JOURNAL OF AIRCRAFT
Vol. 41, No. 2, March–April 2004

Large-Scale Laminar-Flow Tests Evaluated with Linear Stability Theory

Géza Schrauf*
Airbus Deutschland GmbH, 28183 Bremen, Germany

A short overview of the different ways to apply linear stability theory in the form of the e^N method for transition prediction in boundary-layer flow is given. The ATTAS/VFW614, the Fokker F100, and the Airbus A320 flight tests are evaluated and compared to two hybrid laminar-flow tests in the S1MA tunnel. N-factor correlations are given for all five tests. It is shown that transition prediction based on two N-factors, one to model the crossflow instability and a second for Tollmien–Schlichting instability, is superior to the envelope method for hybrid laminar-flow applications. Results concerning the influence of surface roughness on the crossflow instability are discussed. Furthermore, the evaluation shows that in hybrid laminar flow the internal noise coming from the suction system cannot be neglected for the Tollmien–Schlichting amplification.

Nomenclature

C_q	=	suction coefficient
M	=	Mach number
N	=	N factor
N_{CF}	=	N factor of a stationary mode with prescribed wavelength, used for crossflow modes
N_{TS}	=	N factor of a mode with prescribed frequency that propagates in direction of the inviscid streamline, used for Tollmien–Schlichting waves
N_β	=	N factor of a mode with prescribed frequency and prescribed spanwise wave number; here used for stationary crossflow modes
Re	=	Reynolds number

Introduction to Linear Stability Theory

LINEAR local stability theory applied in the form of the e^N method is the standard tool for the design of natural and hybrid laminar-flow wing, tail, and nacelle surfaces in the aircraft industry. This theory considers wave-like disturbances in a laminar boundary layer and allows for the computation of their growth rates. Laminar-turbulent transition is assumed to take place where the most unstable disturbances are amplified by a factor e^N, with N determined by correlation with experiments. As a semi-empirical method based on correlation with experiments, the e^N method works best for flows that are not too different from the ones used for its calibration. Therefore, both large-scale wind-tunnel and flight tests are required.

The e^N method was first developed for two-dimensional, incompressible boundary layers and later extended to three-dimensional, compressible flows. In two dimensions a wave-like disturbance can be identified by its frequency alone. Other quantities, such as wave number or wavelength, are then determined from the dispersion relation. The extension to three-dimensional boundary layers introduces an additional degree of freedom without providing an additional relation. Therefore, in addition to the frequency, a second quantity must be specified to identify an instability wave for the N-factor calculation. Possible choices are 1) the wave propagation direction, 2) the wavelength, 3) the spanwise wave number, or 4) a fourth possibility is to choose the wave with the largest local amplification at each station in the boundary layer.

Each of the four choices is the basis for a procedure or strategy to calculate N factors. Details can be found in (Refs. 1 and 2).

On a typical swept wing of a transport aircraft, boundary-layer transition can be caused by three different mechanisms. A not yet fully understood mechanism can induce transition directly at the attachment line. Leaving the attachment line, the flow direction changes rapidly from a spanwise to a chordwise direction. The boundary layer then becomes three-dimensional and develops a strong crossflow velocity component with an inflection point that causes the crossflow instability. At larger spanwise positions the crossflow component weakens, that is, the flow becomes more two-dimensional and thus unstable with respect to Tollmien–Schlichting waves. Both, the crossflow (CF), as well as the Tollmien–Schlichting (TS) instability, can be modeled by the e^N method.

Short Descriptions of the Experiments

In this paper we evaluate two hybrid laminar-flow (HLF) tests performed in the ONERA S1MA wind tunnel. The first test was carried out within the European ELFIN program in spring 1992 with a half-scale model of the ATTAS/VFW614 wing glove equipped with a suction leading edge.[3] The installed model is shown in Fig. 1. After having shown that this tunnel was suitable for HLF technology, in autumn 1996 a second test using a wing was especially designed for HLF application (Fig. 2) was conducted. The two tests used different types of pressure distributions so that consistently correlated N factors support the validity of the e^N method and provide a reliable correlation for this tunnel.

In addition to the wind-tunnel tests, three flight tests, two with natural laminar flow (NLF) and one with hybrid laminar flow, are evaluated. The first NLF test was performed in 1989 with the ATTAS/VFW614 aircraft[4,5] shown in Fig. 3. A glove especially designed for N-factor correlation was mounted on the starboard wing. The glove was designed such that the envelopes of the N_{CF}- and N_{TS}-factor curves were approximately linear. Using the results obtained with this glove, a second NLF glove was designed for the Fokker F100 aircraft[6] shown in Fig. 4. The F100 design allowed for larger crossflow amplification in the leading-edge region that would not cause transition. These instabilities were dampened using a suitable pressure distribution behind the leading-edge region so that transition would finally be caused at midchord by Tollmien–Schlichting waves. This concept resulted in N-factor curves that have an envelope with local maximum near the leading edge. The concept proved valid, with the exception that transition occurred somewhat earlier than predicted by linear stability theory, probably because of nonlinear wave interaction. Transition was then observed behind an N-factor maximum causing the so-called pathological cases described in Ref. 7. For this reason, we omitted the design case for

Presented as Paper 2001-2444 at the 19th Applied Aerodynamics Conference, Anaheim, CA, 11–14 June 2001; received 31 January 2002; revision received 8 July 2003; accepted for publication 21 July 2003.

*Project Coordinator and Senior Research Scientist, Aerodynamic Design and Data Domain. Senior Member AIAA.

