tial flow equations with the same degree of accuracy as that for the velocity distributions in Fig. 1.

The pressure distribution on the nose in situ on the two-dimensional slab has been integrated numerically in order to obtain the two-dimensional drag coefficient. The pressure drag coefficient vs the nose-slenderness ratio is shown in Fig. 4, and it is seen that an appreciable suction force is generated on the slender noses and that the drag coefficient increases for increasing slenderness ratio slightly more than linearly. (If the result is a realistic one, it cannot be judged at present. Suitable experimental data seem to be lacking.)

Conclusion

A semiempirical, analytical representation of the numerical solution to the incompressible potential flow equations for the pressure distribution on semi-infinite, two-dimensional bodies with elliptical noses has been obtained for nose slenderness ratios up to unity. The correlation with the theoretical result is very satisfactory. A strong dependence of the nose pressure drag coefficient on the nose-slenderness ratio is evident. Large suction forces are generated on the slender noses. The accuracy of the drag coefficient is not known at present.

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References

[1]Larson, E. S., "The Low Speed Pressure Distribution on Axi-symmetric Elliptic-Nosed Bodies," *Journal of Aircraft*, Vol. 25, No. 10, 1988, pp. 969–970.

[2]Maruhn, K., "Druckverteilungsrechnungen an Elliptischen Rümpfen und ihrem Aussenraum," *Jahrbuch 1941 der Deutschen Luftfahrtforschung*, pp. I135–I145.

[3]Hess, J. L., and Smith, A. M. O., "Calculation of Potential Flow about Arbitrary Bodies," *Progress in Aeronautical Sciences*, Vol. 8, Pergamon, Great Britain, 1967.

Cloud-to-Ground Strikes to the NASA F-106 Airplane

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Introduction

RETURN strokes of cloud-to-ground (CG) flashes are believed to represent the most severe lightning threat to aircraft. Peak current amplitudes for first return strokes (subsequent return strokes are weaker) determined from measurements at ground level have a median value in the range of 20–40 kA with 200 kA occurring at about the 1% level.[1] Current rates of rise derived from measured return stroke electric fields have an estimated mean maximum rise rate of about 1.8×10^{11} A s^{-1} for both first and subsequent strokes.[2] The Society of Automotive Engineers (SAE) recommends using a peak current value of 200 kA and a current rate of rise of 10^{11} A s^{-1} for aircraft lightning tests.[3] The validity of such a lightning threat to aircraft at altitude has been questioned. Direct measurements of return stroke current as a function of altitude do not exist. However, the variation of the current amplitude with height can be deduced by measuring the light intensity of the lightning channel, which is strongly correlated with return stroke current.[4]

This Note describes the CG strike data (20 cases) obtained with the NASA F-106B research airplane during the 1984–86 storm seasons in the vicinity of Wallops Island, Virginia.

Identification of a CG strike

In identifying strikes associated with CG flashes, we searched for a close coincidence, in both time and space, of return stroke channels and lightning attachments to the F-106B. The time and position of CG flashes were determined with the East Coast ground strike location network, which utilized magnetic direction finders manufactured by Lightning Location and Protection, Inc.[5] The airplane and network clocks were synchronized to the WWV time standard to an accuracy of 1 ms. The timing of a CG flash (time of the first return stroke) was recorded, however, to the nearest 10 ms. The moment of a strike attachment to the F-106B was identified by the onboard trigger signal. The position of the airplane in projection on the ground plane was obtained with a tracking C-band radar at Wallops Island.

An aircraft strike was considered to be associated with a CG flash if the range difference between the locations of the return stroke and the airplane during the attachment was within several tens of kilometers, and the associated time difference was less than 1 s. The range difference criterion is based on 1) the range accuracy of the CG locations provided by the ground-strike location network and 2) the range difference caused by the intracloud propagation of a CG flash within the time interval between attachment to the airplane and attachment to the ground. Location errors of an LLP system depend on the range of the flash from the direction finders and, to a lesser extent, on azimuthal angle. For distances typical of F-106B flights near Wallops Island (50–200 km), location errors may vary between 20 and 100 km.[6] A 10 ms time difference between airplane and ground attachment may correspond to a range difference of 1–1000 km depending on the type of lightning process that has taken place between attachments. The propagation speed varies between 10^5 and 10^8 ms^{-1} for different processes in the flash. For distances typical of flights and for the time differences between attachments (see the columns "Range" and "t" in Table 1), location errors are of several tens of kilometers. This is well within the range of distances between locations of attachment shown in column of "R" of Table 1.

The choice of the time difference criterion is based on lightning discharge durations, known to be more than several hundreds of milliseconds long.

