THE EFFECTS OF NOISE ON LAMINAR FLOW CONTROL DRAG REDUCTION SYSTEMS

John S. Gibson
Lockheed-Georgia Company
Marietta, Georgia 30063 - U.S.A.

Abstract

The nature of boundary layer transition from laminar to turbulent flow and the problem of noise as a transition triggering mechanism are described. For historical perspective, the noise sources and laminar flow/noise criteria relative to the X-21A laminar flow control (LFC) research aircraft are reviewed. A more detailed review is given for a passenger LFC transport aircraft, which includes the definition of noise sources, noise predictions on aircraft LFC surfaces, and critically affected LFC areas. Current activities in the area of noise effects on laminar flow are briefly discussed, as are conclusions regarding needed research.

Introduction

From the standpoint of aircraft skin-friction drag, laminar flow in the boundary layer is highly desirable. Reduction of drag by the enhancement of laminar flow in boundary layers has been a part of aircraft design since about the late 1920's, while research work in this area dates back to the early 1900's. However, this subject was not very well understood until the 1930's when boundary layer stability theory had its beginnings.(1) Proofs of the theory were not developed until the 1940's.(2)

According to current understanding, transition from laminar to turbulent boundary layer flow usually results from either of two types of flow instabilty: (1) viscous or (2) inflectional. Viscous instability is the generation and amplification of Tollmien-Schlichting (T-S) waves within a boundary layer. Such instability arising from T-S waves is dependent on thickness Reynolds number in the boundary layer and on the frequency and amplitude of flow disturbances. Under the right conditions, amplification of miniscule flow disturbances is followed by the generation of streamwise traveling vortices which turn into localized turbulent spots, which eventually grow and spread until the entire boundary layer has transitioned from laminar to turbulent flow.

Inflectional instability takes place when the boundary layer velocity profile has an inflection point. Typical of this form of instability is that produced by spanwise flow, or crossflow, that exists due to wing sweep. The swept-wing spanwise pressure gradient deflects the relatively low-velocity air in the boundary layer more than the air outside the boundary layer. This causes the development of a crossflow velocity component in the direction normal to the freestream flow. In most cases the boundary layer crossflow velocity profile has an inflection point, resulting in a flow instability. This type of phenomenon is generally referred to as "crossflow" instability. Similar to viscous T-S instabilities, there is a critical (crossflow) Reynolds number beyond which amplification of miniscule disturbances occurs. Small streamwise vortices then develop, and transition occurs as in the T-S case. In swept-wing cases, "crossflow" instabilities are generally more critical than T-S instabilities.

It has been shown theoretically and experimentally that boundary layer instabilities can be suppressed and transition delayed until further downstream on a flow surface by applying suction to remove the low-velocity boundary layer flow closest to the surface. Wind tunnel tests, with and without suction, were conducted in the 1940's under conditions of rather low freestream turbulence to establish the limits of natural transition and suction-inhibited transition.(3) It was soon found that, even with low freestream turbulence, noise disturbances still existed in the wind tunnels and were apparently causing premature transition. Thus, from essentially the beginnings of laminar flow control (LFC) research, noise has been considered a source of premature boundary layer transition. (Some additional early work related to noise and boundary layer interaction are described in References 4 through 8.) Consequently, aircraft noise criteria were developed and used in the design and operation of the USAF/Northrop X-21A LFC research aircraft during the early 1960's (Figure 1). The X-21A program did prove the technical feasibility of LFC as a drag reduction concept, but was terminated prior to development of and proof of the economic viability of LFC systems. Thus, LFC development came to a virtual standstill from the mid-1960's until the early 1970's, when new efforts to increase aircraft efficiency by reducing drag were started as a result of potential fuel shortages and drastic fuel price increases.

Currently, the LFC approach to significant drag reduction appears to have great potential. Although noise is a known problem which is detrimental to LFC operation, the exact mechanism by which noise affects LFC is still not completely understood. The purpose of this paper is to review the subject of noise effects on LFC systems in the light of current ideas regarding LFC aircraft design.

Discussion

Since the X-21A program had such a significant effect on current approaches to LFC systems, this discussion will start with a review of the X-21A noise experience.