Table 1 Flow and geometry conditions of test cases

Case	$Re \cdot 10^{-6}$	M	Sweep, deg
ELFIN	8–17	0.60–0.74	28
ELFIN II	13–23	0.50–0.82	32–36
ATTAS	12–23	0.33–0.67	19.5–22.4
Fokker 100	17–30	0.50–0.80	17–24
A320 Fin	15–40	0.60–0.82	40

Fig. 1 ELFIN HLF test.

N-factor correlation and only used off-design cases with mostly monotonically increasing envelopes.

The third experiment, shown in Fig. 5, was performed on the vertical tail of an A320 aircraft equipped with a suction leading edge.[8] This test was carried out to demonstrate that HLF technology can be applied to an Airbus aircraft. The test produced many cases not suitable for the present work because transition was observed behind the coating applied for infrared transition detection. In spite of this, many cases are suitable for N-factor correlation.

The range of Reynolds number, Mach number, and leading-edge sweep for the cases presented in this paper are listed in Table 1.

Evaluation with Linear Stability Theory

There are two different types of transition prediction methods that are based on correlated N factors: methods that use only one N factor and methods that use two N factors, one for the crossflow instability and a second one for the Tollmien–Schlichting instability. Within each method the N factors are computed by one of the strategies 1)–4) mentioned above.

Envelope Method

The most commonly used N-factor method is the envelope method based on strategy 4). A lesser known method, the so-called "envelope-of-envelopes" method based on strategy 1), is discussed in Ref. 7. It is not widely used because of its large computational demand. A similar method based on strategy 3) is used within the framework of nonlocal stability theory based on the parabolized stability equations. The evaluation with nonlocal theory will be presented later.

The envelope method has been extensively used for the evaluation of the flight tests with the ATTAS and the Fokker F100 aircraft.[2,9] The results showed that this method is suitable for natural laminar flow. For the Fokker 100 flight test the envelope method produces the smallest scatter of the correlated N factors if they are computed with compressible stability theory that includes surface curvature effects.

In the case of hybrid laminar flow, crossflow amplification depends strongly on the amount of boundary-layer suction applied at the leading edge. As Tollmien–Schlichting waves have their main growth at larger chordwise positions behind the suction panel, they are only indirectly influenced by the leading-edge suction through a modified upstream development of the boundary layer. If suction is used to lower crossflow amplification to an ineffective level, transition occurs at midchord caused by Tollmien–Schlichting waves. Moderate changes in the suction rates do not much influence the transition location as long as crossflow-induced transition is prevented. Because the envelope method integrates both crossflow as well as Tollmien–Schlichting amplification rates into a single N factor, its value at the transition location depends on how much of the contribution coming from crossflow amplification is diminished by suction. Thus, the value of the correlated N factor changes, although there is no change in the physical nature and in the location of the transition.

The effect of a variation in suction in two successive measurements with the A320 HLF fin flying at $M = 0.78$ is shown in Fig. 6. The correlated N factors for the two cases are 5.6 and 8.4. If we would use the mean value 7.0 for transition prediction, we would obtain a transition location of 17% for the case with higher suction and 34% for the other one.

A similar result is found for the ELFIN II HLF S1 test in Ref. 10. These results show that the envelope method is not appropriate for transition prediction in hybrid laminar-flow applications.

Two *N*-Factor Methods

For transition prediction on a transonic wing with high aspect ratio, it is sufficient to consider only waves that propagate in the direction of the inviscid streamline, even though this direction is generally not the direction of the largest TS amplification.[7] This is because, for transonic flow, the local TS-amplification rate varies only slowly with propagation direction. An example using the 12% chord location on the upper side of the Fokker F100 NLF-glove with local Mach number 0.95 is shown in Fig. 7. The local, temporal amplification rate of an instability mode with frequency 5000 Hz is computed with compressible stability theory and plotted over the wave propagation direction. In this case the maximum amplification rate is attained for the direction of 35 deg and is only 1% higher than the rate for 0 deg. Moreover, the amplification rate is not symmetric with respect to the 0-deg direction because the boundary-layer flow is three-dimensional. We notice a local maximum at 83 deg that is associated with a traveling crossflow wave with wavelength 0.004 m, which is no longer amplified at 12% chord. The N factor of this mode is included in Fig. 8 with a dashed line. Furthermore, there is a continuous connection from the Tollmien–Schlichting part of the curve to the crossflow part with a local minimum at 79% so that we have for the frequency of 5000 Hz and for each propagation direction exactly one mode, which is not necessarily amplified.

As the flatness of the TS maximum is encountered for all flows on transonic wings with high aspect ratio, we model the Tollmien–Schlichting instability with strategy 1) using the 0-deg direction, that is, the direction of the inviscid streamline. The N factor computed this way is denoted by N_{TS}. Thus, we obtain for each frequency one N_{TS}-factor curve (compare Fig. 9). Having computed a sufficient number of N_{TS}-factor curves, we use their envelope for the correlation with the measured transition location.

