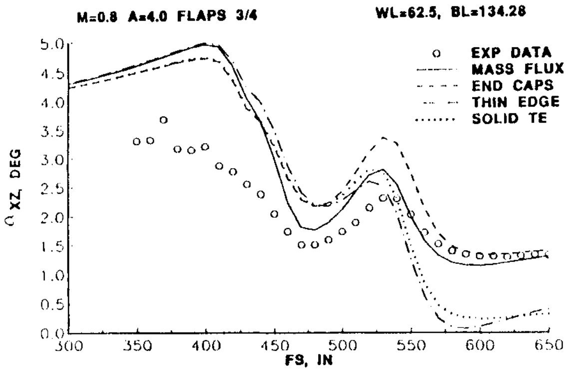
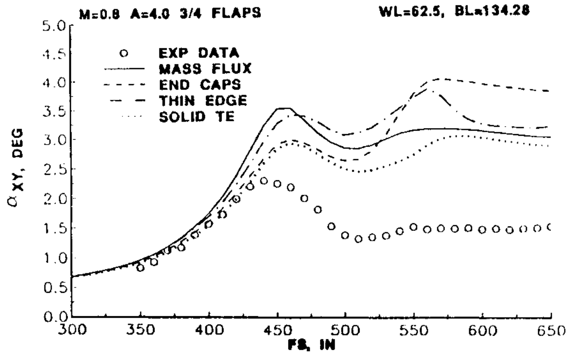


a) Upwash



b) Sidewash

Fig. 3 Flowfield comparison of methods.

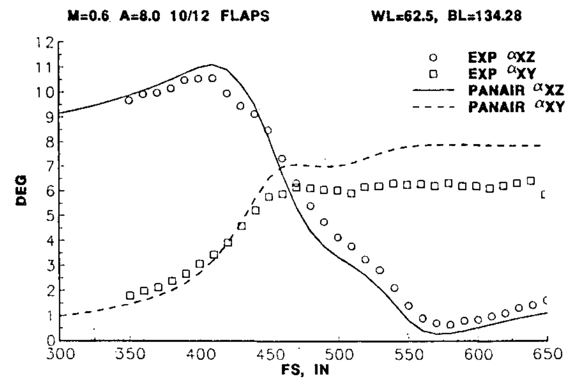


Fig. 4 Mass flux model, case 2.

= 4.0, for a flap deflection of 3-deg leading-edge down and 4-deg trailing-edge down. The inability of the first approach to accurately predict the sidewash flowfield led to the investigation of the other methods. Figure 3a is a comparison of the predicted upwash flowfield for the four methods with experimental data. It can be seen that the boundary condition method best models the upwash flowfield. Figure 3b presents the same comparison for the sidewash flowfield. For this particular flight condition and flap setting, none of the approaches accurately predict the sidewash very well. However, the boundary condition method fares as well as the other methods. The failure of the other methods to model the flowfield is more likely due to the numerical difficulties present in the solution, due to the discontinuity panels, than a failure in the physical modeling. In any event, it is clear that the mass flux specification performs adequately in predicting the flowfield, especially given its simplicity.

Due to the relatively good performance of the boundary condition approach and its ease of application, other conditions were investigated using just this method. Figure 4 presents the flowfield comparisons for $M_\infty = 0.6$, $\alpha = 8.0$, with 10/12 flaps. Again the only discrepancies appear in sidewash.

Conclusions

Several approaches to modeling simply connected flaps with PAN AIR have been investigated. The boundary condition method specifies mass flux through the flap to approximate the turning angle induced by the flap. Each method was compared to the other methods and to experimental data based on the flowfield directly under the outboard pylon.

Relative to the geometric approaches, the boundary condition approach does a very good job of modeling the upwash and sidewash flowfields. In absolute terms, compared to experimental data, this approach matches upwash well and sidewash to various levels, depending on flight condition. The attractive feature of this method is that it requires no geometry changes to a properly peneled baseline model in order to model flap settings. Analysis of many different flap configurations therefore becomes possible in a short time period. This method should apply equally as well to elevator and rudder deflection analysis. Due to its simplicity and accuracy, the boundary condition method of simply connected flap modeling provides an excellent tool for flowfield analysis.