Summary of CG Strikes to the F-106B During 1984-86 Seasons

During three thunderstorm seasons (1984–86), the NASA Storm Hazards Program was devoted to studying lightning strikes to aircraft in the lower altitude regions of thunderstorms. The most obvious altitude at which an aircraft may intercept a main part of the return stroke is below the cloud base. However, the probability of obtaining lightning strikes at such low altitudes decreases drastically, as shown in the analyses of the commercial airline data.[7] Therefore, attempted interceptions of the main return stroke channels

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Table 1 Summary of cloud-to-ground strikes to the F-106B[a]

Day of 1984	Strikes IC	Strikes CG	t^a (CG), ms	R, km	dI/dt,[c] A s^{-1}, peak	I,[d] kA, peak	Alt, km	Range
July 16	5	1	−90	6	0.57E+10	N.A.	6.0	85
Aug. 9	1	4	−10	24	16.15E+10		7.6	205
			+50	54				
			−30	26				
			+30	25				
Aug. 13	2	2	−110	29	6.08E+10	N.A.	6.6	173
			+90	29				
Aug. 14	2	3	+50	12	12.73E+10	N.A.	7.8	132
			+20	23			6.0	136
			+40	15			6.3	107
Day of 1985								
June 18	3	2	+450	17	0.58E+10	5.6	5.4	161
			+120	26			5.4	162
July 31	4	2	−52	52	4.9E+10	25.6	5.7	115
			+430	60				
Aug. 8	5	2	−70	46	9.7E+10	3.0	5.1	95
			−110	46			5.0	91
Day of 1986								
July 26	0	2	−180	16	5.7E+10	—[h]	4.9	155
			−110	3			5.3	124
Aug. 8	9	2	−700	26	5.4E+10	22.0	5.0	55
			−110	27			5.0	68

[a]t is the time difference between a direct strike to the F-106B and a return stroke of a CG strike. [b]"Range" is a range to the F-106B from NASA Wallops at the moment of strike. [c]dI/dt is a peak current rise rate determined with peak detector. [d]I is a peak current value determined with peak detector. [e]"Alt" is an altitude of the F-106 during the strike. [f]R is a range difference in km between locations of attachments. [g]Means not available. Signs (−) and (+) refer to occurrence of the strike to the airplane before or after the return stroke to the ground. [h]Value is < 2.5 of the full scale.

seemed unreasonable and costly for a research program. Realizing this fact, flights were conducted inside the clouds, between 6 km altitude and the cloud base with expectations that CG strikes to the F-106B would involve upper or intracloud portions of return strokes.

The summary of data on CG strikes to the F-106B is shown in Table 1. Statistically, the sample size is not sufficient to arrive at final conclusions. However, even a data set of such limited size is valuable since there are no data on CG strikes to aircraft in the literature.

Out of a total of 20 CG strikes to the F-106B, only one strike is believed to be associated with the first return stroke. For this one strike on August 9, 1984, there was a 10 ms time difference between lightning attachment to the airplane and attachment to the ground. As just discussed, the 10 ms time difference falls within the time accuracy of CG flash detections by the ground network. The remaining 19 strikes occurred either before (10 cases) or following (9 cases) the first return stroke. It is not known whether strikes that attached to the airplane prior to the first return stroke were triggered by the aircraft or were intercepted portions of a naturally occurring flash. In the case of multiple attachments to aircraft with the first strike either preceding or following the first return stroke, subsequent return strokes (in a multiple CG flash) could still propagate through the airplane.

Airborne measurements of lightning strike currents and current rates of rise present a serious technical challenge. Continuous analog recording of current pulses in the attached channel was frequency limited (400–150 kHz) and, thus, could not be used to evaluate current amplitudes. Also, digital recording of current pulses (frequency band of 8 MHz) within a single (per strike) time window of a few milliseconds[8] provided only a random sampling of current pulses in the beginning of the strike. Therefore, the peak current measurements were made with a peak detector, which had an accuracy of ±2.5% of full scale. This method produces a single peak current value and a single current rise rate value for each flight that establishes the upper limit of the current rise rates and amplitudes for all strikes occurring during a given flight. Therefore, it is not possible to distinguish CG strikes from non-CG strikes or to distinguish current pulses during the different stages of the flash (e.g., initial negative stepped leader pulses, recoil streamers, or return strokes).

Discussion and Concluding Remarks

During the three years (1984–86) of penetrating storms at low altitudes, the NASA F-106B research airplane obtained 88 lightning strikes of which 20 were associated with CG flashes. Thus, CG strikes constitute a significant portion (23%) of the total number of lightning strikes to an airplane at altitudes below 6 km. The trends we observed in the limited data set (see Table 1) are as follows.

1) The probability that an aircraft will encounter the first return stroke of the CG flash is low (one case of 20 total).

2) In the majority of CG strikes, time differences between attachments of the lightning channel to the airplane and channel attachments to the ground (tens of ms) are about two orders of magnitude greater than that expected (a fraction of ms, at a return stroke propagation speed of 10^8 m s^{-1}) for first return strokes striking both aircraft and ground. This means that processes other than the first return stroke are involved in a CG lightning strike.

3) Peak current values of 26 and 22 kA, measured on the F-106B, are not necessary from CG strikes. If assumed to be produced by CG strikes, these peak currents are comparable to average currents in return strokes measured at ground level, between 20 and 40 kA.[1]

4) Peak current rates of rise, if assumed to be produced by CG strikes, range from 0.6×10^{10} to 1.6×10^{11} A s^{-1}. These values are close to those estimated by Weidman and Krider[2] at ground level.

