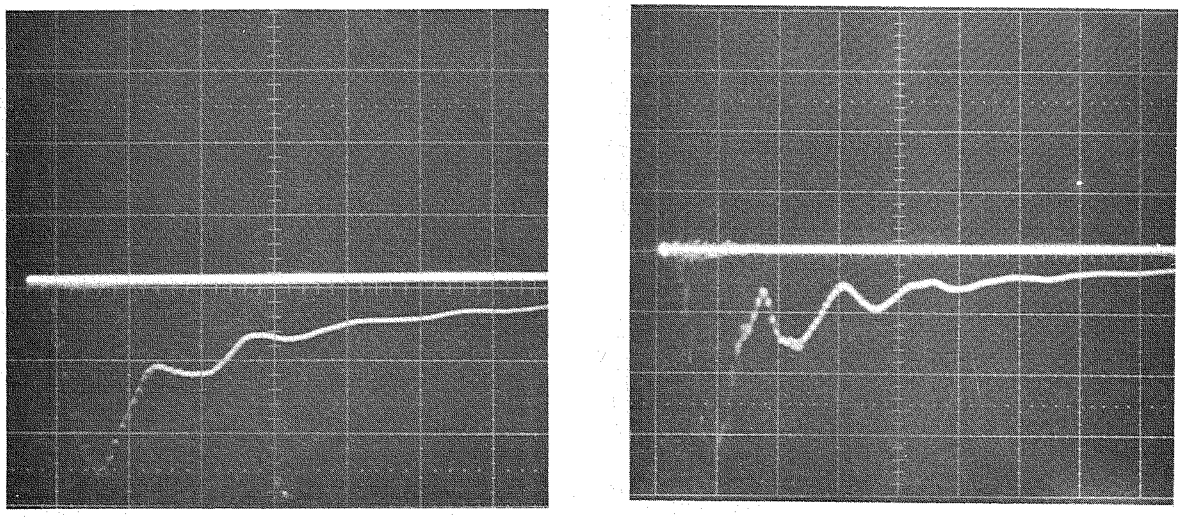


100A/div 100A/div

Pitot Boom Tail

Induced Voltage

Test 210 Test 212



50 Ohm Termination 1 Megohm Termination

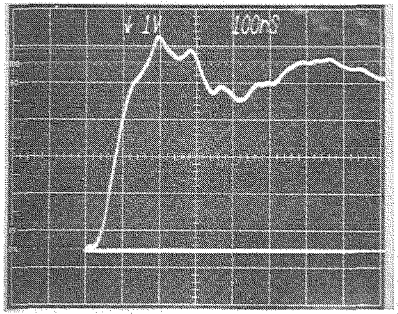
Both Oscillograms 2V/div, 1 µs/div

Figure 31 - Induced Voltage Measurements With A 2 x 50 µs Wave Test Current.

Using the LCLN generator, a current with 120 ns risetime was injected into the aircraft. Figure 32 shows both the input current and the resulting induced voltage measurement. The highest frequency evident in the measurement is about 10.6 MHz. See Figure 30 for more voltage and current oscillograms.

Applied Current

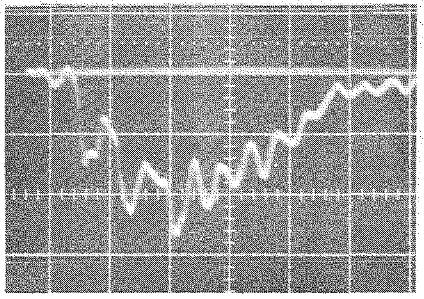
Test 235



20A/V
100ns/div

Induced Voltage

Test 235



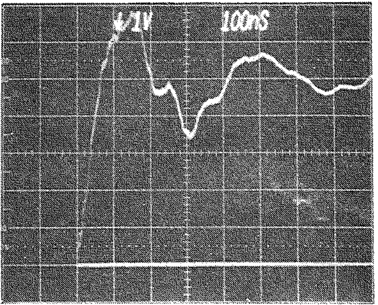
1V/div
200ns/div

Figure 32 - LCLN Applied Current and Induced Voltage. (120 ns risetime)

