10th INTERNATIONAL AEROSPACE AND GROUND CONFERENCE on LIGHTNING AND STATIC ELECTRICITY

ICOLSE
PARIS 1985

XVII[e] CONGRÈS INTERNATIONAL AÉRONAUTIQUE

Organisés par l'ASSOCIATION AÉRONAUTIQUE
ET ASTRONAUTIQUE DE FRANCE
PARIS
10-13 juin 1985

les éditions de physique

publiés avec le concours du Centre National de la Recherche Scientifique

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XVII^e CONGRÈS INTERNATIONAL AÉRONAUTIQUE

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10th ICOLSE - XVIIe CIAé

La 10ème Conférence Internationale sur la Foudre et l'Electricité Statique (ICOLSE), jumelée avec le XVIIème Congrès International Aéronautique, est organisée par l'Association Aéronautique et Astronautique de France (A.A.A.F.) sous le Haut Patronage

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Message du Président
de l'ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE
DE FRANCE

En 1785, il y a exactement deux cents ans, le plus illustre Américain de l'époque, Benjamin FRANKLIN, quittait la France pour regagner définitivement les Etats-Unis, au terme d'une mission diplomatique qui jetait les bases de deux siècles d'amitié et d'alliance entre les deux peuples. Ce même homme avait écrit, trente ans plus tôt, un ouvrage scientifique remarquable dans lequel il attribuait à l'électricité l'origine de la foudre.

Depuis cette époque, les applications industrielles de l'électricité ont connu un développement prodigieux, sans cependant que la connaissance de ses manifestations naturelles progresse tout à fait au même rythme, et c'est peut-être aujourd'hui dans la mesure où le phénomène naturel apparaît comme perturbateur de l'application que son étude est vigoureusement reprise.

C'est un honneur pour la France d'accueillir les lointains disciples de Benjamin FRANKLIN venus des Etats-Unis et du reste du monde pour s'entretenir des moyens de protéger l'Humanité, exposée à tant de nouveaux périls, contre celui qui lui apparut longtemps comme la manifestation privilégiée de la colère des dieux.

P. CONTENSOU

Message from the President
of the ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE
DE FRANCE

Exactly two hundred years ago, in 1785, the most famous American of the period, Benjamin FRANKLIN, left France to return to the United States for good, at the end of a diplomatic mission which laid the foundation of two centuries of friendship and alliance between the two peoples. This same man had - some thirty years before - written a remarkable scientific work in which he attributed the origin of lightning to electricity.

Since this period, industrial applications of electricity have enjoyed a tremendous development, without, however, the understanding of its natural manifestations having kept up the same pace. But, today, in the measure that this natural phenomenon appears as a perturbing element in these applications, its study is being vigorously pursued.

It is an honor for France to welcome the present-day disciples of Benjamin FRANKLIN from the United States and from the rest of the world, to discuss together the means of protecting Humanity - which is exposed to so many new dangers - from this particular one which was for so long considered as the special manifestation of the anger of the gods.

P. CONTENSOU

CONFERENCE D'OUVERTURE

PROTECTION A LA FOUDRE DES AVIONS MODERNES
Le point de vue de l'Avionneur

D. LEROUGE
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INTRODUCTION

A l'instar d'autres secteurs industriels, l'industrie aérospatiale accomplit une profonde mutation technologique et technique. Celle-ci est principalement axée sur l'emploi à grande échelle de matériaux composites et l'utilisation d'une électronique omniprésente, appelée à traiter toutes les fonctions de l'avion.

Cette évolution, qui permet d'accroître les performances de l'avion et d'étendre son domaine opérationnel, ne peut être acceptée qu'au prix d'une parfaite maîtrise de la sécurité des vols pour toutes les conditions d'environnement rencontrées.

Or, la susceptibilité de l'avion moderne aux effets directs et indirects de la foudre, s'est sensiblement accrue. Trois raisons principales sont responsables de cette situation :

1 - La faible conductivité, voire l'absence de conductivité des matériaux composites (carbone, kevlar).
2 - La vulnérabilité accrue des composants micro-électroniques aux transitoires de tension ou d'énergie.
3 - Le rôle critique de l'électronique pour assurer les fonctions vitales de l'avion.

Ainsi, l'Avionneur se trouve-t-il confronté à des problèmes nouveaux en matière de protection qui réclament des solutions aptes à restaurer un équilibre qui semblait momentanément compromis.

SITUATION ACTUELLE

Dans cette période de transition où l'Avionneur manque de références (les Spécifications ne sont plus adaptées, les conditions applicables aux équipements ne sont pas encore fixées), ses efforts se sont déjà concentrés à la résolution ponctuelle des problèmes apparus lors d'essais aux effets directs ou indirects de la foudre :

- sur les matériaux composites :
  - pour assurer une meilleure tenue mécanique des éléments situés en zones exposées (bords de fuite d'empennages ou de voilure) ou minimiser les endommagements de surface.
  - pour renforcer la protection aux basses fréquences.
  - pour améliorer les liaisons électriques des assemblages structuraux pseudo-isolés.