References

[1]Magnus, A. E., and Epton, M. A., "PAN AIR—A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations Using a Higher Order Panel Method, Vol. 1, Theory Document (Version 1.0)," NASA-CR-3251, 1980.

[2]Sidwell, K. W., Baruah, P. K., and Bussoletti, J. E., "PAN AIR—A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations Using a Higher Order Panel Method, Vol. 2, User's Manual (Version 1.0)," NASA-CR-3252, 1980.

[3]Saaris, G. R., "A502H User's Manual—PAN AIR Technology Program for Solving Problems of Potential Flow About Arbitrary Configurations," Boeing Document D6-54703, Feb. 1990.

[4]Carmichael, R. L., and Erickson, L. L. "PAN AIR—A Higher Order Panel Method for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations," AIAA Paper 81-1255, June 1981.

[5]Cenko, A., Tseng, W., and Madson, M., "Potential Flow Applications to Complex Configurations," AIAA Paper 91-1634, June 1991.

[6]Cenko, A., and Tessitore, F., "Evaluation of Methods for Predicting Complex Aircraft Flowfields," *Journal of Aircraft*, Vol. 25, No. 5, 1988, pp. 453–458.

[7]Tinoco, E. N., Ball, D. N., and Rice, F. A. II, "PAN AIR Analysis of a Transport High-Lift Configuration," *Journal of Aircraft*, Vol. 24, No. 3, 1987, pp. 181–187.

Lightning Threat to Aircraft: Do We Know All We Need to Know?

Vladislav Mazur*
NOAA/National Severe Storms Laboratory, Norman, Oklahoma 73069

Introduction

THE problem of lightning threat to aircraft has two aspects: 1) strike avoidance, and 2) aircraft protection. Let us address these two issues separately.

Received Oct. 16, 1991; revision received April 21, 1992; accepted for publication May 1, 1992. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

*Physicist, Storm Electricity and Cloud Physics Group.

Lightning Strikes, Weather Conditions and Natural Lightning Rate

For strike avoidance we need to know where in electrified clouds strikes to aircraft may take place and with what probability. This information is useful to pilots, aviation meteorologists, and possibly to air-traffic controllers.

Three major research programs studying lightning-aircraft interaction: 1) NASA Storm Hazards program (1980–1986); 2) USAF/FAA Lightning Characterization program (1984–85, 1987); and 3) French Transall program (1984, 1988), although focusing on in-flight measurements of strike parameters also produced significant new data about environmental conditions conducive to lightning strikes to aircraft in summer thunderstorms. Thunderstorms were the obvious choice to conduct such measurements because of the belief that lightning hazards occur where lightning activity naturally exists.

The important thing we learned from this experience about lightning-aircraft interaction was that all lightning strikes in storms at flight altitudes about 7 km (high altitudes) and about 90% of strikes at altitudes below 7 km (low altitudes) are triggered by the aircraft itself.[1-3] Thus, the main factor contributing to lightning strike to aircraft is not the presence of natural lightning activity, but the presence of a sufficient ambient electric field to initiate a discharge on an aircraft of given size, configuration, and speed. It was also shown that only about 10% of strikes at low-flight altitudes are actually intercepted natural lightning flashes.[2,3]

The previous beliefs that lightning strikes to aircraft somehow relate to the presence of turbulence were dismissed. Most lightning strikes in summer storms occur in light rain and light turbulence conditions.[2] We also learned, from data obtained with the NASA F-106B instrumented airplane during high altitude storm penetrations, that the probability of triggering lightning decreases with the increasing rate of natural lightning.[1] A similar conclusion was made in rocket-triggered lightning experiments: the probability of triggering lightning is very low when the rate of natural lightning is high and vice versa (personal communications with J. L. Boulay, P. Laroche, and W. Jefferies). This seemingly paradoxical phenomenon may be understood if we consider a natural triggering mechanism in storms and compare it with an artificial triggering by aircraft. When the natural triggering mechanism is active, it works like a firing electrode for a large gap discharge (lightning flash) starting it each time when an ambient electric field inside the cloud is ready to support propagation of this discharge. In such a case, an additional source of triggering (aircraft or rocket with a wire) does not produce lightning initiation being out of phase with the big gap (cloud) electric field.