The last element in the LCLN generator is an inductor. Shorting out that inductor will lower the high frequency output impedance of the line and reduce the risetime of the current pulse. Figure 33 shows the induced voltage and applied current pulse corresponding to this condition. Figure 34 shows a more complete set of voltage and current oscillograms. The 10.6 MHz frequency is much more pronounced than before. Another measurement was also taken without the 50 ohm termination on the oscilloscope. The amplitude of the 10.6 MHz doubled but no higher frequencies were evident. That measurement oscillogram was not of good enough quality to be reproduced. The two induced voltage oscillograms of Figure 32 and 33 were taken on an oscilloscope inside the F-8 fuselage and the quality was not good. The extra traces on Figure 33 are due to trigger problems.

Applied Current

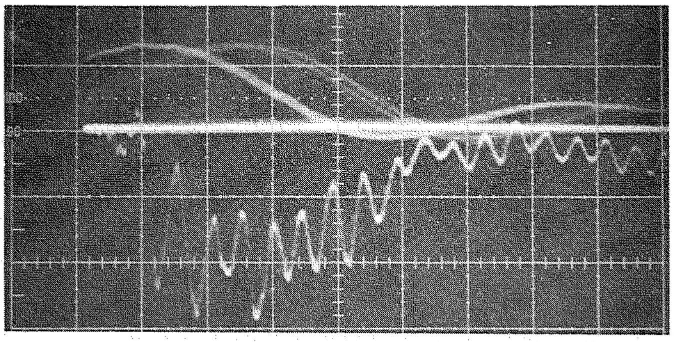
Test 238



20A/div
100ns/div

Induced Voltage

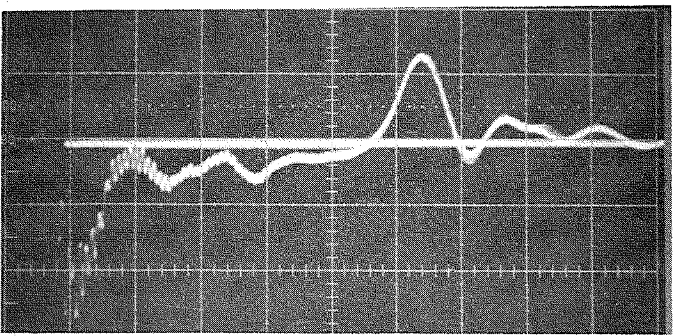
Test 238



Extra traces due to trigger problems

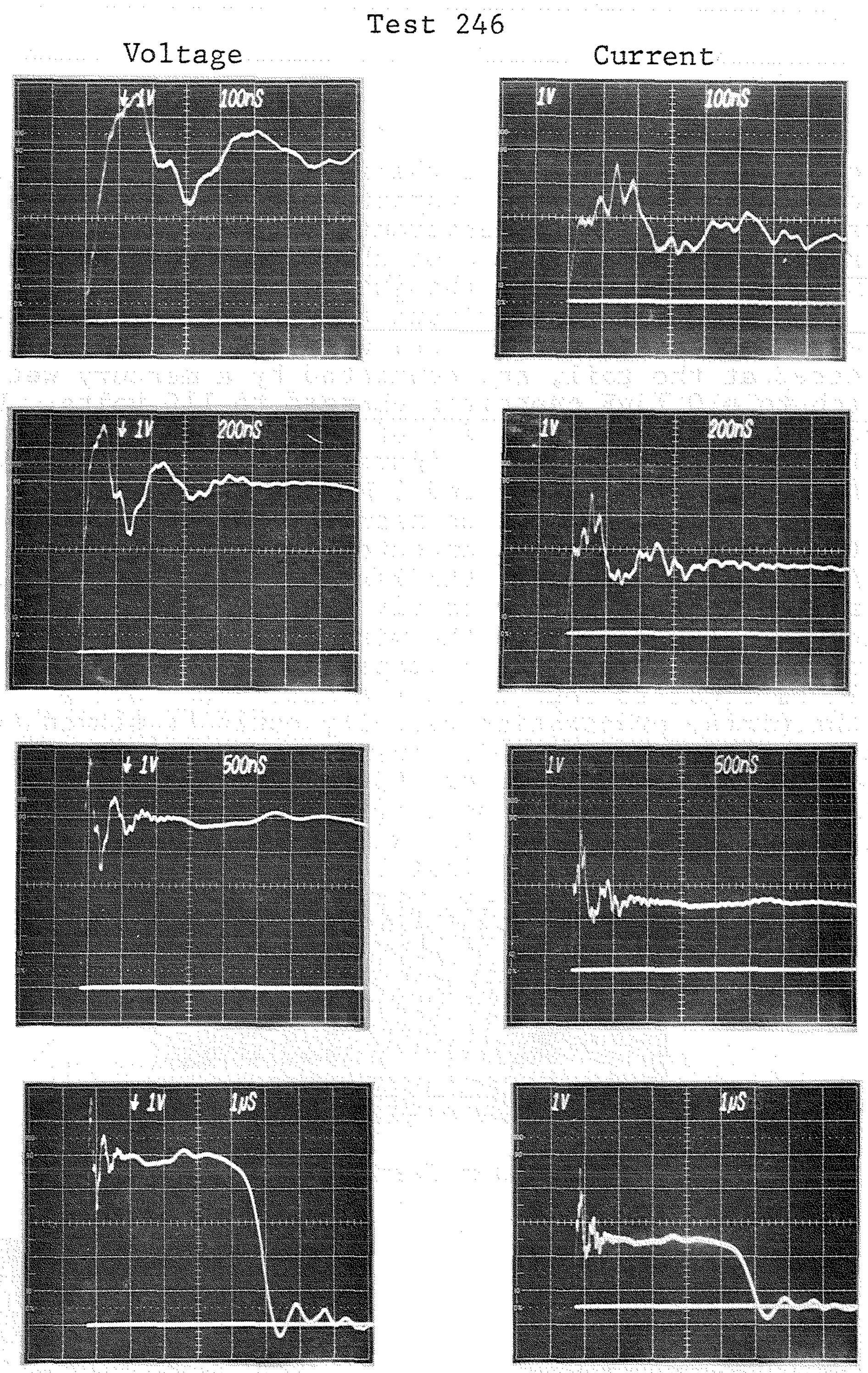
1V/div
200ns/div

Test 240



1V/div
1μs/div

Figure 33 - LCLN Fast Applied Current and Induced Voltage. (90ns risetime)

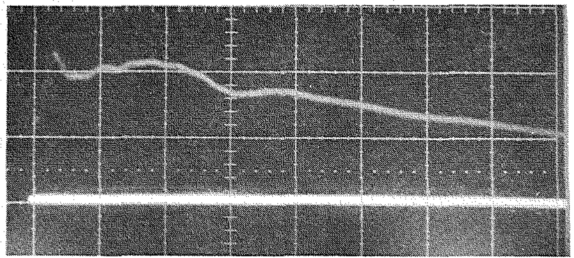


All Voltage Oscillograms are 5190V/div
All Current Oscillograms are 20A/div

Figure 34 - LCLN Fast Applied Current Pulse Voltage and Current Oscillograms (90 ns) at Different Sweep Rates.