X-21A LFC Airplane Program

The X-21A LFC/noise sensitivity program was largely based on experimental data from a series of wind tunnel and flight tests, which comprise the largest such effort ever performed. Some of

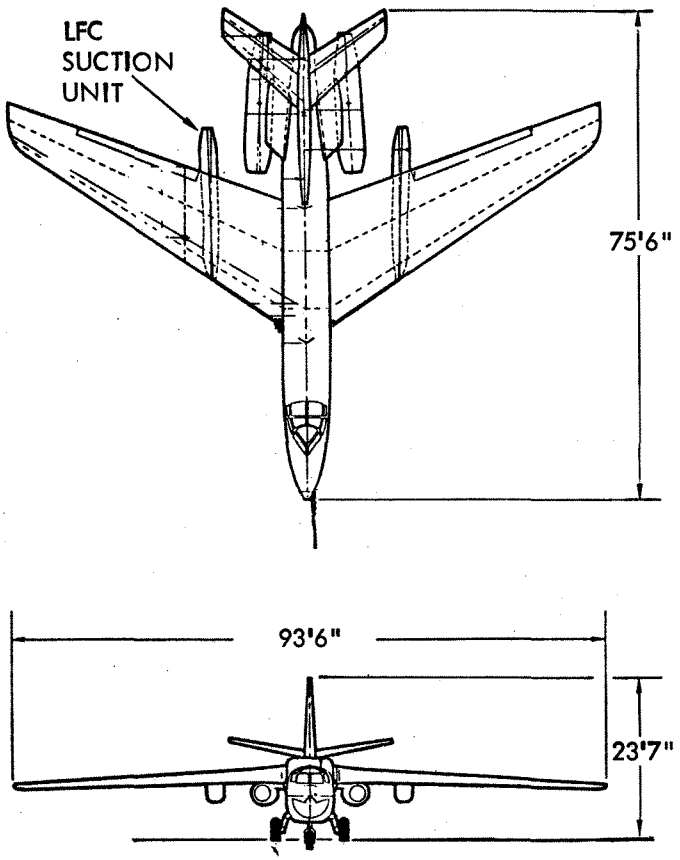

Figure 1. X-21A Experimental LFC Airplane

the data are still being used today. The following paragraphs briefly review some of the concerns, tests, and results.[9]

The noise sources of primary concern on the X-21A were propulsion system broad-band jet noise, propulsion system discrete-frequency turbomachinery noise, fuselage turbulent boundary layer broadband noise, and LFC suction/duct system noise. The earliest experiments were to try to determine the mechanism by which noise disturbances cause transition and to determine maximum allowable noise amplitudes. Experiments with external sound were conducted on a 30° swept-wing model in Northrop's 7 x 10-ft tunnel, which had been acoustically treated to minimize sound reflectons. The model was subjected to discrete and broadband noise. Some additional tests of noise emanating from LFC duct/slots were also completed in the 7-ft tunnel as well as in the NASA Ames 12-ft tunnel on a larger 33° swept-wing model. Some of the results from these experiments are shown in the next two figures. Figure 2 shows the allowable slot-duct internal sound pressure level in decibels (dB) for several angles of attack at a constant Reynolds number. Notice that in each case there is a frequency range that is most critical. Likewise, Figure 3 shows similar trends for external discrete-frequency noise and broadband noise. The conclusions were that the most sensitive condition for noise-induced transition occurred when the frequency of the acoustic disturbance coincided with the theoretical critical frequency range for amplified boundary layer oscillations which confirmed previous work on flat plates of a more general nature.[2] The allowable sound level could be increased in areas of high

(REF. 9)

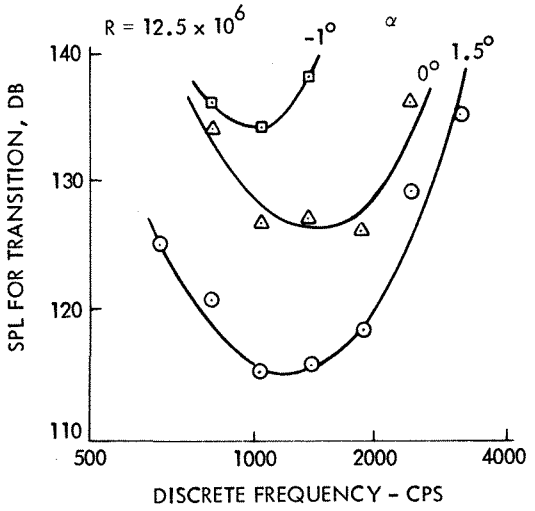

Figure 2. Criticality of Frequency for Internal LFC Ducting Noise as a Function of Angle of Attack, α