In line with this explanation are observations showing that the decaying stage of the storm is the most dangerous for penetrating aircraft: the probability of aircraft-triggered lightning as well as chances to succeed with a rocket-triggered lightning are the highest at this time.[2] Although the cloud is still electrified during the decaying stage, the natural triggering mechanism there is very weak, evidence of which is a lack of natural lightning activity. Thus, an aircraft or a rocket with a trailing wire becomes a likely source of lightning initiation due to its conductivity and size.

As far as the safest place for aircraft penetration, we learned from the experience of the NASA Langley Storm Hazards and FAA/USAF programs that the longest flight time needed to obtain a lightning strike to aircraft is at altitudes near and below cloud base. The question of whether these altitudes may be considered the safest for aircraft in relation to lightning hazards remains to be proven.

While storm penetrations with instrumented aircraft provided scientific data on environmental conditions conducive to lightning hazards, the same kind of data on lightning hazards to aircraft in winter storms, marginally electrified stratiform, and mixed phase clouds are totally lacking. What is known from pilots' surveys is that the majority of reported strikes to civil aircraft and space vehicles in the U.S. occurred in marginally electrified and mixed phase clouds,[4] and in Japan the majority of reported strikes occurred in winter storms.[5]

Marginally electrified and mixed phase clouds do not produce natural lightning. Furthermore, we presently do not know how to evaluate the magnitude and structure of the electric field inside these clouds remotely without entering them. Therefore, the study of electric hazards in these clouds should be more comprehensive than in thunderstorms, and should include in situ and remote sensing for electrical and microphysical parameters, kinematic modeling of electrification processes, and in situ measurements of electric discharges to aircraft. The objective of such a study would be to identify the cloud electrical condition (field intensity and structure) by its association with microphysical parameters and cloud kinematics from radar observations with Doppler and polarization diversity radars.

Unfortunately, after the last in-flight program conducted by the FAA in 1987 there is no further commitment from U.S. government agencies to in situ measurements of lightning-aircraft interaction. The FAA has decided not to support the combined U.S.—France program that was designed partly to investigate electrical hazards to aircraft in the marginally electrified clouds. The USAF was unable to support the proposed exploratory study of electrification mechanisms in stratiform clouds utilizing opportunities of the CAPE-91 program. The NASA Airborne Electric Field program presently underway with a single objective to evaluate the electric field inside "nonthunderstorm" clouds is an example of an engineering rather than a scientific approach to solving this problem.

Since the problem of lightning hazards to aircraft in most common weather conditions of marginally electrified clouds remains unsolved, the Atlas-Centaur accident of 1987[6] should be a constant reminder to us that this could happen again.

Aircraft Protection: Engineering vs Scientific Approach

In simple terms, an engineering approach to the evaluation of the lightning threat to aircraft consists of flying an instrumented airplane in thunderstorms in order to encounter lightning strikes, to measure some of their parameters, and to apply results to aircraft testing and certification. A scientific approach is based on the comprehension of the entire lightning strike process to the degree that affects the aircraft, to measure and evaluate all components of the process, and to synthesize results for applications. Let us review what we did measure during past in-flight programs, how well we did measure it, and how well our measurements represent the lightning threat to aircraft.

Most quantitative measurements of lightning strikes were made during the initial attachment of the lightning channel to the aircraft.[2-9] With a maximum frequency range up to 80 MHz in digital recording systems, the short (minimum duration of a few microseconds) records were obtained to characterize individual pulses during the initiation stage.[10] Continuous records of electromagnetic waveforms for the entire strike duration (hundreds of milliseconds) were made at frequency ranges up to 2 MHz.[3,11,12] The peak detector used during the NASA storm hazards program, although having a wide frequency band, produced records that were random (one record per flight) and, therefore, could not be identified with any of the lightning processes.