- sur les réservoirs de carburant non métalliques :
  - afin d'éliminer les risques importants d'étincelages internes capables de provoquer une explosion.

- sur les équipements électroniques et les circuits associés :
  - en vue de minimiser les perturbations et éviter la détérioration des circuits d'interface, sachant que la redondance d'un système peut être mise en défaut si la perturbation affecte simultanément les circuits concernés.

Il est certain que l'étude de la protection d'un avion doit être conduite selon une méthodologie rigoureuse et que les principes de protection doivent être correctement établis dès les premières étapes de la conception d'un nouvel avion : les éléments structuraux ou revêtements composites se prêtent mal aux modifications ; de même, les modifications d'une électronique de plus en plus complexe et intégrée sont coûteuses et peuvent compromettre les délais de réalisation.

POUR LE FUTUR

L'effort de recherche de ces dernières années s'est déjà concrétisé par une meilleure connaissance du phénomène naturel, notamment en vol, et de ses conséquences sur les matériaux et les systèmes de l'avion.

Pour la mise en œuvre d'une méthode globale de protection, l'Avionneur souhaite que l'action entreprise se poursuive, et même que lui soient fournis rapidement les moyens d'action et de décision, dans les domaines qui reflètent ses besoins immédiats et qui sont :

- L'étude des mécanismes de couplage direct ou par diffusion

Cette étude à la fois théorique et expérimentale doit tenir compte de la géométrie et de la répartition des nouveaux matériaux qui recouvrent des zones importantes d'un avion moderne (pointe avant, compartiment électronique, voilure, compartiment moteurs).

- L'analyse du comportement d'ensembles électroniques complexes au foudroiement naturel

L'étude du foudroiement en vol a déjà fourni des résultats très positifs tels : la trajectographie de la foudre en balayage (F-106B), les premières mesures de couplage électromagnétique à travers des ouvertures (TRANSALL04) ou encore le spectre électromagnétique émis (C-580 et TRANSALL04).
Il paraît nécessaire de poursuivre ces essais afin de compléter les informations de caractérisation de la foudre et de son interaction avec l'avion.
En complément de ces essais, il serait utile de soumettre des électroniques de techniques récentes aux conditions réelles de foudroiement et comparer ensuite les réponses obtenues à celles issues de la simulation au sol, qui laisse subsister un doute quant à sa représentativité. Une expérience de ce type conduirait à réaliser une installation capable de mettre en évidence les divers modes de couplage qui apparaîtront sur l'avion pour lequel le système est conçu.

- Les programmes de calcul électromagnétique 3D

Les formes géométriques d'un avion, l'assemblage de ses éléments constitutifs, les matériaux utilisés et les cheminements de ses circuits électriques sont d'ores et déjà informatisés.
La prochaine étape devrait conduire à y associer un programme de couplage électromagnétique dans le double but :

1) de pouvoir évaluer, dès les premières étapes de conception d'un nouveau projet d'avion, les niveaux induits sur les circuits reliant les équipements de l'avion.

2) de procéder ensuite à l'étude d'optimisation des protections, en considérant l'ensemble des exigences de protection liées aux conditions d'environnement applicables.

- La définition des niveaux de protection applicables aux équipements et des méthodes d'essais correspondantes

La protection électromagnétique globale d'un système est répartie entre :
. l'avion
. les circuits
. les équipements.

Pour fixer la part qui incombe aux deux premiers, l'Avionneur doit connaitre les niveaux que peut supporter l'équipement, niveaux auxquels il sera soumis lors des essais de qualification.
Les documents existants fixant les conditions applicables et décrivant les méthodes d'essais (DO160/ED14, SAE AE4L, MIL STD 1757, STANAG...) doivent être mis à jour ou complétés.
L'expérience actuelle montre que l'Avionneur est amené à multiplier les essais et renforcer la protection au niveau de l'avion en attendant qu'une normalisation apparaisse.

- Les moyens de contrôle initial et de maintenance

De nouveaux besoins sont apparus pour le contrôle des protections applicables aux matériaux composites associés ou non à des éléments classiques très conducteurs.
Qu'il s'agisse du contrôle des métallisations de surface ou des liaisons entre éléments voisins, les méthodes de contrôle sous courant continu appliquées aux structures métalliques s'avèrent inutilisables.
Les techniques qui seront proposées devront permettre de juger de l'état initial et de la tenue dans le temps des solutions appliquées pour la protection aux effets directs et indirects de la foudre et la protection électromagnétique générale de l'avion.

CONCLUSION

Un travail important reste à accomplir avant de fournir une réponse satisfaisante aux questions qui se posent encore concernant :

- la caractérisation de la menace
- la vulnérabilité de l'avion et de ses systèmes
- le choix des protections
- les méthodes et moyens d'essais.