The circuit wire used for the induced voltage measurements was described in the previous report. At the base of the tail, the wire was grounded with measurements made line to ground near the cockpit. The total length of the circuit was 8 to 10 m. The 10 MHz oscillations were thought to have some relationship to this dimension. To investigate the natural frequencies of the wire, direct tests on the wire were conducted. The wire was disconnected at the tail, and connected by a mercury wetted relay switch to a 0.1 μF capacitor charged to 110 volts. Measurements were made at the front end of the wire in the same manner as for the induced voltages. Figure 35 shows the voltages appearing at the scope with 50 ohm and 1 Megohm terminations at the scope. The wire transmitts the nearly vertical wavefront from the switch and with 50 ohms connected, shows no tendancy to oscillate. At higher impedances, the leading edge shows steps, which may be reflections at approximately 100 ns. The only observable frequency is 2.4 MHz. Since the wire is open at one end (measurement) and shorted at the other (capacitor), the mode of oscillation will be equal to four transit times. Due to the insulation around the wires, propagation velocity could be slowed to 2×10^8 m/s minimum velocity, 3×10^8m maximum. The 2.4 MHz oscillations correspond to a transit time of 105 ns. At 3×10^8 m/s that represents 32 m, at 2×10^8 m/s the length would be 21 m. Both of these numbers are much longer than the wire.