Measurements described above produced a population of statistically compounded pulses (their amplitudes, rise times, and durations) that characterize strike initiation with an acceptable accuracy.[13] Measurements of other processes involved in strike development following the initiation are less precise because of the limited frequency band width of recorders and the sometimes small number of samples.

The scientific interpretation of airborne measurements advanced the hypothesis that a lightning strike starts at the aircraft as a bidirectional leader with positive and negative leaders exiting from the aircraft's extremities that have maximum charges of opposite signs.[14] This hypothesis was verified in numerous laboratory studies[15,16] and most recent airborne measurements (personal communication with J. P. Moreau).

After initiation on the aircraft, the lightning strike develops inside the cloud similarly to natural lightning discharge and may become either an intracloud or cloud-to-ground (CG) flash, depending on the environmental electrical conditions and flight altitude. During such development, the aircraft remains part of the lightning channel for most of flash duration (hundreds of milliseconds). Thus, the similarity between processes in triggered and natural lightning, especially for processes following the initiation, is rather obvious.[17] This means that we can apply definitions of natural lightning processes to the aircraft-triggered lightning.

We learned the following from the scientific analysis of lightning strike development:

1) All lightning strikes to aircraft at high altitudes (>7 km) develop after their initiation similar to intracloud flashes.[1]

2) At altitudes of 7 km and below, about 25% of lightning strikes develop into CG flashes.[18]

3) The intracloud development of lightning strikes is characterized by a continuing current flow of positive leaders and intermittently occurring negative recoil streamers.[14]

4) The amplitudes of return strokes reaching the aircraft are much smaller than those measured at the ground level. They are comparable to, or less than, the amplitudes of both the recoil streamers intercepting the aircraft during the intracloud development of the strike and the negative leader pulses during the initiation process.[11,19]

5) New initiation processes may take place during the intracloud lightning development of the strike.[11]

This new knowledge is not reflected yet in the technical document, the SAE AE4L committee report (Orange Book),[20] that defines technical criteria for lightning strike protection of the aircraft systems in the U.S. The latest version of this document revised in January 1989 still equates a lightning strike to aircraft to a cloud-to-ground flash and uses the reference book[21] as a source of data. The analysis of airborne lightning data obtained during the past decade, however, clearly identifies a typical lightning strike as similar to an intracloud rather than to a cloud-to-ground natural flash. Therefore, the present zonal application of current waveforms on the aircraft's surface described in the Orange Book should be corrected. The correction may require 1) a review of airborne data already obtained with zones and waveforms attached to them identified; and 2) possibly new airborne measurements of current waveforms and video images of strikes for assisting in zone identification.

The direct strike environment, as presently seen from scientific analysis of airborne data, includes the following elements:

1) Component A is a series of current pulses during the lightning initiation process on aircraft with a peak amplitude of at least 20 kA (possibly 55 kA), a pulse duration of a fraction of microseconds to less than 2 μs, a series duration of maximum 20 ms, a pulse rate of up to 20 ms^{-1},[14] and a peak rate of rise of 4.0×10^{11} A s^{-1}.[13] Component A is present in 90% of all lightning strikes to aircraft. Measurements listed are obtained with sufficient frequency band width and from a statistically significant population of samples. The maximum value of 55 kA was measured by the peak detector on the NASA F-106B airplane during a noncloud-to-ground strike.[13] Because of the ambiguity of the measurement, this peak value can be attributed either to component A or B pulses.

2) Component B is a single pulse of negative recoil streamer or dart leader with a duration from tens of microseconds to a few hundred microseconds, a peak amplitude of several kiloamperes, possibly up to 55 kiloamperes (see comment about component A), and a rise time of hundreds of nanoseconds.[11,12] Measurements of amplitudes and rise times are, however, frequency limited. Component B is present in all lightning strikes to aircraft inside thunderstorms, although the number of pulses per strike varies.