L'Avionneur ne peut attendre que tout soit finalisé. Actuellement, à la lumière des plus récents travaux, il s'efforce de choisir les solutions les plus aptes à assurer la sécurité des avions de formule nouvelle qui sont déjà en construction. En l'absence de critères plus précis, ces protections sont souvent surdimensionnées, avec l'inconvénient de réduire les avantages issus des techniques nouvelles.

Dans ces conditions, il paraît urgent de définir les nouvelles règles de conception ou de réglementation s'appliquant aux avions incorporant des technologies ou techniques modernes ; ce travail devrait largement tenir compte des options ou orientations qui auront été retenues au cours de la période de transition.

KEYNOTE ADDRESS

PROTECTION OF MODERN AIRCRAFT AGAINST LIGHTNING

A manufacturer's point of view

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INTRODUCTION

Like many other industrial fields, the aerospace industry is experiencing deep technical and technological changes. These changes are mainly directed towards the use at a large scale of composite materials and generalization of active avionics to deal with all aircraft functions, including those which are critical for the flights.

This development, which improves the aircraft performance and increases its operational range, can only be accepted at the cost of a perfect control of the flight safety, for all encountered environmental conditions.

In the meantime, susceptibility of today's aircraft to lightning direct and indirect effects has noticeably increased. Three main reasons are responsible for this situation :

1 - The low, or even the absence of conductivity of composite materials (carbon, kevlar).
2 - The increased vulnerability of microelectronic components to voltage or energy pulses.
3 - The critical role of electronics to insure the aircraft vital functions (fly by wire, engine control, etc...).

Thus, the aircraft manufacturer has to cope with new problems in the field of protection, requiring solutions to restore a balance which seemed temporarily compromised.

PRESENT SITUATION

In the transition period, where the aircraft manufacturer lacks references (specifications are no longer adapted and applicable requirements to equipment not yet defined) efforts have been concentrated on punctual solutions to problems which appeared during tests performed to study direct and indirect lightning effects :

- on composite materials :
  . to ensure a better mechanical behaviour of components located in exposed areas (tail or wing trailing edges), or to minimize surface damages.

- on non-metallic fuel tanks :
  . to eliminate important risks of internal sparking capable of inducing an explosion.

- on electronic equipment and associated circuits :
  . to minimize upset of electronic systems and avoid failure of interface circuits, taking into account the fact that redundancy of a system can be lost, should the disturbance simultaneously affect the concerned circuits.

It is certain that studies to harden aircraft must be conducted according to a rigorous methodology and the protection principles be well established from the first design stages of a new aircraft, as composite materials can hardly be modified ; likewise, modifications of more and more complex and integrated electronic systems are expansive and can jeopardize the program time schedule.

THE FUTURE

Research efforts of these last years have already led to a better knowledge of the natural lightning phenomenon, particularly in flight, as well as of its consequences on the aircraft materials and systems.

In order to develop a global protection method, the aircraft manufacturer wishes that the action in the fields which reflects its immediate needs be continued and means of action and of decision quickly supplied, amongst said needs are :

- Study of coupling mechanisms, through apertures or by diffusion

This study, which is theoretical as well as experimental, must take into account both the geometry and the location of new materials covering large areas of modern aircraft (nose cone, electronic compartment, wings, engine compartment).

- Analysis of the behaviour of complex electronic systems to natural lightning

Study of lightning in flight has already supplied very positive results such as : swept stroke trajectography (F-106B), measurements of electromagnetic coupling through openings (TRANSALL04), or data on the radiated electromagnetic spectrum (C-580 and TRANSALL04).
It seems necessary to continue these trials in order to complete the characterization of lightning and its interaction with the aircraft.
In addition, it would be useful to evaluate new electronic systems under real lightning conditions in order to compare the results to those gathered from ground simulations, which remain questionable. Installation of new systems would lead to reproduce all coupling modes found in modern aircraft.

- 3D electromagnetic computing codes

The aircraft geometry, the assembly of its components, the structural materials used and cables routing are already available in computer data file.
The next step could be the association of an electromagnetic code, in order to :

1) evaluate induced levels in circuits connecting the various equipment units.

2) optimize hardening of the equipment in relation with the overall protection requirements, as imposed by the environmental conditions.

- Definition of the protection levels to equipments units and related test methods

The overall electromagnetic protection of a system is shared between :
. the aircraft
. the circuits
. the equipment units

In order to determine the protection covering the two first items, the aircraft manufacturer must know the threat level the equipment can stand.
Documents listing applicable conditions and describing test methods must be either updated or completed (DO160/ED14, SAE AE4L, MIL STD 1757, STANAG...).
Present experience shows that the aircraft manufacturer is led to multiply tests and reinforce protections at the aircraft level, pending issue of a standardization.