(REF. 9)

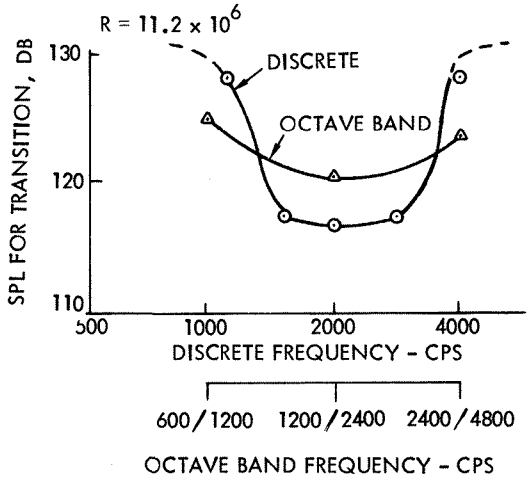

Figure 3. Criticality of Frequency for External LFC Surface Noise

flow acceleration or by increased suction rates, both of which tend to stabilize the boundry layer. The combination of noise and surface roughness was found to be very detrimental to laminar flow.

Based on the previously mentioned tests, and other data available at the time, an allowable noise disturbance versus chord Reynolds number design chart was evolved. This criterion, shown in Figure 4, gives allowable noise in terms of flow disturbance velocity ratio, where u is the actual air-particle fluctuation velocity (corresponding to a given sound pressure or noise level) and U_o is the freestream velocity.[10] Due to frequency dependency being incompletely evaluated, it was left out of this criterion. The resulting criterion is based on total sound level and was then purposely rather conservative.

The X-21A engines were moved from the wings to the aft fuselage, sound choked or sonic inlets

were installed, and other noise reduction efforts were made, based on the noise criterion. Subsequent LFC flight tests of the completed X-21A seemed to indicate that the criterion could be relaxed somewhat (on the order of the equivalent of 6 dB), but this was never made a firm conclusion because of questions about the test procedures. The final degree of wing area successfully laminarized was approximately 80% for the upper wing surface and 62% for the lower surface.(11)