When a return stroke of a CG flash that started at the ground with a peak current of 200 kA and a current rate of rise of 10^{11} A s^{-1} reaches an airplane at flight altitude, its peak current and rate of rise will be much smaller. Applying the exponential decrease of the return stroke light intensity[9] [(exp) – 0.6n, where n is the altitude of the airplane in km] to the variation of the peak current in return strokes with altitude results in a peak return stroke current of 10 kA at 5 km altitude, which is in the range of values measured on the F-106B. The rate of current rise from the peak detector measurements is, however, much greater than that expected with the exponential decrease of its maximum values with altitude.

When a CG strike initiates on the airplane, the peak current is expected to be at its maximum on the airplane, rather than at the ground, whereas the highest rate of rise may occur anywhere along a negative stepped leader channel. The maximum values of peak currents and rate of rise measured on the F-106B were 54 kA and 3.8×10^{11} A s^{-1}, respectively, during the flights with non-CG strikes to the airplane.[8] Since the majority of strikes to the F-106B were triggered on the airplane,[10] it is reasonable to suggest that the largest peak values of currents and rates of rise characterize triggered strikes rather than intercepted return strokes of CG flashes. The SAE criteria on peak current rates of rise, although based on a worst-case assumption of the first return stroke attachment to the airplane with peak values equal to those measured at the ground, match in-flight measurements of current rates of rise measured during triggered strikes. The SAE criteria on peak currents, however, far exceed the predicted values of return stroke currents at flight altitudes and are also much greater than the values measured during triggered strikes.

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References

[1]Uman, M., *The Lightning Discharge,* Academic, Orlando, FL, 1987.

[2]Weidman, C. D., and Krider, E. P., "The Fine Structure of Lightning Return Stroke Wave Forms," *Journal of Geophysical Research,* Vol. 83, 1978, p. 6239–6247.

[3]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.

[4]Idone, V. P., and Orville, R. E., "Correlated Peak Relative Light Intensity and Peak Current in Triggered Lightning Subsequent Return Strokes," *Journal of Geophysical Research,* Vol. 90, 1985, pp. 615–6164.

[5]Orville, R. E., Henderson, R. W., and Bosart, L. F., An East Coast Lightning Detection Network," *Bulletin of the American Meteorologic Society,* Vol. 64, No. 9, 1983, pp. 1029–1037.

[6]MacGorman, personal communication, 1989.

[7]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.

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

[9]Jordan, D. M., and Uman, M. A., "Variation in Light Intensity with Height and Time from Subsequent Lightning Return Strokes," *Journal of Geophysical Research,* Vol. 88, 1983, pp. 6555–6562.

[10]Mazur, V., "A Physical Model of Lightning Initiation on Aircraft in Thunderstorms," *Journal of Geophysical Research,* Vol. 94, 1989, pp. 3326–3340.

Freestream Turbulence Effects on Airfoil Boundary-Layer Behavior at Low Reynolds Numbers

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Introduction

WITH the increased interest in the application of remotely piloted vehicles (RPVs) comes the need for a better understanding of the aerodynamic problems associated with airfoil performance at low Reynolds numbers. For airfoils in this regime, it is well known that transition from laminar to turbulent flow and flow separation are highly sensitive to the disturbance environment.[1] The formation of laminar separation bubbles at low Reynolds numbers, and their dependence on freestream disturbances, complicates the study of airfoil performance compared to flows at more conventional Reynolds numbers. Boundary-layer sensitivity to flowfield conditions often leads to varying results for identical airfoil models in different wind tunnels.[2] Mueller et al.[1] presented results from the addition of a wire mesh screen upstream of the wind-tunnel test section for which the turbulence intensity was raised from an ambient level of 0.08% to a level of 0.3%. The hysteresis associated with the laminar separation bubble on a Wortmann FX 63-137 airfoil in the lift and drag curves disappeared with the addition of the screen. Marchman[2] likewise found a reduction in the lift hysteresis for the Wortmann airfoil when the freestream turbulence level was raised from 0.02 to 0.2%. Both groups of investigators noted the dependence of the effect of a disturbance upon its frequency content.

Early investigators used empirical data to correlate freestream turbulence levels with the momentum thickness Reynolds number R_θ at transition.[3] Hall and Gibbings[3] discuss the earlier work of Hilsop,[4] who tested the effects of varying mesh grids upon transition location. Indications were that at the same turbulence intensity level, the larger mesh grid was less effective in promoting early transition. No correlation of the mesh size with turbulence length scale was given. Abu-Ghannam and Shaw[5] studied transitional behavior using six turbulence grids producing turbulence levels from 0.5 to 5%. Correlations were established between turbulence levels and the starting and ending values of R_θ during the transition process. Turbulence length scales were calculated from a time correlation, but it was noted that the effect of turbulence scale was small and therefore neglected.

Meier and Kreplin[6] considered the effects of grid-generated turbulence levels from 0.06 to 1%. By spectral analysis, they attempted to separate the effect of turbulence intensity from

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