3) Component C is a continuing current lasting for hundreds of ms with low frequency variations of higher amplitudes and tens of milliseconds long. An average amplitude is a few tens of amperes, and maximum amplitudes are hundreds of amperes.[14] The component C is present in all aircraft-triggered strikes. Measurements are statistically sufficient.

4) Component D is return stroke pulses with a duration of several hundreds of microseconds, a peak amplitude of up to 26–30 kA, and rates of rise of less than 1.6×10^{11} A s^{-1}.[18] The component D is present in about 25% of lightning strikes at altitudes below 7 km. The unambiguous measurements of peak amplitudes with a wide frequency band are lacking. More in-flight measurements are needed to obtain a statistically sufficient population of samples.

The SAE AE4L report needs to be upgraded to include the testing and certification criteria that reflect the characterization of lightning strike processes obtained from the analyses of airborne measurements during the last decade. Although some estimates of lightning parameters are not supported by a statistically significant number of samples, e.g., in cloud-to-ground strikes to aircraft, they nevertheless represent a realistic picture of lightning-aircraft interaction and with this reservation should be mentioned in the SAE AE4L report.

Lightning Threat to Aircraft: What Else Do We Need to Know?

In-flight research programs during the last decade were conducted only in summer thunderstorms where lightning strikes to aircraft are very similar to natural lightning flashes. Although there is a strong indication that the physics of strike initiation in winter thunderstorms, stratiform, and mixed-phase clouds would be the same as in thunderstorms, we lack scientific data on the characteristics of electrical discharges under these conditions. Presently, we project our knowledge of lightning strikes to aircraft in summer thunderstorms on those experienced in other environmental conditions. This assumption is not justified yet, and therefore misleading or possibly erroneous. By conducting in-flight measurements we need to determine the characteristics of strikes to aircraft in winter storms and marginally electrified nonthunderstorm clouds to find out how much they are the same or different from those in summer thunderstorms. It is expected that owing to the different strength, spatial extension, and distribution of electric fields inside winter storms and nonthunderstorm clouds, the strikes there may differ from those in summer storms. By the same reasons, the cloud regions with the highest probability of lightning strikes to aircraft may be quite different from those in summer storms. The long-term goal of this investigation would be to gain the ability—using remote sensing techniques—to evaluate a threat of aircraft-triggered lightning prior to penetration of a given cloud by a given space vehicle.

In spite of significant progress made in the evaluation of lightning hazards to aircraft in summer thunderstorms, this task is not completed yet. Additional airborne measurements with a wide frequency band are needed for the statistical evaluation of current waveforms for processes during intracloud and cloud-to-ground development of lightning strikes following initiation (recoil streamers, dart leaders, return strokes, and new initiations).

Acknowledgments

This work was supported in part by FAA Grant DTFA 03-87-A-00021. The author is grateful to Michael Glynn of the FAA Technical Center for his support.

References

[1]Mazur, V., Fisher, B. D., and Gerlach, J. C., "Lightning Strikes to an Airplane in a Thunderstorm," *Journal of Aircraft*, Vol. 21, No. 8, 1984, pp. 607–611.

[2]Mazur, V., Fisher, B. D., and Gerlach, J. C., "Lightning Strikes to a NASA Airplane Penetrating Thunderstorms at Low Altitudes," *Journal of Aircraft*, Vol. 23, No. 6, 1986, pp. 499–505.

[3]Reazer, J. S., Serrano, A. V., Walko, L. C., and Burket, H. D., "Analysis of Correlated Electromagnetic Fields and Current Pulses During Airborne Lightning Attachments," *Electromagnetics*, Vol. 7, 1987, pp. 509–539.

[4]Plumer, J. A., Rasch, N. O., and Glynn, M. S., "Recent Data from the Airlines Lightning Strike Reporting Project," *Journal of Aircraft*, Vol. 22, 1985, pp. 429–433.

[5]Goto, Y., and Narita, K., "Lightning Interaction with Aircraft and Winter Lightning in Japan," *Research Letters on Atmospheric Electricity*, Vol. 6, 1986, pp. 27–34.