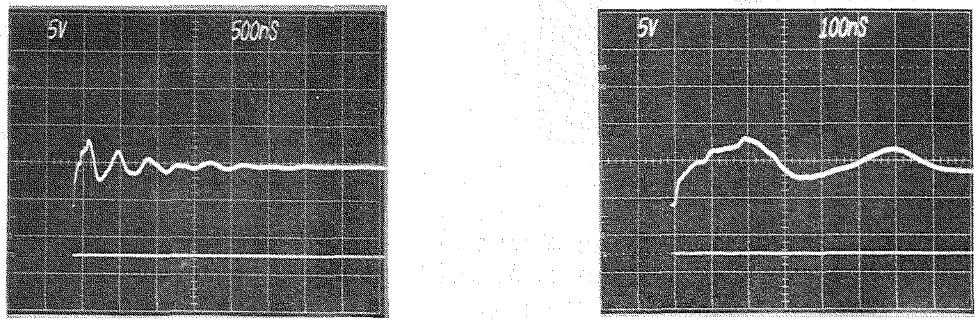
Test 246



50V/div 500ns/div

50 Ohm Termination

Test 248 Test 248



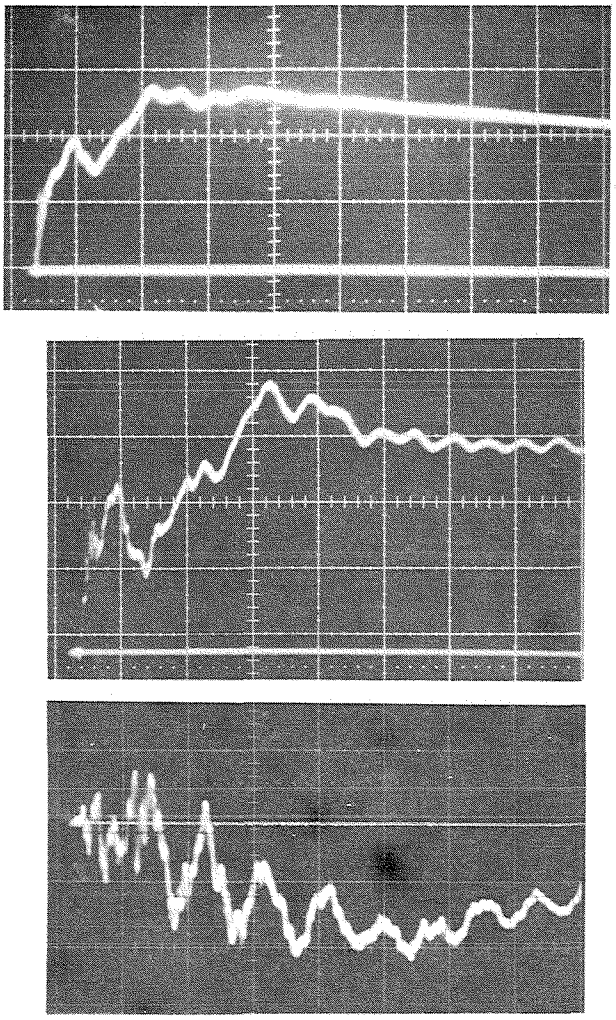
50V/div 500ns/div
1 Megohm Termination

50V/div 100ns/div
1 Megohm Termination

Figure 35 - F-8 Circuit Wire Natural Frequency Tests.

The 100 ns steps could possibly represent reflections. If they correspond to two transit times, they could possibly represent lengths of 10 to 16 m. At four transit times, they would correspond to 5 to 8m lengths. The 10-16 m length is too long and no mode of reflection corresponding to two transit times appears possible. The 8 m, four transit time mode does appear possible but the waveform should have a drop between the steps which are not present. Therefore, it is doubtful that the 100 ns steps are related to any transit times.