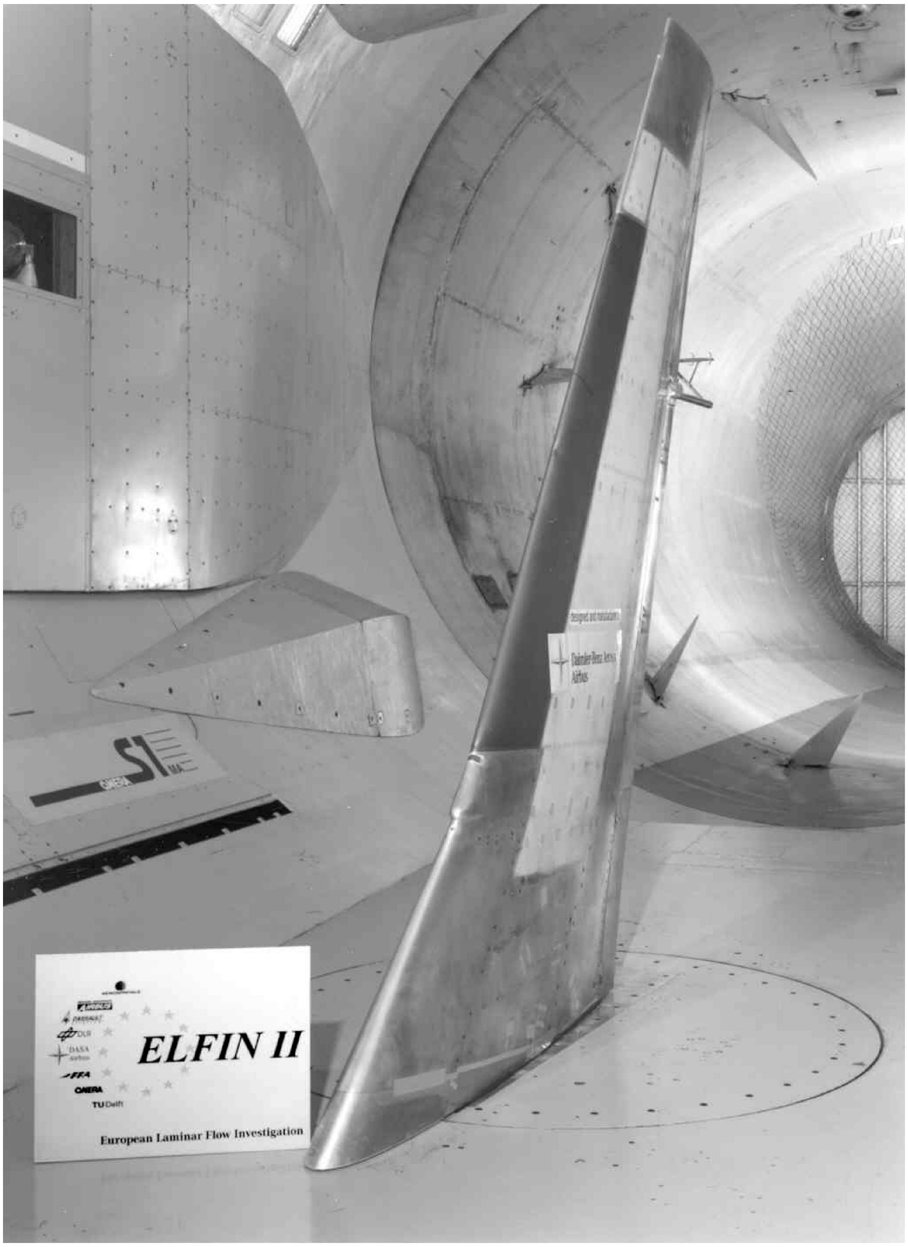

Fig. 2 ELFIN II HLF test.

Fig. 3 ATTAS/VFW614 NLF flight test.

Fig. 4 F100 NLF flight test.

Fig. 5 **A320 HLF flight test.**

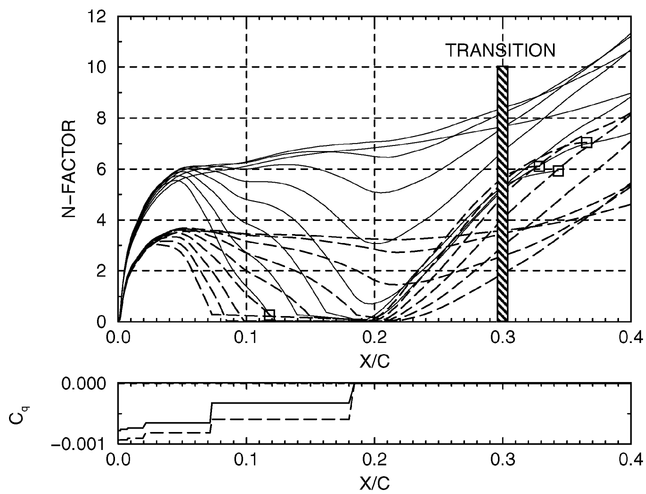

Fig. 6 **Suction variation and its effect on the envelope method *N* factors obtained with compressible stability theory without surface curvature for the A320 HLF fin.**

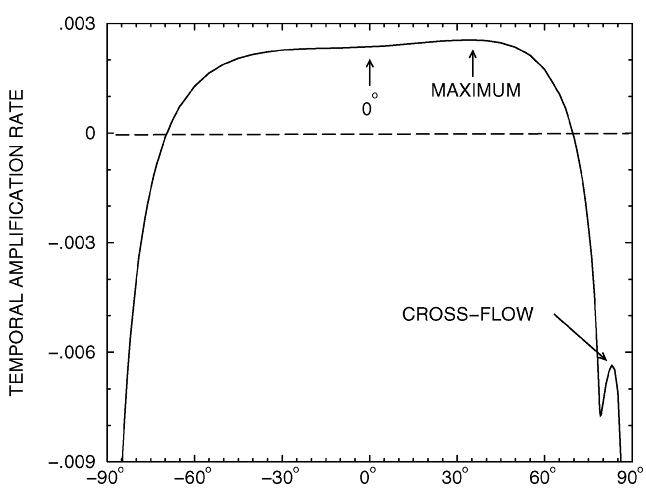

Fig. 7 **Variation of the local temporal amplification rate of the 5000-Hz mode with wave propagation direction at the position $X/C = 0.12$.**