- Initial check and maintenance equipment

New requirements came up to check protections applied to composite materials which can be associated or not to highly conductive structural elements.
Previous test procedures using D.C. methods on metal structures are unusable in tests made on composite aircraft.
Techniques to come should provide for the possibility to measure both the initial state and the changes due to aging for any solution selected to protect the aircraft against direct and indirect effects of lightning as well as other electromagnetic threats.

CONCLUSION

An important work is still to be performed before giving a satisfactory answer to yet unsolved questions covering :

- threat characteristics
- vulnerability of the aircraft and its systems
- selection of protections
- test methods and test equipments.

The aircraft manufacturer cannot afford to wait until everything is set. For the present time, and considering the latest developments, the manufacturer must select solutions ensuring safety of new aircraft. Precise criteria not being available, these protections are often overdimensioned, thereby loosing some of the advantages coming from new techniques.

Under these conditions, it seems urgent to define new recommendations or instruction rules specific to aircraft incorporating the latest technologies or techniques ; this work should, as much as possible, take into account choices already made or trends adopted by the manufacturer during the transition period.

TECHNICAL PROGRAM

Session 1A
STATISTICAL DATA AND STANDARDS
Chairman : M. DILL

1A-1 R.L. GARDNER, L. BAKER, J.L. GILBERT, C.E. BAUM and D.J. ANDERSH.- Comparison of published HEMP and natural lightning on the surface of an aircraft 1

1A-2 J.C. CORBIN.- Military standard for lightning protection of aerospace vehicles 9

Session 2A
COUPLING AND INDIRECT EFFECTS
Chairman : R.A. PERALA

2A-1 H.D. BRÜNS and H. SINGER.- Electromagnetic interaction of external impulse fields with aircraft 13

2A-2 K.G. LOVSTRAND, BO WAHLGREN et al.- Finite difference analysis of lightning strike to CFC wing* ....

2A-3 E. GRORUD and M. SOIRON.- Induced surface currents and fields on a conducting body by a lightning strike (frequency domain) 21

2A-4 Y. BENIGUEL.- Induced current surface density after a direct lightning strike on an aircraft 25

2A-5 P. LEVESQUE, J. TAILLET, G. LABAUNE, S. LARIGALDIE and J.C. ALLIOT.- A study of the physical mechanisms and the perturbations created by the attachment of an arc to a conducting cylinder 29

2A-6 R. HESS.- The effects of finite linear characteristics inherent in the physically realizable devices associated with cable injection tests 37

Session 1B
METEOROLOGY AND THUNDERSTORM STUDIES : MICROPHYSICS
Chairman : A.J. ILLINGWORTH

1B-1 P. LAROCHE, M. DILL, J.F. GAYET and M. FRIEDLANDER.- In-flight thunderstorm environmental measurements during the Landes 84 campaign 59

1B-2 J.F. GAYET, C. DUROURE, R.G. SOULAGE and P. LAROCHE.- Location of lightning strokes on aircraft in storm field with measured electrical, microphysical and dynamical properties 67

1B-3 P. GONDOT and A. DELANNOY.- In-flight electrical conductivity measurements 71

1B-4 C.P.R. SAUNDERS and E.R. JAYARATNE.- Electric charge transfer during riming 77

Session 2B
METEOROLOGY AND THUNDERSTORM STUDIES : ELECTRIC PARAMETERS
Chairman : B. VONNEGUT

2B-1 E.P. KRIDER, R.J. BLAKESLEE and L.M. MAIER.- Thunderstorm currents and lightning charges at the NASA Kennedy Space Center 83

2B-2 M. BALA, K.C. MATHPAL and J. RAI.- Ground electrostatic field changes due to lightning 89

2B-3 Y. GOTO, K. NARITA, M. NAITO and R. FUNAYAMA.- Electric fields produced by winter thunderstorms....... 97

2B-4 P. PRADEEP KUMAR and J. RAI.- Electric field changes due to lightning in tropical thunderstorms.............. 105

Session 3A
LIGHTNING SIMULATORS : DESIGN
Chairman : B.J.C. BURROWS

3A-1 L.H. RILEY.- United States Army missile command lightning simulation test facility.................................... 111

3A-2 J.L. HEBERT, L.C. WALKO and J.G. SCHNEIDER.- Design of a fast risetime lightning generator.................. 115

3A-3 J.L. HARRISON, Y.G. CHEN, E. GALICKI, W. RICHARDSON, J.R. LIPPERT and D. HEIDLEBAUGH.- A severe threat-level lightning simulator*...

3A-4 R.A. PERALA, P.M. McKENNA, T.H. RUDOLPH and J.D. ROBB.- Implementation of a crowbar switch in a Marx generator/peaking capacitor lightning simulator system... 121

3A-5 M. MODRUSAN and P. WALTHER.- Aircraft testing with simulated lightning currents of high amplitudes and high rate of rise*...