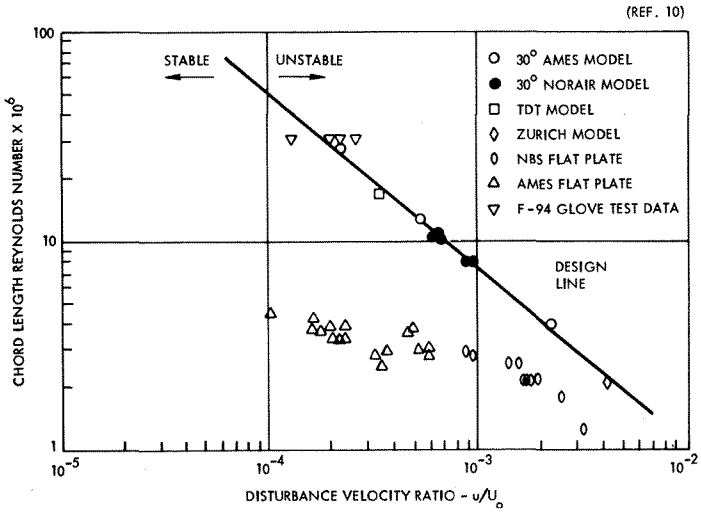

Figure 4. Original Acoustically Induced Transition Design Criterion

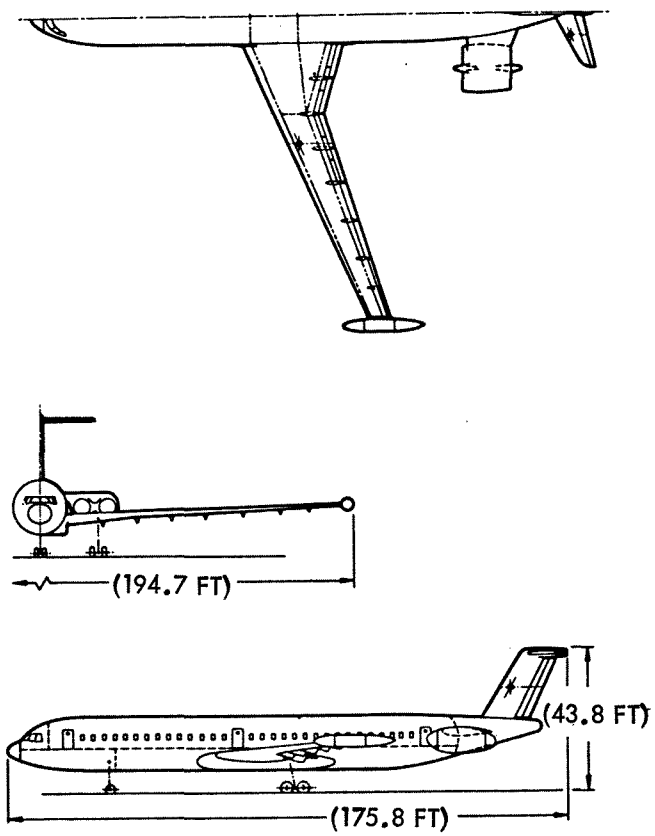

Figure 5. LFC Passenger Transport Design

Lockheed LFC Aircraft Design Study

The end of the X-21A program in the mid-1960's marked the close of an era of LFC research that had continually advanced since the 1940's. As previously mentioned, it took the fuel crisis of the 1970's to revive interest in LFC. One of the first efforts to determine the potential of LFC in present and future environments was a NASA-sponsored LFC transport aircraft design study performed by the Lockheed-Georgia Company.(12,13) One of the final design aircraft is shown in Figure 5. This is a 200-passenger, Mach 0.8 transport aircraft with a range of 5500 nautical miles. Most of the fixed-wing and empennage structures are covered with LFC suction slots. These feed through a ducting system to suction pumps mounted in the mid-fuselage belly areas.

The LFC/Acoustics portion of this design study consisted of four parts:

1. Development of an appropriate noise-induced boundary transition criterion.
2. Prediction of acoustic environments on LFC surfaces in cruise.
3. Identification of noise-vulnerable areas on the LFC surfaces.
4. Minimization of noise effects on LFC surfaces.

The first task was to answer the old question of how much noise the successful operation of an LFC system can withstand. Because no recent information was available, the X-21A criterion was utilized in a modified empirical form. Since the study aircraft design points were essentially fixed in terms of cruise Mach number and altitude, the generalized Reynolds number and disturbance velocity ratio scales could be replaced with scales of chord length and sound pressure level, respectively. The resulting criterion was as shown in Figure 6. Again, insufficient frequency dependency trend data were available, and the empirical criterion is in terms of total or overall sound pressure level. It was assumed that, on the wings and empennage involved, noise in the frequency range of 500 to 5000 Hz was most critical.

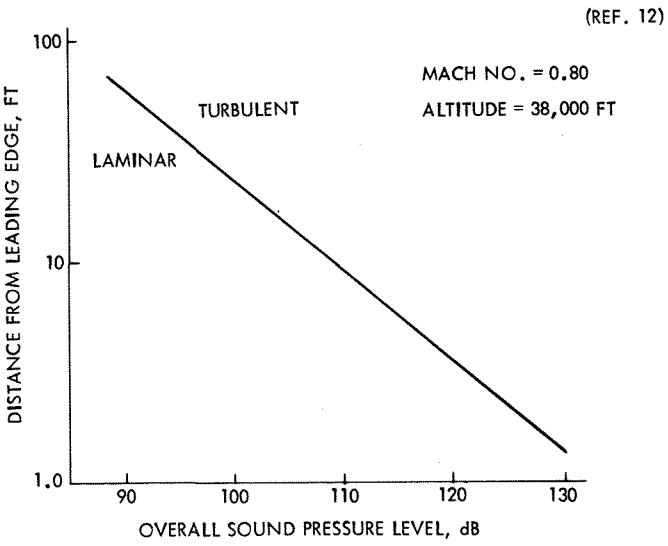

Figure 6. Adapted Acoustically Induced Transition Design Criterion

The noise prediction task involved propulsion system noise sources including the fan stage, compressors, turbine, combusion, and several forms of jet noise, as depicted in Figure 7. The LFC suction units produce noise from similar kinds of sources. The turbulent boundary layer flow on the fuselage and other non-LFC surfaces also produces noise (e.g., Reference 14). Additional noise-producing phenomena, such as oscillating shocks and separated flows, were considered. Internal noise sources were also examined, including suction unit noise propagating through the suction ducts and slots, noise generated by turbulent flow in corners and bends in the ducts, and flow/acoustic resonance effects in the suction slot/duct system. Of the many noise sources, the jet, the fan, and the fuselage boundary layer were calculated to be the worst, as summarized in Table I. Other sources could cause locally significant problems.