A final fast rise test was attempted using the mercury wetted relay and a 0.1 μF capacitor charged to 110V. Figure 36 shows input current, return wire current at the side of the aircraft and the induced voltage measured. The external measurements were made with a portable oscilloscope under the wires and some external noise on the measurement is present. Current pulse risetimes are about 50 ns on the initial rise. If the total applied current is measured, the input current risetime is 150 ns.



Test 252
100ns/div
0.5A/div
Input Current
(Pitot Boom)

Test 253
100ns/div
0.05A/div
Return Current
(Return Conductor)

Test 253
100ns/div
.010V/div
Induced Voltage

Figure 36 - Fast Rise Current and Induced Voltage Test.

The predominant frequency is 11.8 MHz, which is 11% higher than before. However, for this final test, the mercury wetted switch was fastened directly on the pitot boom. In all other tests, the switch was physically positioned about one meter away from the front of the boom. Also a shorter set of connections from the switch to the return lines was made to reduce the circuit inductance. Connections were made from the back of the pulse generator directly out (perpendicular to the boom) to the eight return wires. These physical changes in the return conductor configuration are probably responsible for the change in the induced voltage frequency.

Superimposed on top of the 11 MHz are one or two higher frequencies ranging from 40-80 MHz. The lower frequency component appears to be about 20% of the 11 MHz signal while the higher component is closer to 2% of the amplitude. The source of these higher frequencies is not at all clear and must have something to do with short transmission line reflections in the external aircraft circuit.

It appears that the aircraft transfer mechanism does not have an upper frequency roll-off. If current pulses of 100 ns or longer risetime are applied, the induced voltage will have frequency components of 10-20 MHz in it. If the applied current pulse has risetimes of 50 ns, then the induced voltage will contain frequencies of 40-80 MHz.

CONCLUSIONS

Simulation Studies

Performing an LTA test on an aircraft requires installing that aircraft in a facility with a return conductor system around it. The aircraft and the return conductors form a transmission line but the facility and the return conductors also form transmission lines. The applied simulation pulse is applied between the aircraft and its return conductors but it also couples and excites the lines formed outside of the return conductors. Installing resistive connections between the return conductor and the facility absorbs this coupled energy and reduces interference due to waves travelling on these transmission lines.

The amount of energy coupled out of the primary test transmission line can be reduced by increasing the number and placement of the return conductors. The resulting array of return conductors may not be practical for performing induced voltage tests because of the congestion caused around the aircraft.

The travelling TEM wave introduced at the nose of an aircraft proceeds down the fuselage, refracts at the wings, proceeds out and back the wings, reflects, goes back to the tail, refracts again before returning to the nose. The TEM wave travels at the speed of light but proceeds along an average path which is considerably longer than the fuselage length of the aircraft.

The aircraft transmission line impedance changes at each geometric change in aircraft shape. As the applied pulse risetime gets faster, reflections/refractions from these transmission line changes become more pronounced and begin to have a definite effect on the applied current waveshape. The reflection/refraction process appears to definitely limit the effective risetime of an applied current pulse to times on the order of 100 ns.

Severe lightning stroke models calling for current risetimes of 100 ns or less are presently being discussed by some investigators. Lightning induced voltage tests to such models can probably be best accomplished using the LCLN generator system. Smooth waveshapes with risetimes of 100 ns can be accomplished by several variations of this generator. It also lends itself to repetitive pulse testing because of its lower energy requirements.

The use of high voltage triggered gaps to perform simulated lightning tests at very fast current risetimes must be done with caution. Inherent non-linearities and statistical jitter in the breakdown of such gaps can, if not properly accounted for, unduly influence the test results. The use of repetitive pulsing was found to be very helpful in determining the repeatability and stability of the applied pulse. Single pulse work would not have pinpointed the problem as quickly.

Response Measurement Systems

For the majority of test situations, the analog fiber optic data link appears to provide a sufficient instrumentation system. Some care and judgement must be exercised in using these systems due to their limited operating range. Sufficient bandwidths are commercially available for induced voltage testing applications.