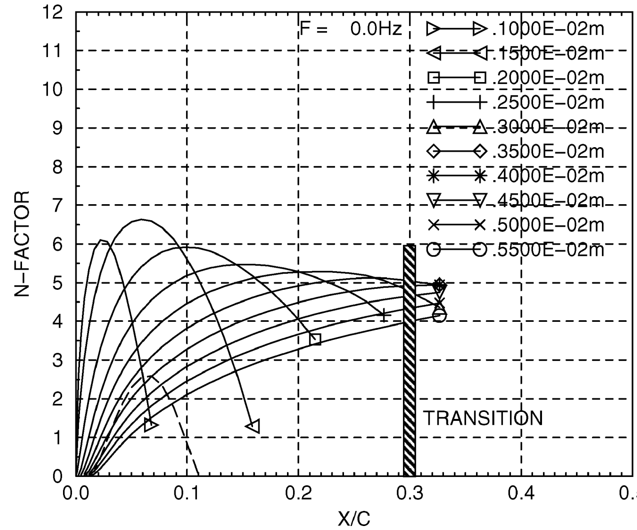

Fig. 8 ***N* factors of stationary CF modes obtained with compressible stability theory: - - - -, traveling 5000-Hz crossflow mode of the second local maximum in Fig. 7.**

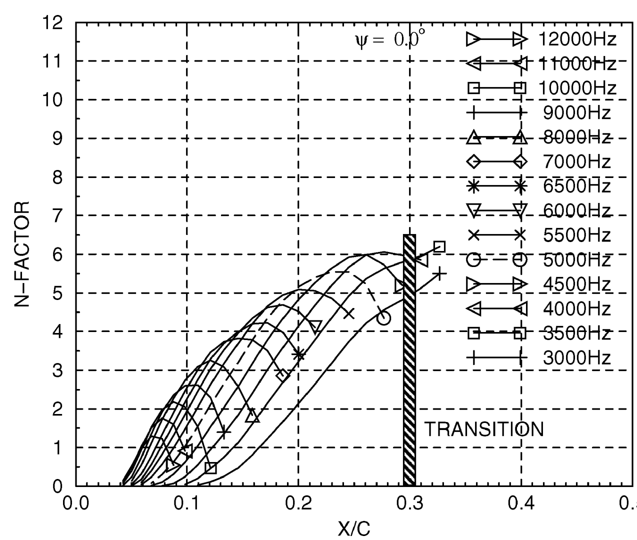

Fig. 9 **N_{TS} factors of the case of Fig. 8 obtained with compressible stability theory: - - - -, 5000-Hz mode.**

In a low-turbulence environment stationary crossflow waves, that is, crossflow vortices, dominate the transition process.[11,12] Experimental and numerical simulations indicate that stationary crossflow vortices grow until a saturated state consisting of a deformed boundary-layer flow with embedded crossflow vortices is reached. The final transition to turbulence is then caused by secondary instabilities of this flow state.[13] As this state can only be reached with sufficiently strong linear amplification of the crossflow vortices, we concentrate, within our engineering approach to transition prediction, on the development of those stationary modes. An example is given in Fig. 8. We observe the large amplification of modes with short wavelengths at the leading edge. According to linear stability theory, these modes are damped out long before transition occurs. This is, however, not the case in nonlinear theory, in which all modes are retained because of nonlinear wave interaction.[14] Whether or not those short-wave modes have any influence on transition is currently not known.

Even though we emphasize the importance of the stationary modes for the transition process, we recognize that within the framework of linear stability theory traveling crossflow waves often exhibit larger amplification rates. However, the importance of the stationary CF modes is again supported by experimental results[15] that show that traveling CF waves are more efficiently damped by suction than stationary CF vortices.

Visualizations of stationary crossflow vortices show that they have approximately constant wave length so that choice 2) is appropriate. For wings with high aspect ratio, we can also apply strategy 3) reflecting the symmetry condition for an infinitely long, swept wing.

Using strategy 2), we compute N_{CF}-factor curves for many stationary modes with different prescribed wavelengths and correlate the envelope of those curves with the measured transition location as indicated in Fig. 8. Analogously, we can use the envelope of N_β-factor curves obtained with strategy 3).

Using the two-N-factor method, we get, for each experimental flow condition, a correlated N_{TS} factor and also a correlated crossflow N factor obtained with strategy 2) or 3), that is, we obtain an (N_{CF}, N_{TS})- or an (N_β, N_{TS})-factor pair. Plotting the pairs for many flow conditions of an experiment in the (N_{CF}, N_{TS}) plane, we observe that the pairs form a band characteristic for the wind-tunnel or flight experiment. This band is the necessary outcome of a test program to calibrate the e^N method and is now used as the basis for transition prediction in future aircraft design.[16]

Wind-Tunnel Results

The experiments considered here were evaluated with the boundary-layer and stability codes presented in Refs. 17–19. For all experiments the same parameter settings were used.

For a swept wing with high aspect ratio, both strategies, 2) and 3), give similar crossflow N factors. Therefore, correlations using the (N_{CF}, N_{TS})- and (N_β, N_{TS})-factor pairs are equivalent, as shown in Fig. 10 for the ELFIN II S1MA HLF wind-tunnel experiment. Here, N_{CF} is computed using strategy 2) and N_β with strategy 3). Previously, the equivalence was shown for the ATTAS (Ref. 2) and for the Fokker F100 (Ref. 9) flight tests.

For the same experiment we show in Fig. 11 the influence of compressibility on correlated N factors. Compressibility has a larger influence on Tollmien–Schlichting N factors than on the N factors for crossflow vortices, as was also observed in all other laminar-flow experiments.