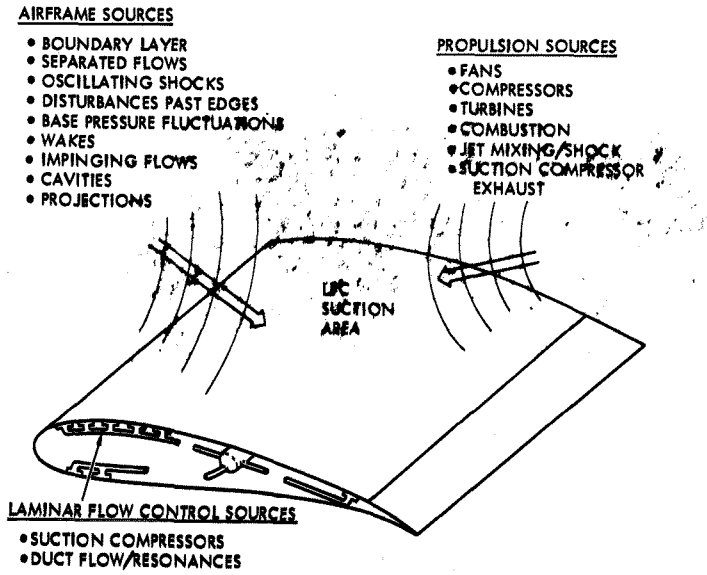

Figure 7. Potential Noise Sources Detrimental to LFC Operation

All the sources, except those totally dependent on cruise flow phenomena (turbulent B.L., oscillating shock, etc.), were first estimated for static, sea-level conditions. This was done because essentially all existing noise prediction methods are based on those same conditions. Then, the predictions were modified by empirical means to take into account high-velocity and high-altitude effects on basic noise generation and noise propagation. This is a highly complex procedure which involves multiple transformations. As an example of one of these problems, consider the noise propagation path from engine fan noise to a spot near the wing tip, as illustrated in Figure 8. Statically, noise radiated from the fan will propagate along r to the spot called "actual receiver," defined in space by coordinates x, y, r, ϕ. However, when the aircraft is moving forward at rather high subsonic speed, the noise propagating along r misses the wing altogether because the wing tip has moved forward. The noise propagating along r', which arrives at the point called "apparent receiver," arrives at the same time as the wing tip, which is moving forward. So now the noise which reaches the wing tip has to travel further along a different path angle.

TABLE I. NOISE SOURCE CHARACTERISTICS AND ESTIMATED RANKING

Source	Characteristics	Importance in creating transition
EXTERNAL NOISE SOURCE CHARACTERISTICS		
Propulsion Units		
Jet	Broad band, to 2,000 Hz	1
	Shock cell, discrete	1
	Shock associated noise	1
Fan	Discrete (MPT and tone), 500 to 5,000 Hz Inlet and discharge, with suppression	1
Turbine	Discrete and broad band, above 5,000 Hz Discharge, suppressed	2
Suction Units	Gas generator, compressor and turbine whines above 5,000 Hz	2
	Pump Compressor whine above 5,000 Hz	2
	Possible shock noise in jet exhaust	2
Boundary Layer	Turbulent boundary layer over fuselage and adjacent to LFC areas. High OASPL's at surface (128 dB), but poor radiation.	1
Other		
Free stream incident turbulence	Broad band	3
Oscillating shocks on and in the vicinity of LFC surfaces	Discrete frequency	3
Local separated flow areas	Broad band	3
INTERNAL NOISE SOURCE CHARACTERISTICS		
Suction engine	Pump, compressor whine, transmitted through duct, about 5,000 Hz	2
Duct self noise	Flow noise in duct created by dirty flow, tortuous path, etc., broad band	2
Duct slot resonances	Could cause chugging at suction slot, discrete frequency	2