Session 4A
LIGHTNING SIMULATORS : MEASUREMENTS
Chairman : J.A. PLUMER

4A-1 C.J. HARDWICK and V.P. DUNKLEY.- The observation of high frequency $\dot{B}$ and $\dot{D}$ transients excited on a fuselage by an impulse generator.. 127

4A-2 C. EASTERBROOK and R. PERALA.- The utility of low level and threat level testing methods in assessing lightning hardness of composite and all metal aircraft*..

4A-3 L.C. WALKO and J.L. HEBERT.- Lightning simulation tests in FAA CV-580 lightning research aircraft........... 137

4A-4 D.B. WALEN.- Lightning simulation tests on a graphite/epoxy airplane mockup*...

Session 5A
FUEL IGNITION HAZARDS
Chairman : G.A.M. ODAM

5A-1 W.E. HUTCHINSON, M.L. VINCENT and J. CARTER.- Lightning protection for composite fuel tanks*............

5A-2 R.O. BRICK.- Multipath lightning protection for composite structure integral fuel tank design........................ 149

5A-3 F.J. ANDERSON, G.D. FREIER, T.S. LEE and J.D. ROBB.- Optical detection methods for testing of fuel tank lightning ignition hazards.. 157

Session 3B
PHENOMENOLOGY AND CHARACTERIZATION OF LIGHTNING :
GROUND MEASUREMENTS
Chairman : E.P. KRIDER

3B-1 K. NARITA, Y. GOTO and R. FUNAYAMA.- Bipolar lightning in winter season at Maki, Japan*......................

3B-2 E.M. THOMSON, P. MEDELIUS, M. RUBINSTEIN, M.A. UMAN, J. JOHNSON and J.W. STONE.- Horizontal electric fields from lightning return strokes.. 167

3B-3 C. WEIDMAN, J. HAMELIN and M. LE BOULCH.- Lightning VHF and UHF emissions and fast time resolved measurements of the associated electric field variations.. 175

3B-4 P. RICHARD, F. BROUTET and A. BONDIOU.- Spatial characterization of the VHF-UHF lightning radiation*

3B-5 A. BONDIOU, I. TAUDIERE and P. RICHARD.- Temporal characterization of the VHF-UHF lightning radiation*

3B-6 C. LETEINTURIER, E.P. KRIDER and J.C. WILLETT.- Submicrosecond structure of the radiation fields produced by lightning........ 185

Session 4B
PHENOMENOLOGY AND CHARACTERIZATION OF LIGHTNING :
MODELIZATION
Chairman : P.L. RUSTAN

4B-1 B. HUTZLER, C. RIQUEL and J.-P. RIU.- High voltage laboratory tests and lightning phenomena........ 191

4B-2 S. LARIGALDIE.- High current surface discharge propagation analysis - Application to the lightning leader..... 197

4B-3 P.R.P. HOOLE and J.E. ALLEN.- Lightning magnetic field calculation using finite element method........ 205

4B-4 P. HUBERT.- A new model of lightning subsequent stroke - Confrontation with triggered lightning observations........ 211

4B-5 T.S. VERMA.- On the regeneration of multiple strokes in lightning flashes*........

4B-6 J.A. BICKNELL and R.W. SHELTON.- The energy requirements of an aircraft triggered discharge........ 217

4B-7 A. BONDIOU, G. LABAUNE and J.P. MARQUE.- Electromagnetic radiation associated with the breakdown of air at atmospheric pressure........ 223

Session 6A
PHENOMENOLOGY AND CHARACTERIZATION OF LIGHTNING :
TRIGGERED LIGHTNING
Chairman : M.A. UMAN

6A-1 H.W. KASEMIR.- Differences and similarities of cloud to ground discharges and lightning discharges triggered from the ground*........

6A-2 P. LAROCHE, A. EYBERT-BERARD and L. BARRET.- Triggered lightning flash characterization........ 231

6A-3 Z.I. KAWASAKI, M. NAKANO, T. TAKEUTI and T. NAKAI.- Group velocity of lightning return stroke currents 241

Session 7A
PHENOMENOLOGY AND CHARACTERIZATION OF LIGHTNING :
AIRBORNE MEASUREMENTS
Chairman : J.L. BOULAY

7A-1 N.O. RASCH and M.S. GLYNN.- Survey of lightning hazard and low altitute direct lightning strike program.... 247

7A-2 P.L. RUSTAN Jr., B.P. KUHLMAN and J.M. REAZER.- Airborne and ground electromagnetic field measurements of lightning........ 253

7A-3 P.L. RUSTAN Jr. and J.P. MOREAU.- Aircraft lightning attachment at low altitudes........ 259

7A-4 B.D. FISHER, P.W. BROWN and J.A. PLUMER.- Research in lightning swept-stroke attachment patterns and flight conditions with the NASA F-106B airplane........ 267

7A-5 V. MAZUR, B.D. FISHER and J.C. GERLACH.- Lightning strikes to an airplane penetrating thunderstorms at low altitudes*........