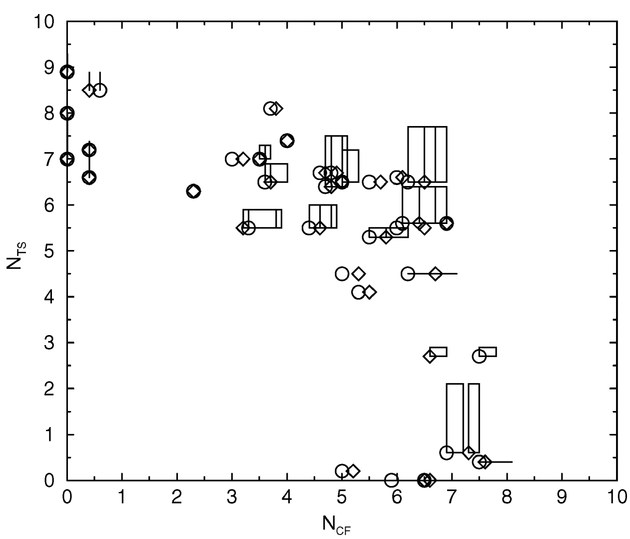

Fig. 10 N factor pairs of the ELFIN II S1MA wind-tunnel tests obtained with incompressible stability theory: ○, (N_{CF}, N_{TS}); and ◇, (N_β, N_{TS}).

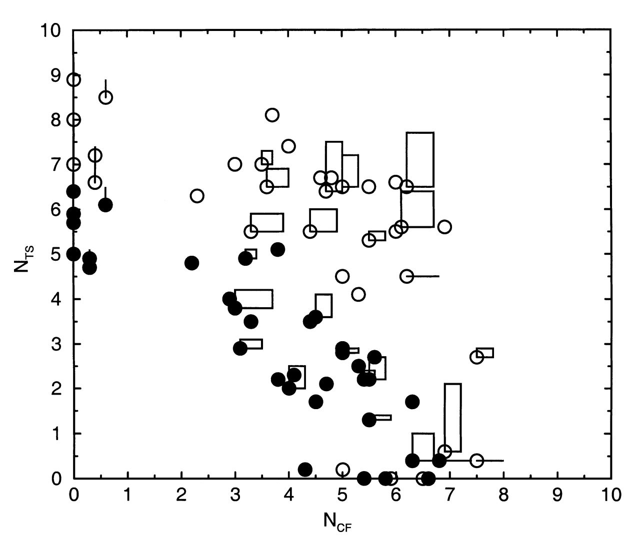

Fig. 11 Comparison of (N_{CF}, N_{TS}) factor pairs of the ELFIN II S1MA wind-tunnel tests obtained with stability theory: ○, incompressible; and ●, compressible.

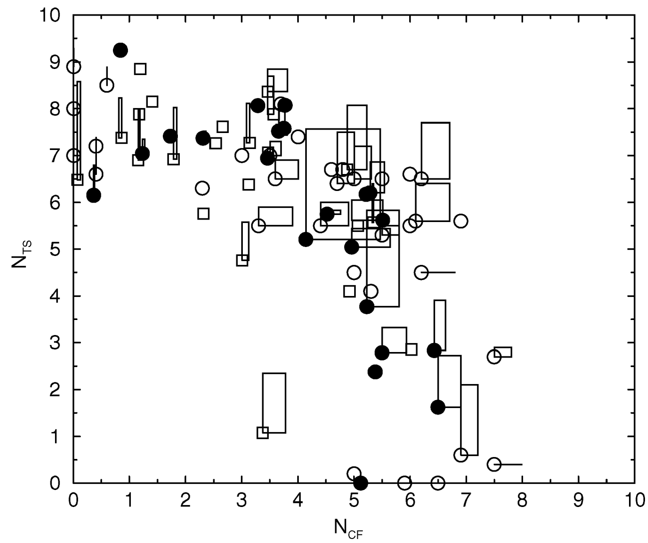

Fig. 12 Correlated (N_{CF}, N_{TS})-factor pairs of the ELFIN II S1MA test: ○, on the HLF panel; ●, on the NLF panel; and □, of the ELFIN HLF test obtained with incompressible theory.

A small section of the ELFIN II model had a polished surface without suction holes in order to simultaneously produce natural laminar-flow results under identical flow conditions. On the NLF panel transition occurred much closer to the leading edge, as expected. The correlated N-factor pairs of the NLF cases are included with bullets in Fig. 12. It was surprising to find that these N-factor pairs coincide well with the ones obtained for the part with suction. This contradicts the findings of Ref. 20 according to which the correlated N_{CF} factors for the HLF cases should be smaller than the ones for the NLF cases because the surface on the suction panel is rougher than that on the NLF panel and, thus, would create higher initial amplitudes leading to smaller N_{CF} factors at transition.

The reason for the coincidence of the N_{TS} factors for the panels with and without suction is also remarkable as Tollmien–Schlichting waves are susceptible to sound. As the level of the external sound reaching the boundary layer from outside as well as the level of the internal sound of the suction system coming from inside through the suction holes are both very high, the influence of each effect cannot be distinguished from the other. Even though, in flight tests, the level of external sound is much lower than in the wind tunnel, no clear picture has yet emerged on the respective influences of external and internal sound on the growth of Tollmien–Schlichting waves. This question needs further investigation. Similar results are obtained with compressible stability theory as shown in Figs. 13 and 14.