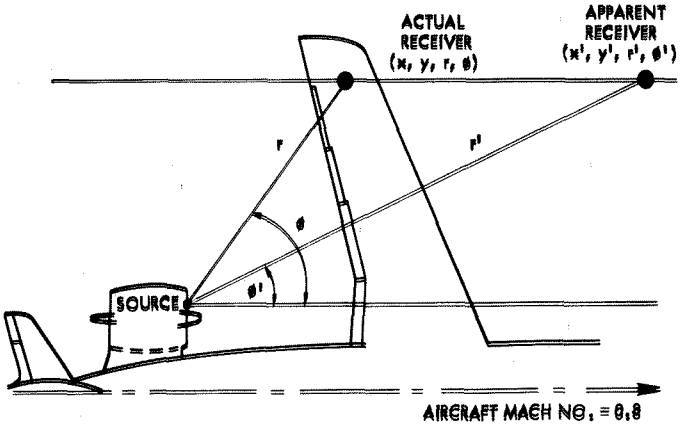

Figure 8. Moving Noise Source and Receiver Relationships

When all corrections and transformations are taken into account, calculated overall noise levels on one of the design aircraft are as shown in Figure 9. The engines have already been moved away from the wings for noise reasons (also to eliminate pylon interference with LFC surfaces). In this particular case, the only remaining noise-critical area occurred on the empennage, as shown in Figure 10, and was dominated by the propulsion system noise sources. The nacelle is already

(REF. 12)

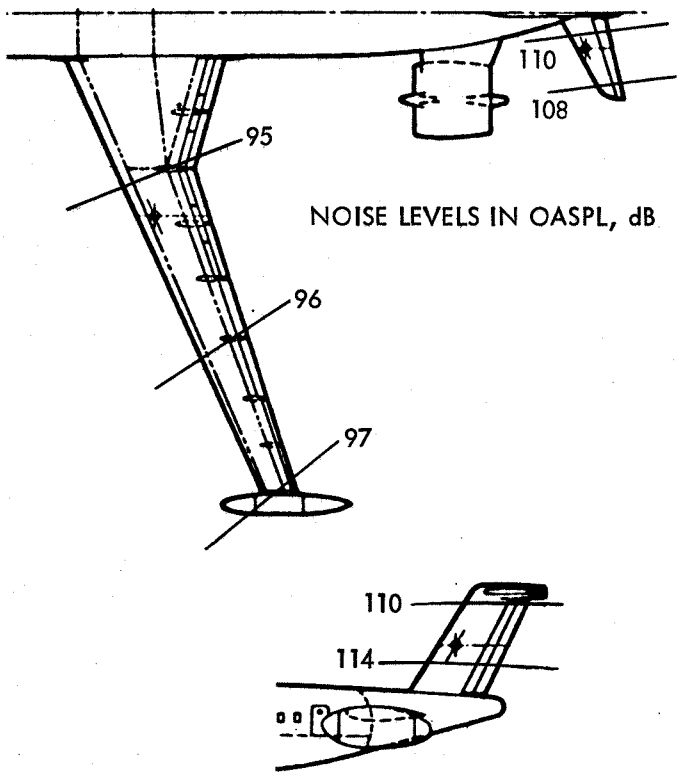

Figure 9. Estimated Cruise Noise Levels

(REF. 12)

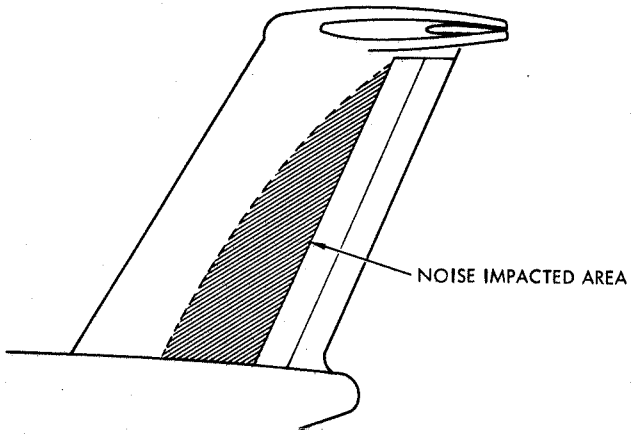

Figure 10. Noise Impacted LFC Surface Area

acoustically treated, since the aircraft must also meet stringent community noise takeoff and landing requirements, which helps minimize the LFC noise problems as well.