7A-6 J.P. MOREAU and J.C. ALLIOT.- E and H fields measurements on the transall C160 aircraft during lightning flashes........ 281

Session 8A
SUSCEPTIBILITY AND PROTECTION OF AVIONICS
Chairman : J. BISHOP

8A-1 W.W. EVERETT III and W.W. EVERETT Jr.- Microprocessor susceptibility at RF power levels associates with lightning strokes*........

8A-2 R.L. VAUGHN.- Airworthiness considerations of lightning strike protection for helicopter digital engine controls* ....

8A-3 R. HESS.- Implications associated with the operation of digital data processing in the presence of the relatively harsh EMP environments produced by lightning 289

8A-4 B.I. WOLFF and R.A. EARLE.- A new form of transient suppressor 293

Session 5B
GROUND SYSTEMS PROTECTION
Chairman : C. GARY

5B-1 R.B. CARPENTER Jr. and M.D. DRABKIN.- A 12 year study of lightning strike prevention systems 299

5B-2 YAN MUHONG.- A numerical calculation of space charge layer created by corona due to a ground artificial point beneath thunderstorm 305

5B-3 CHANGMING GUO.- Can lightning strike inhibitor inhibit lightning ?* ....

5B-4 N. KITAGAWA, K. ISHIKURA and H. OHTA.- The evaluation of the step voltage caused by lightning flashes to ground* ....

5B-5 B.G. MELANDER.- The effects of termination impedance on lightning current measurements and lightning threat definition* ....

5B-6 R.T. HASBROUCK.- Investigation of the lightning vulnerability of nuclear explosive test systems at the Nevada test site 311

5B-7 I. MLADENOVIĆ and A. VORGUČIĆ.- Stepped leader and striking distance 321

5B-8 A. VORGUČIĆ and I. MLADENOVIĆ.- Exposition to the lightning current of objects situated near to the vertical lightning rod 325

5B-9 C.N. GOLUB.- Lightning and logistics. Cape Canaveral - A proving ground for lightning research 329

Session 6B
LIGHTNING LOCATORS
Chairman : J. HAMELIN

6B-1 R.E. ORVILLE Sr., R.B. PYLE, R.W. HENDERSON, R.E. ORVILLE Jr. and R.A. Weisman.- Characteristics of cloud-to-ground lightning flashes along the east coast of the United States 333

6B-2 M.W. MAIER and W. JAFFERIS.- Locating rocket triggered lightning using the LLP lightning locating system at the NASA Kennedy Space Center 337

6B-3 W.A. LYONS, R.B. BENT and W.H. HIGHLANDS.- Operational uses of data from several lightning position and tracking systems (LPATS) 347

6B-4 L.W. PARKER and H.W. KASEMIR.- Ranging and azimuthal problems of an airborne crossed loop used as a single-station lightning locator 357

Session 9A
AIRCRAFT SYSTEMS PROTECTION
Chairman : H. KNOLLER

9A-1 J.R. LIPPERT, R.C. BEAVIN and J.E. LAVOIE.- Development and demonstration of atmospheric electricity hazard protection* ....

9A-2 W.W. COOLEY.- Lightning protection tradeoffs for indirect effects protection* ....

9A-3 A.R. CARLSON and D.L. TAGUE.- A study of EMP/lightning on F-16 aircraft* ....

9A-4 J.L. TER HASEBORG and H. TRINKS.- Special protection circuits against transient currents for aircraft systems 363

9A-5 J. BISHOP, A. AKED, C.W. POWELL and H.M. RYAN.- Aspects of lightning protection schemes for radomes (Paper received too late to be included in its session) 499

9A-6 C. KING.- Lightning-induced transient test on a transport aircraft.......... 367

Session 10A
STRUCTURES AND MATERIALS
Chairman : J. SKIBA

10A-1 T.S. LEE and W.Y. SU.- Time-convoluted hotspot temperature field on a metal skin due to sustained arc stroke heating.......... 371

10A-2 T.S. LEE and J.D. ROBB.- Ring discharge on the backsurface of a composite skin with ohmic anisotropy in response to frontal high current injection.......... 377

10A-3 H.-P. WENTZEL, C.M. HERKERT, Th. THIELE and G. BOES.- Development and testing of protection measures for reinforced composites against lightning strike.......... 383

10A-4 Th. THIELE and G. BOES.- Lightning stroke tests at the CFRP horizontal stabilizer of alpha jet.......... 395

10A-5 H. EBNETH.- Simulated lightning tests on Baymetex C protected graphite-epoxy laminates.......... 403

Session 7B
ELECTROSTATICS
Chairman : J.E. NANEVICZ

7B-1 A.J. ILLINGWORTH and S.J. MARSH.- Static charging of aircraft by collisions with ice crystals*..........