In addition to the ELFIN II results, we include in Figs. 12 and 13 the recalculated results of the ELFIN HLF S1MA wind-tunnel experiment using the 1:2 model of the ATTAS NLF glove equipped with a suction leading edge. For both incompressible as well as compressible stability theory, the correlated (N_{CF}, N_{TS})-factor pairs of the ELFIN tests agree very well with the ones obtained with the ELFIN II HLF wing even though two different types of pressure distributions were used. Thus, Figs. 12 and 13 constitute a good basis for transition prediction with the e^N method in the S1MA wind tunnel.

Flight-Test Results

In Fig. 15 we present the results using incompressible stability theory for the three flight experiments with the ATTAS/VFW614, the Fokker F100, and the A320 aircraft. The F100 results shown here with black squares do not include the so-called pathological cases[7,9] for which transition occurs behind the N-factor maximum. For the

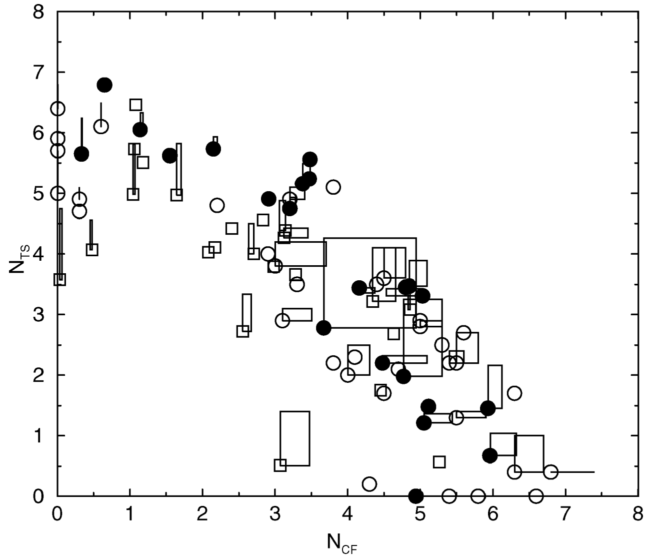

Fig. 13 Correlated (N_{CF}, N_{TS})-factor pairs of the ELFIN II S1MA test: ○, on the HLF panel; ●, on the NLF panel; and □, of the ELFIN HLF test obtained with compressible theory.

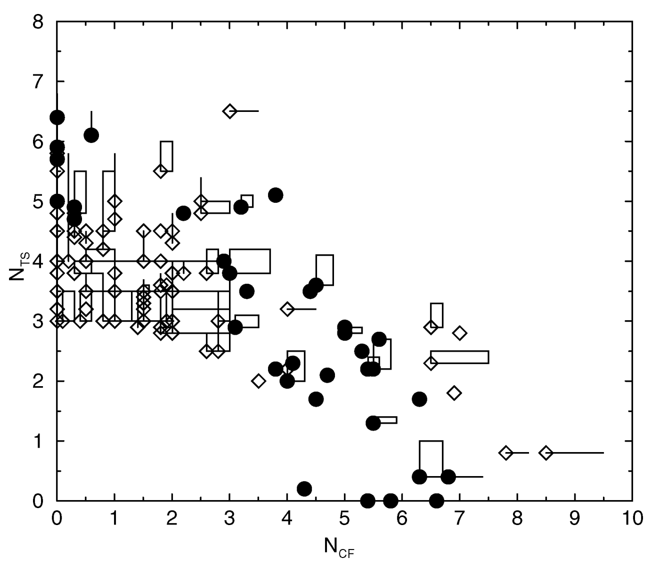

Fig. 14 Comparison of (N_{CF}, N_{TS})-factor pairs of ◇, the A320 fin tests and ●, the ELFIN II S1MA test on the HLF panel obtained with compressible theory.

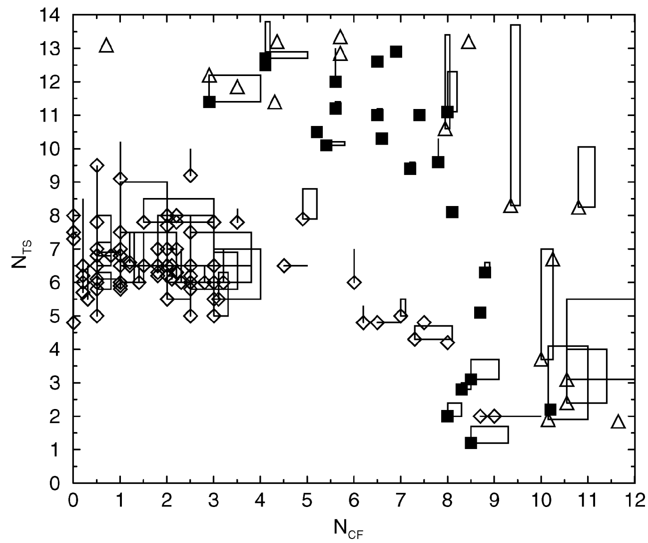

Fig. 15 Correlated (N_{CF}/N_{TS})-factor pairs of the △, ATTAS; ■, the Fokker 100; and ◇, the A320 HLF fin flight tests obtained with incompressible theory.

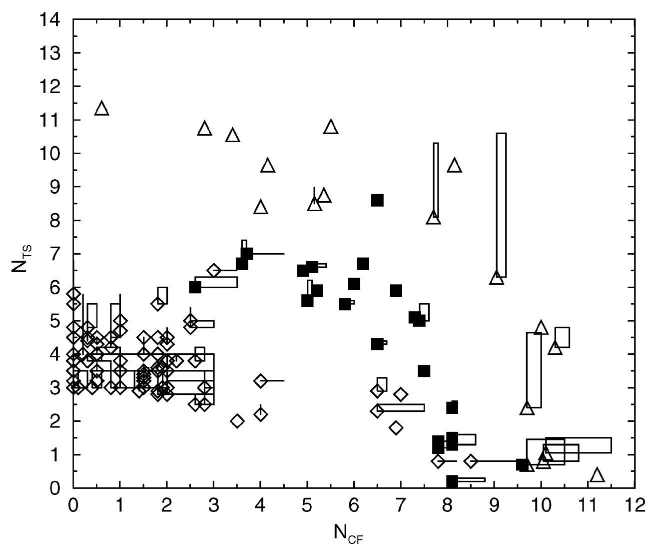

Fig. 16 Correlated (N_{CF}/N_{TS})-factor pairs of the △, ATTAS; ■, the Fokker 100; and ◇, the A320 HLF fin flight tests obtained with compressible theory.