Depending on the exact location, laminar flow was desired on the empennage LFC surfaces in the presence of noise up to a chord Reynolds number of 44×10^6. To achieve this for the case discussed, a 10 to 20% increase (over design amounts) in suction is needed in the noise-critical area. While the noise problems of the LFC study aircraft are significant, they do appear to be controllable and do not overly penalize the aircraft as long as adequate precautions, as discussed, are taken.

Current Developments

The initial Lockheed LFC aircraft design study, just described, is now being followed by more detailed analytical and design studies, and related development test programs at Lockheed, Boeing, and McDonnel-Douglas. Lockheed is also under contract with NASA to develop improved aircraft cruise noise prediction methods and better LFC noise sensitivity criteria.

In the noise prediction area, more systematic and exacting procedures are being developed for each significant noise source. This includes the mathematical definition of the source, improved high-speed, high-altitude transformations, and the resulting calculated noise field over the aircraft LFC structural areas.

In the noise criteria area, two efforts are in work. The first is an improved empirical procedure which takes into account noise directivity and frequency. The second is a new theoretical study based on Mungur, who has developed a theory for the mechanism by which sound generates hydrodynamic disturbances in shear layers.[15] Two equations are derived from the linearized Navier-Stokes equation; one governs the sound field and the other governs the fluctuating vorticity field. The latter, when written in the form of an inhomogeneous Orr-Sommerfield equation, represents the generation of fluctuating vorticity by a sound field and its convected diffusion and amplification (or decay) in a viscous boundary layer. Sound coupling is shown to occur only in the boundary layer, and in the case of a flat plate, acoustic excitation is most intense at the leading edge of the plate. The acoustically induced vorticity source strength is linearly proportional to the sound pressure and its derivative, as well as being a function of the sound-field frequency and directivity.

Other theoretical approaches to acoustically induced flow transition are those of Yates,[16] who utilizes a sound-to-flow vortex coupling method of flow excitation, and Tam, [17] who proposes a method of direct coupling of sound and flow fluctuations. Additional work in the sound/flow coupling area is known to be progressing at several academic, industry, and government institutions in the United States and Europe.[18-22]

Not all the work in the sound/flow coupling area is aimed at transition inhibition. Several investigtors have looked at the use of sound as a turbulence generator in drag and stall suppression studies.[5,23,24] Here, premature transition and turbulence are purposely caused by the introduction of sound to minimize or prevent laminar flow separation on airfoils and bluff bodies.

Conclusions

We can currently evaluate the effects of noise on aircraft LFC systems by rather conservative methods based largely on X-21A era technology. To make more accurate LFC/noise sensitivity predictions, further advances are needed in the definition of sensitivity parameters and in cruise noise prediction methods. Both of these areas require strong experimental programs to strengthen and extend current analytical approaches to the problems.

In the noise sensitivity area, theoretical work should be extended to take into account fully three-dimensional flow effects and the finite acoustical effects of airfoil leading and trailing edges. Experimental work is needed to prove or disprove current theoretical trends. Currently, work, and plans for work, are underway in these technical areas at several locations.

In the noise prediction area, experimental work is needed to confirm present analytical techniques, or to indicate the trends of new methods for transforming propulsion-type noise predictions from static, sea level to high altitude-high speed conditions. The degree of noise radiation from turbulent boundary layer flows and separated flows still presents a question that must be answered through suitable tests. There is no suitable test facility that has the needed high-velocity capability with a low air drive noise environment, as well as an anechoic test section for accurate noise measurements. Consequently, testing must be done on flight test vehicles, or suitable ground-based facilities must be developed.

Acknowledgement

The author gratefully acknowledges the assistance of Mr. Guy Swift and Dr. Parma Mungur in the preparation of this paper.

References

1. SCHLICHTING, H.: Lecture Series; "Boundary Layer Theory, "NACA Technical Memo No. 1217, Feb. 1947.

2. SCHUBAUR, G. B. and SKRAMSTAD, H. K.: "Laminar-Boundary-Layer Oscillations and Transition on a Flat Plate," NACA Technical Report No. 909, 1948.