Measurements of induced voltage frequencies as a function of applied current risetimes show that no upper frequency limit exists. Since the transfer function is due to aperture coupling, this result is not unexpected. In fact, as the energy contained in the applied pulse at the upper frequencies increases, the transfer function may actually increase as the wavelengths approach the aperture dimension. The internal wire harness does not seem to exhibit or add any frequency limits of its own to the response. It appears to act as a passive transmitter without oscillating within itself. The frequencies observed on the induced voltage waveform seen to be related to external reflected waves on the airframe.

APPENDIX

Personal Safety
High Voltage, High Current Test Area Operations

Introduction

The following paragraphs address the safety aspects and concerns of any individual who is conducting or supporting High Voltage or High Current (simulated lightning) test operations.

Safety is each and every person's responsibility and concern. Even though technical responsibility for safety during an operation may have been assigned to a specific individual, you are ultimately responsible for your own actions. It is of very small comfort to be able to blame your or someone else's injury on a third party if the exercise of common sense on your part could have avoided the problem.

The following paragraphs are intended to acquaint you with the fundamental knowledge required to allow you to choose the safest course of action for the prevention of accidents associated with High Voltage and High Current tests. The hazards addressed here are the special hazards associated with high voltage. In addition to these special hazards, we must always be aware of the general hazards (i.e., tripping, falling, slipping, eye protection from flying debris, etc.) around any laboratory environment. Safety rules for the general hazards are documented elsewhere.

Attitude

Safety must be part of the job. Most accidents happen when we fail to maintain a safety consciousness. We have all experienced the "dumb accident", where in retrospect the consequence of our actions was very obvious, but due to some preoccupation we failed to observe common sense rules. Examples range from getting burned from a hot component after soldering in the electronics shop, to adjusting a "hot" circuit without de-energizing the power supply and getting a shock.

In many areas of work such inattention to safety will result in injuries ranging from minor to serious (loss of limbs, etc.). In working with High Voltage and High Current test circuits, very often the first accident will be the last! We don't get very many second chances. Therefore, we must always be conscious of the safety aspects of working with this type of equipment. We must form attitudes that result in safe work habits.

Hazards

To protect ourselves from potential hazards associated with High Voltage and High Current test apparatus, we must be able to recognize the hazards. The basic hazard associated with High Voltage and High Current testing is the generation of electrical voltages at very high levels which are capable of travelling several meters along conductors or several 10's of centimeters through the air. During the tests it is important that both distance and/or an electrically grounded shield be kept between the test system and yourself. A secondary and equally dangerous hazard involved in both High Voltage and High Current test circuits is the use of storage capacitors which can retain lethal electrical charges after the equipment is de-energized.

Many test operations require or suggest that test areas are to be operated only by two or more persons. This does not relieve or reduce any of the previous discussion. It is the duty of the second person to insure that the first is observing the safety rules and to provide prompt medical attention in case of accident. However, at the point an accident has occurred, we have already failed from the safety standpoint and are in a recovery mode. We must not allow the accident in the first place because in this type of testing, a severe accident is most likely a fatal accident. Safety must come first!

First Basic Safety Rule

The most basic general safety rule to follow in High Voltage or High Current work is: NEVER TOUCH ANY PART OF THE TEST CIRCUIT OR APPARATUS THAT YOU HAVE NOT PERSONALLY OBSERVED TO HAVE BEEN GROUNDED. If you adhere to this rule, you will be safe from electrical hazards.

In the design and construction of a test circuit and its apparatus, automatic grounding equipment, safety fences and lights are provided to protect personnel. Most laboratories require that two men be present to observe one another, etc., but none of these conditions take the place of the basic grounding safety rule.

After a test circuit has been de-energized, the safety gates and circuits opened, then you will enter the test area to inspect, change samples, adjust the circuit or whatever. First of all, if you do not have a specific reason to approach the test circuit - DON'T. Never unnecessarily expose yourself to any hazard. If you must enter the area and work on an item, whether it is connected with the test circuit or not, either ground it yourself or observe someone else grounding the item, as necessary. When you must work on the capacitors, be sure that both terminals of all capacitors have been grounded and tied together. This is very important when working with series capacitors. Both ends can be at ground and the intermediate terminals at hazardous voltages. Just touching the top and then the center will only chase the charge around. The capacitor must be shorted end to end and to ground.