A320 HLF fin flight tests, we evaluated 200 cases, 95 of which delivered useful results for the N-factor correlation. The results shown here were obtained with averaged suction velocities computed with the measured mass flows in the tubes connecting the suction chambers and the collector ahead of the compressor. Because of nonuniformity of the porous panel, caused by unequal spacings of the suction holes and hole blockages, the local suction velocities are somewhat different from the averaged suction velocities. It was shown in Ref. 21 that the difference between averaged and local suction velocities only becomes important if transition occurs just behind the end of the suction panel (or over the suction panel, in which case its location cannot be determined by infrared thermography). As this is not the case for the results presented here, we expect only a minor shift in the correlated N factors if local suction velocities are used for the evaluation.

Because of leading-edge suction, there are only a few crossflow cases available for N-factor correlation. They were obtained for the pressure or windward side of the fin by flying with sideslip. It is surprising that those N_{CF} values agree well with the Fokker F100 flight-test results. The F100 values themselves are smaller than than the N_{CF} factors obtained for the ATTAS glove. Up to now, this has been attributed to the seemingly smoother glove surface used in the ATTAS tests. With compressible stability theory the same relation between the N_{CF} factors is obtained for the evaluation as shown in Fig. 16.

For the Tollmien–Schlichting cases the incompressible N_{TS} factors correlated for the ATTAS and the F100 flight experiment both reach the same level, approximately 12, and are nearly twice as high as the correlated N_{TS} factors for the A320 fin. As mentioned before, the reason for this lower N-factor level of the HLF cases could be the sound generated by the suction system.

With compressible stability theory a lower N-factor level is obtained for all flight tests. However, the F100 N_{TS} factors no longer agree with Mach numbers reached with the Fokker F100 aircraft as the compressible N_{TS} factors become smaller with increasing Mach number.[22]

In Fig. 17 we compare the correlated N-factor pairs of the A320 HLF fin with the HLF cases of the ELFIN II wind-tunnel experiment. We see that, in spite of the much higher external sound level in the wind tunnel, the Tollmien–Schlichting N factors for wind tunnel and flight test are approximately the same, indicating the dominance of the interior sound of the suction system. Therefore, the sound

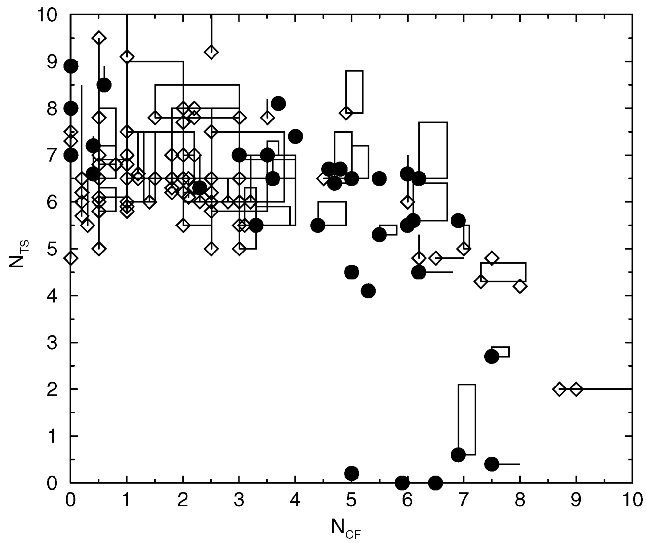

Fig. 17 Comparison of (N_{CF}, N_{TS})-factor pairs of ◇, the A320 fin tests and ●, the ELFIN II S1MA test on the HLF panel obtained with incompressible theory.

generated by the suction system itself should be included in future investigations.

Furthermore, the magnitude of the N_{CF} factors for the flight test is somewhat larger than that obtained in the wind-tunnel experiment. This is also observed for the compressible stability theory shown in Fig. 14. As there are only very few CF-data points, the significance of this observation must be confirmed before a recommendation can be made as to relax the suction requirements in future design.

Conclusions

Different procedures for transition prediction with the e^N method based on one and two N factors were discussed. It was shown that the envelope method, which is an one-N-factor method, is not suitable for transition prediction in hybrid laminar flow. For the two-N-factor methods correlations using incompressible as well as compressible linear stability theory were presented for five large-scale experiments: two within the ONERA S1MA tunnel and two NLF flight tests using the ATTAS/VFW614 as well as the Fokker F100 aircraft and the flight tests with the A320 HLF fin. Two observations are made: first that in the wind tunnel the same crossflow N factors were obtained for the HLF and the NLF part of the wing, and, second, that the internal sound produced by the suction system plays an important role.

Acknowledgments

This work has been supported by the ELFIN, ELFIN II, and HYLDA projects of the Industrial and Materials Technologies Program of the European Commission as well as the German TLF and RaWiD programs.

References

[1] Arnal, D., "Boundary Layer Transition: Predictions Based on Linear Theory," *Special Course on Progress in Transition Modeling*, AGARD Rept. 793, AGARD, Neuilly-sur-Seine, France, 1994, pp. 2-1–2-63.