3. PFENNINGER, W.: "Untersuchungen uber Reibung sverminderunger an Tragflugeln, insbesondere mit Hilfe von Grenzschichtabsaugung," Mitteilung, No. 13 des Inst. fur Aerodynamik, E.T.H., Zurich, 1946.

4. BOLTS, F. W., KENYON, G. C., and ALLEN, C. Q.: "The Boundary Layer Transition Characteristics of Two Bodies of Revolution, a Flat Plate, and an Upswept Wing in a Low Turbulence Wind Tunnel," NASA TND-309, April 1960.

5. BROWN, F. N. M.: "See The Wind Blow," Privately Printed by the Author, 1971,pp. 36, 67.

6. JACKSON, F. A., and HECKL, M. A.: "Effect of Localized Acoustic Excitation of the Stability of a Laminar Boundary Layer," ARL Report 62-362, Wright-Patterson Air Force Base, Ohio, June 1962.

7. KNAPP, E. F.; and ROCHE, P. J.: "A Combined Visual and Hot-Wire Anemometer Investigation of Boundary-Layer Transition," AIAA Journal, vol. 6, no. 1, January 1968, pp. 29-36.

8. SPANGLER, J. G., and WELLS, C. S.: "Effects of Free Stream Disturbances on Boundary Layer Transition," AIAA Journal, vol. 6, no. 3, March 1968, pp. 543-545.

9. PFENNINGER, W. and REED, V. D.: "Laminar-Flow Research and Experiments," Astronautics and Astronautics, July 1966, pp. 44-50.

10. ANTONATOS, P. P.: "Laminar Flow Control-Concepts and Applications," Astronautics and Aeronautics, July 1966, p. 35.

11. WHITES, R. C., SUDDERTH, R. W., and WHELDON, W. G.: "Laminar Flow Control on the X-21," Astronautics and Aeronautics, July 1966, p. 41.

12. STURGEON, R. F., et al: "Study of the Applications of Advanced Technologies to Laminar Flow Control Systems for Subsonic Transports," NASA CR-133949, Washington, D.C., May 1976.

13. STURGEON, R. F.: "The Development and Evaluation of Advanced Technology Laminar-Flow Control Subsonic Transport Aircraft," AIAA Paper 78-96, January 1978.

14. GIBSON, J. S.: "Boundary Layer Noise Measurements on a Large Turbofan Aircraft," Paper I-10, 70th meeting of the Acoustical Society of America, Nov. 4, 1965, J.A.S.A. (1965) Vol. 38, p. 921.

15. MUNGUR, P.: "On the Sensitivity of Shear Layers to Sound," AIAA Paper 77-1369, October 1977.

16. YATES, J. E.: "Interaction With and Production of Sound by Vortex Flows," AIAA Paper 77-1352, October 1977.

17. TAM, C. K. W.: Bulletin of the American Physical Society, Vol. 22, No. 10, Nov. 1977.

18. SCHILZ, W.: "Experimentalle Untersuchungen zur Akustischen Beeinflussung der Stromungs Grenzschicht in Luft," Acoustica, 1965/66, Vol. 16.

19. SHAPIRO, R. P.: "The Influence of Sound Upon Laminar Boundary Layer Instability," MIT Report 83458-83560-1, Sept. 1977.

20. KACHANOV, YU. S., KOZLOV, V. V., and LEVCHENKO, V. YA.: Izv. Sib. Otd. Akad. Sc. USSR, Sez. Tech. Nauk., VIP 13, No. 3, 1975.

21. THOMAS, A. S. W. and LEKOUDIS, S. G.: "A Note on Sound and Tollmein-Schlichting Waves Measured in a Blasius Boundary Layer," Lockheed-Georgia Company, submitted for publication in the Journal of Fluid Mechanics, 1978.

22. MILLER, G. and CALLEGARI, A.: "The Effects of Acoustic Disturbances on Boundary Layer Transition," New York University Report NYU/DAS No. 78/01, January 1978.

23. COLLINS, F. G., and ZELENEVITZ, J.: "Influence of Sound upon Separated Flow Over Wings," AIAA Journal, Vol. 13, No. 3, March 1975.

24. CHANG, P. K.: "Drag Reduction of an Airfoil by Injection of Sound Energy," Journal of the Aerospace Sciences, September 1961.