7B-2 B. GARDINER, J. HALLETT and C.P.R. SAUNDERS.- Field observations of aircraft charging in convective clouds.......... 423

7B-3 P. LAROCHE.- Airborne measurements of electrical atmospheric fields produced by convective clouds*..........

7B-4 M.L. PRICE, R.A. PERALA, G. EDLIN and C.B. MOORE.- Dust electrification during large explosions.......... 431

7B-5 J.E. NANEVICZ and E.F. VANCE.- Corona threshold determination by three-stage physical modelling of aircraft.......... 441

7B-6 H. SCHNEIDER.- Live tests on static electricity in fuelling of aircraft.......... 451

7B-7 D. KÖNIGSTEIN.- Hand-held electrostatic charge distribution measuring system.......... 461

Session 8B
SPACECRAFT PROTECTION AGAINST STATIC ELECTRICITY
Chairman : J.P. CATANI

8B-1 L. LEVY.- A new understanding of breakdowns in the day sections of geosynchronous orbit.......... 467

8B-2 J.E. NANEVICZ and R.C. ADAMO.- Status of critical issues in the area of spacecraft charging.......... 475

8B-3 J.P. MARQUE.- Propagation mechanisms analysis of electrostatic discharges on satellites*..........

8B-4 B.M. SHUMAN and H.A. COHEN.- A charge control system for spacecraft protection*..........

8B-5 M. BLEZ, J. THAYER and J.E. NANEVICZ.- Spacecraft materials test in a continuous, broad energy-spectrum electron beam.......... 485

AUTHOR INDEX.......... 509

*Paper not available for incorporation into this book.

COMPARISON OF PUBLISHED HEMP AND NATURAL LIGHTNING ON THE SURFACE OF AN AIRCRAFT

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Abstract - High Altitude EMP, (HEMP) and Lightning are both electromagnetic environments which threaten aircraft. These environments interact with aircraft in different ways, however. In this paper, we compare currents and changes on the surfaces of various simple aircraft-like geometries. We use these resulting currents and charges to compare lightning and HEMP.

I. INTRODUCTION

High altitude EMP (HEMP) and its concomitant electromagnetic environment potentially threaten an aircraft. HEMP, a short (~ 0.1 µs) pulse of large amplitude (~ 50 kV/m) arrives at aircraft essentially as a plane wave. Although this pulse generally contains no oscillations (zero crossings), it's Fourier transform shows frequency content over a wide band, with significant content up to 100 MHz. For present purposes we use a well-known public domain HEMP waveform.

Lightning, another potential threat, can interact with an aircraft in two essentially different ways. First, for a nearby strike, the electromagnetic fields generated in and near the stroke channel impinge on the aircraft. Second, for a direct strike on the aircraft, the stroke current actually flows on the conducting structure of the aircraft. The first of these effects may be called field interaction and the second, current injection. It is reasonable to expect that the latter may have larger effects than the former because the strike current path is along the aircraft.

Because of the increasing concerns about these two threats, this study assessed the differences between the electromagnetic environment associated with HEMP and that associated with natural lightning, including the manner in which they affect aircraft. The investigation was based on the environments suggested by public domain literature for HEMP and by published data for natural lightning. These environments are described in Section 2 of this paper. The comparison of the two threats was based on the currents and charges on a simple geometry representative of the characteristics of an aircraft that were caused by the two electromagnetic environments. In Section 3 several simple analytical models are presented to relate the currents and charges to the environments. These models are then used to compare the two threats to aircraft in Section 4.

In Section 5, operational considerations for the two threats are presented. Lightning is improbable but damaging to aircraft. Exposure to HEMP is essentially certain for military aircraft in war but is more likely to cause indirect damage to electronic systems than the direct damage often caused by lightning.

Section 6 presents the conclusions of the study, that below about 1 MHz lightning dominates, above 10 MHz HEMP dominates, and between the two limits the interaction of the environment with the aircraft is sufficiently complex that either may dominate, depending on the details of the aircraft.

II. ENVIRONMENTS

This section presents the electromagnetic environments produced by HEMP and lightning. The environment for HEMP is that presented in the public domain [Ref. 1]. The lightning environment is derived from a number of references which present actual measurements of lightning electrical characteristics. In this paper the mechanism of HEMP and the various arguments used for determining a lightning environment are only summarized. For more detail see reference 2.

HEMP Environment

The generation of HEMP by a nuclear device is described in detail in an article by Longmire [Ref. 1]. In this paper we are primarily concerned with high altitude EMP which is characterized by an exoatmospheric nuclear detonation and a source region which extends from 20 to 40 km altitude and geographically over regions as large as the continental United States.