The purpose of grounding hazardous voltage sources is to conduct any electrical energy contained on the item to ground without passing through you. The ground stick is therefore a very important item. The rod or part you hold, must be a non-conductor. Plastic or dielectric material is the best. Plastic PVC water pipe is an economical material. Varnished wood is acceptable if it is kept relatively dry. A metal shepherd's hook must be installed on the end and connected to a conductor which leads to a ground point. Ideally, a copper braid (16mm or AWG # 9 equivalent) should be used to connect the metal hook to ground. The conductor should be uninsulated so that you can visually observe that the metal hook is grounded. Also an uninsulated conductor allows you to connect to several capacitor terminals at once and still remain connected to ground. Braids are also more flexible and less apt to tangle. Standard insulated wire can be used temporarily but be sure it can conduct the current when you ground a charged capacitor. An exploding ground wire will be almost as much a hazard as the charged capacitor. One ground stick should be permanently attached to each test generator plus others should be available for use at other points in the area of test.

Second Basic Safety Rule

The test item, generator, circuit and hazardous voltages must be contained within a grounded fence or barrier which will keep all personnel away from the test area. Obviously, the fence or barrier must be constructed and/or positioned so that no one outside of the barrier can come in contact with the circuit or close enough for the circuit to arc over the barrier to personnel. We must also make sure that nothing can extend the test area to outside of the barrier (i.e., wings, etc.) even though it is not actively involved in the present tests, will violate the barrier. Suppose someone were touching the wing and the test circuit arcs to the wing, that person is just as likely to be dead as if he had been standing inside the barrier by the test circuit. Therefore, nothing shall extend from inside the test barrier to the area outside. This includes instrumentation cables as well as electrical cables lying on the floor. Since instrumentation cables must come out of the test area, they must be shielded and the shields terminated and grounded at the point where they leave the test area. Then, if the circuit arcs to the cable, the electrical charge will follow the shield to its grounding termination and not continue on out of the test area.

Sometimes, it may not be practical, due to the size of the system under test to confine it to the normal test area, then the entire room or building must be regarded as the test area and treated accordingly.

Summary

Two basic rules of safety for electrical hazards exist:

1) Never touch anything without grounding it.

2) Confine the hazardous voltages within the test area.

If you don't have to touch it - DON'T! If you must touch it, ground it first. Hazardous voltages are often classified as greater than 240-480 volts, etc., but more people have been killed by 120 volts than by all higher voltages combined. Since only a few milliamperes of current passing through the heart will kill you, any voltage which will deliver those milliamperes can be hazardous. So respect all electrical voltages.

The first rule extends to all electrical apparatus since no one would ever be injured by electrical circuits if they had grounded the point they are about to touch.

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16. Abstract

The lightning-induced voltage test technique (LTA) was introduced in 1974. Since then, research and development work has resulted in some fundamental changes in the techniques and understanding of the test. Revised test technique procedures and the reasons behind them are given in terms of the type of information desired from the test.

Test technique research reveals that the aircraft, in the test configuration, represents an interconnected set of short transmission lines of different impedances. When the test generator switch closes, voltage and current traveling waves propagate along the aircraft. At points where the transmission impedance changes (i.e., wings, tail, etc.), reflection and refractions occur. The bulk of the wave energy travels out the wings and tail following a path which is long compared to the length of the aircraft. Consequently, the times required for oscillations gave the impression that the waves were propagating at velocities lower than the speed of light.

As faster and faster risetime pulses are applied to the aircraft, the interconnected, different impedance, short transmission line response becomes a bigger and bigger factor in the observed response. Ultimately, the pulse risetime applied is governed by the transmission line characteristics rather than the external generator characteristics. The limit appears to be, for the F-8 at least, about 100 ns.

The induced voltage frequency content is related to the external environment and the internal cables do not appear to provide any resonance. As the applied current pulse risetime went from 2 μs down to less than 100 ns, observable induced voltage frequencies went from 700 kHz to 50 MHz.

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