[2] Schrauf, G., "Transition Prediction Using Different Linear Stability Analysis Strategies," AIAA Paper 94-1848, June 1994.

[3] Bieler, H., and Priest, J., "HLFC for Commercial Aircraft—First ELFIN Test Results," *Proceedings of the First European Forum on Laminar Flow Technology*, DGLR-Report 92-06, DGLR, Bonn, Germany, 1992, pp. 193–200.

[4] Redeker, G., Horstmann, K. H., Köster, H., Thiede, P., and Szodruch, J., "Design of Natural Laminar Flow Glove on a Transport Aircraft," AIAA Paper 90-3043-CP, Aug. 1990.

[5] Horstmann, K. H., Redeker, G., Quast, A., Dreßler, U., and Bieler, H., "Flight Tests with a Natural Laminar Flow Glove on a Transport Aircraft," AIAA Paper 90-3044-CP, Aug. 1990.

[6] Voogt, N., "Flight Testing of a Fokker 100 Aircraft with Laminar Flow Glove," *Proceedings of the Second European Forum on Laminar Flow Technology*, AAAF Rept., AAAF, Paris, France, 1996, pp. 2-3–2-14.

[7] Schrauf, G., Perraud, J., Vitiello, D., Lam, F., Stock, H. W., and Abbas, A., "Transition Prediction with Linear Stability Theory—Lessons Learned from the ELFIN F100 Flight Demonstrator," *Proceedings of the Second European Forum on Laminar Flow Technology*, AAAF Rept., AAAF, Paris, France, 1996, pp. 8-58–8-71.

[8] Henke, R., "The Airbus A320 HLF Fin Programme," *Nouvelle Revue d'Aeronautique et d'Astronautique*, Vol. 209, No. 2, pp. 53–55.

[9] Schrauf, G., Perraud, J., Vitiello, D., and Lam., F., "Comparison of Boundary Layer Transition Prediction using Flight Test Data," *Journal of Aircraft*, Vol. 53, No. 6, 1998, pp. 891–897.

[10] Schrauf, G., "Linear Stability Theory Applied to Wind Tunnel and Flight Experiments," *Computational Fluid Dynamics '98, Invited Lectures Minisymposia and Special Technological Sessions of the Fourth European Computational Fluid Dynamics Conference*, edited by K. D. Papailiou, D. Tsahalis, J. Périaux, and D. Knörzer, Vol. 2, Wiley, New York, 1998, pp. 126–131.

[11] Bippes, H., "Instability Features Appearing on Swept Wing Configurations," *Laminar-Turbulent Transition*, Springer-Verlag, Berlin, 1990, pp. 419–430.

[12] Deyhle, H., and Bippes, H., "Disturbance Growth in an Unstable Three-Dimensional Boundary Layer and its Dependence on Environmental Conditions," *Journal of Fluid Mechanics*, Vol. 316, 1966, pp. 73–113.

[13] Koch, W., Bertolotti, F. P., Stolte, A., and Hein, S., "Nonlinear Equilibrium Solutions in a Three-Dimensional Boundary Layer and their Secondary Instability," *Journal of Fluid Mechanics*, Vol. 406, 2000, pp. 131–174.

[14] Herbert, T., and Schrauf, G., "Crossflow-Dominated Transition in Flight Tests," AIAA Paper 96-0185, Jan. 1996.

[15] Abegg, C., Bippes, H., and Bertolotti, F. P., "On the Application of Suction for the Stabilization of Crossflow Instability over Perforated Walls," *New Results in Numerical and Experimental Fluid Mechanics II, Contributions to the 11th AG STAB/DGLR Symposium*, edited by W. Nitsche, H.-J. Heinemann, and R. Hilbig, Vieweg, Brunswick, Germany, 1999, pp. 1–7.

[16] Schrauf, G., Bieler, H., and Thiede, P., "Transition Prediction—The Deutsche Airbus View," *First European Forum on Laminar Flow Technology*, DGLR Rept. 92-06, DGLR, Bonn, Germany, 1992, pp. 73–82.

[17] Schrauf, G., "A Note on the Calculation of the Effective Sweep Angle and the Attachment Line Reynolds Number," MBB-Report TE2-1636, MBB Transport- und Vehrkehrsflugzeuge, Bremen, Germany, March 1988.

[18] Schrauf, G., and Atkin, C., "Laminar Boundary Layer Theory for Transition Prediction using PSE, Part I: Boundary Layer Equations," *Aerodynamics Conference 2001*, April 2001, Royal Aeronautical Society, London.

[19] Schrauf, G., "COAST3—A Compressible Stability Code. User's Guide and Tutorial," Deutsche Airbus, Rept. EF-040/98, Deutsche Airbus, Bremen, Germany, July 1998.

[20] Crouch, J. D., and Ng, L. L., "Variable N-Factor Method for Transition Prediction in Three-Dimensional Boundary Layers," *AIAA Journal*, Vol. 38, No. 2, 2000, pp. 211–216.

[21] Schrauf, G., "Evaluation of the A320 Hybrid Laminar Fin Experiment," *Proceedings of the Fifth European Computational Fluid Dynamics Conference*, edited by E. Onate, G. Budega, and B. Suarez, ECCOMAS, Barcelona, Spain [CD-Rom] 2000.

[22] Atkin, C., and Schrauf, G., "Progress in Linear Stability Methods for Design Applications," *Proceedings of the Fifth European Computational Fluid Dynamics Conference*, edited by E. Onate, G. Budega, and B. Suarez, ECCOMAS, Barcelona, Spain [CD-Rom] 2000.