HEMP is generated by the interaction of weapon gamma rays with the atmosphere. Weapon gammas scatter electrons from molecules in the atmosphere and produce a radial current. This radial current would not radiate if the weapon is immersed in a uniform atmosphere. Since the weapon is above the earth's atmosphere the symmetry is broken and the EMP radiated field is produced. These forward scattered electrons are bent in the earth's magnetic field and produce a transverse current which radiates efficiently. The primary electrons produce a number of secondary electron-ion pairs which form a background conductivity. The air conductivity limits the electric field to a saturation value. For this study, the saturation field is about 60 kV/m. Sophisticated codes are used to calculate the field levels for HEMP and these calculations agree well with experimental data.

The incident HEMP waveform depends on a number of factors including: height of burst, device type, atmospheric conditions, and distance from the explosion. To avoid this complexity during the system design process a guideline waveshape is used. A waveform presented in reference 1 is:

$$E(t) = \frac{E_0}{e^{-(t-t_0)/\tau_r} + e^{(t-t_0)/\tau_f}} \qquad (1)$$

where

E_0 = 60 kV/m (saturation field)

τ_f = 250 ns is the fall time

τ_r = 2 ns is the rise time constant

and u(t) is unit step function.

In this comparison of HEMP and lightning, HEMP will treated as an incident plane wave with the waveform described by Equation 1. With this waveform, the peak amplitude is the predicted saturation value of 60 kV/m. While the peak field of HEMP depends strongly on device design and burst height, this field provides a reasonable representation of an expected HEMP wave-form.

Lightning Environment

In this report, the current, that is the electromagnetic environment for direct and nearby strikes, is assumed to be produced in a return stroke because it typically has the largest currents and rates of rise. Detailed descriptions of the sequence of events in a lightning discharge and relevant definitions are contained in Uman [Ref. 3] and Golde [Ref. 4].

To characterize the lightning environment, which is the lightning current, three figures of merit are sufficient to specify the double exponential waveform of Equation (1). The three figures of merit considered here are:

(1) Peak Current
(2) Peak rate of rise of the current
(3) Integral of the pulse

Since the detailed theoretical modeling effort applied to HEMP has not been applied to lightning, it was necessary to use empirical techniques to determine the figures of merit listed above. All of the available measurements from which estimates of lightning current parameters are derived may be divided into three classes:

(1) Tower measurements
(2) Measurements on aircraft in flight
(3) Radiated field inference of current

Data from each of these sources were used to estimate the current in the lightning channel. This current within the channel establishes the lightning current waveform that constitutes the threat.

Tower Measurements.

Tower measurements of lightning currents are made using current sensors installed on metal towers located where there is normally a great deal of lightning activity, generally mountain peaks. Since the tower is part of the lightning discharge circuit, the effect of the tower itself on the measurements must be considered.

Useful summaries of lightning currents and rates of rise of the current are given in Uman [Ref. 3], Golde [Ref. 4], and Garbagnati [Ref. 5]. Of those summaries, only the data presented by Garbagnati is fast enough to see characteristic times of 100 ns or less, so that data will be shown here. The longer version of this paper [Ref. 2] contains a more complete presentation of the data. The maximum rate of rise reported is less than 10^{11} A/s. Other sets of tower measurements confirm this data. When corrected for ground reflection even the maximum rate of rise observed by Ericsson [Ref. 6] is very near 10^{11} A/s, as well.

At this time, tower measurements constitute the only low altitude, cloud to ground lightning current measurements available.

Aircraft Measurements.

Electromagnetic measurements made on an aircraft in flight represent another useful data base for determining the electromagnetic environment caused by lightning. Two recent sources provide data on the effects of lightning direct strikes on aircraft.

The peak rate of rise measured on the boom in front of the F-106B [Ref. 7] is particularly interesting since it has the largest rate of rise of the current. In spite of the low (13.9 kA maximum) peak currents, the peak rate of rise found by taking a graphical derivative of the current records was 1.3 x 10^{11} A/s. Significantly, the maximum value closely approximate the 10^{11} A/s maximum rate of rise seen in the tower measurements.

Currents Inferred from Field Measurements.

Another method of determining the current in a discharge is to derive the current from distant field measurements. The difficulty with this method is that the current derived from the fields is not unique and unfolding the very complicated early time current evolution of lightning is not a trivial task since no quantitative model exists for the early part of the return stroke.

Since the recently published research using this method suggests very fast rates of rise in return strokes the methods used will be more closely examined.

Uman, et al. [Ref. 8] derive the relationship between the electric field and the current in the lightning channel under a restrictive set of assumptions. The initiation point must be at the ground and the current waveform must propagate up the channel at uniform velocity and without distortion of the waveshape as it propagates. It is also assumed that the fields are entirely in the radiation zone.

Correcting the above modeling to account for the return stroke currents that initiate from a point about 100 m from the ground rather than at the ground reduces the current and derivative values by a factor of two.

For subsequent strokes there is no initiation region as described here. However, for subsequent strokes there is a memory of the location of the channel. The breakdown wave is limited in propagation velocity by the velocity of light rather than the velocity of propagation for return strokes. Near the