[6]Christian, H. J., Mazur, V., Fisher, B. D., Ruhnke, L. H., Crouch, K., and Perala, R. A., "The Atlas/Centaur Lightning Strike Incident," *Journal of Geophysical Research*, Vol. 94, No. D11, 1989, pp. 13, 169–13, 177.

[7]Pitts, F. L., "Electromagnetic Measurements of Lightning Strikes to Aircraft," *Journal of Aircraft*, Vol. 19, 1982, pp. 246–250.

[8]Rustan, P. L., Kuhlman, B., Showalter, J., and Reazer, J., "Electromagnetic Measurements of Lightning Attachment to Aircraft," *Proceedings of the 8th International Aerospace and Ground Conference on Lightning and Static Electricity*, Fort Worth, TX, June 21–13, 1983, pp. 45.1–45.8.

[9]Moreau, J. P., and Alliot, J. C., "E and H Fields Measurements on the Transall C160 Aircraft During Lightning Flashes," *Proceedings of the 10th International Aerospace and Ground Conference on Lightning and Static Electricity*, Paris, France, June 10–13, 1985, pp. 281–287.

[10]Thomas, M. E., and Carney, H. K., "1984 Direct Strike Lightning Data," NASA-TM-87690, 1986.

[11]Mazur, V., and Moreau, J.-P., "Aircraft-Triggered Lightning: Processes Following Strike Initiation that Affect Aircraft," *Journal of Aircraft*, Vol. 29, No. 4, 1992, pp. 575–580.

[12]Moreau, J. P., and Larigaldie, S., "Description and Interpretation of Aircraft Lightning Attachment-Electric and Magnetic Field Measurements and Video Observations," *Proceedings of the 1991 International Aerospace and Ground Conference on Lightning and Static Electricity*, Coco Beach, FL, April 16–19, 1991, pp. 2-1–2-11.

[13]Pitts, F. L., Lee, L. D., Perala, R. A., and Rudolph, T. H., "New Methods and Results for Quantification of Lightning-Aircraft Electromagnetics," NASA TP 2737, 1987, 63 p.

[14]Mazur, V., "A Physical Model of Lightning Initiation on Aircraft in Thunderstorms," *Journal of Geophysical Research*, Vol. 94, No. D3, 1989, pp. 3326–3340.

[15]Bicknell, T. A., and Humood, B. M., "Bipolar Corona and Aircraft Triggering Discharges," *Proceedings of the 9th International Aerospace and Ground Conference on Lightning and Static Electricity*, Orlando, FL, June 26–28, 1984, pp. 4.1–4.4.

[16]Labaune, G., Moreau, J. P., Alliot, J. C., Cobin, V., Hutzler, B., Riguel, G., and Garbedian, R., "Experimental Study of the Interaction Between an Arc and an Electrically Floating Structure," *Proceedings of the 11th International Aerospace and Ground Conference on Lightning and Static Electricity*, Dayton, OH, June 24–26, 1986, pp. 27.1–27.9.

[17]Mazur, V., "Triggered Lightning Strikes to Aircraft and Natural Intracloud Discharges," *Journal of Geophysical Research*, Vol. 94, No. D3, 1989, pp. 3311–3325.

[18]Mazur, V., and Fisher, B. D., "Cloud-to-Ground Strikes to the NASA F-106 Airplane," *Journal of Aircraft*, Vol. 27, No. 4, 1990, pp. 466–468.

[19]Mazur, V., Fisher, B. D., and Brown, P. W., "Multiple Cloud-to-Ground Strike to the NASA F-106B Airplane," *Journal of Geophysical Research*, Vol. 95, No. D5, 1990, pp. 5471–5484.

[20]SAE Committee AE4L, "Recommended Draft Advisory Circular: Protection of Aircraft Electrical/Electronic Systems Against Indirect Effects of Lightning," Society of Automotive Engineers Committee Rept. AE4L-87-3, Feb. 1987.

[21]Uman, M. A., *The Lightning Discharge*, Academic Press, New York, 1987.