Boundary Layer Transition Analysis of the Scaled Supersonic Experimental Airplane

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ABSTRACT

Boundary layer transition characteristics of the scaled supersonic experimental airplane was numerically analyzed to confirm its natural laminar flow (NLF) wing design. Using conventional incompressible and newly developed compressible transition prediction codes based on an e^N method, the NLF characteristics were well confirmed through the following results. (1) The step function type target pressure distribution applied in the NLF wing design was found to be optimum. (2) Comparing the transition N value estimated by the compressible code with experimental results obtained by NASA, wide laminar region of the NLF wing was expected. (3) Laminar boundary layer profiles estimated by a Navier-Stokes code led to smaller N value than one by the compressible boundary layer code. (4) No transition due to attachment-line contamination was predicted.

INTRODUCTION

National Aerospace Laboratory (NAL) is promoting the National Experimental Supersonic Transport (NEXST) Program[1]. In the aerodynamic design of the unmanned and non-powered scaled supersonic experimental airplane (NEXST-1), an original natural laminar flow (NLF) wing concept was applied to reduce its friction drag[2, 3]. A target pressure (Cp) distribution[4] to delay natural transition and a newly-developed CFD-based supersonic inverse method[5] were combined to design the wing geometry.

In this NLF wing design, transition analysis plays a major role. We used a well-known transition prediction code called SALLY[6] based on an e^N method as a practical tool. In general, the e^N method estimates the so-called N value defined as integrated amplification rates of small disturbances. If a critical N value corresponding to natural transition ("transition N value") is specified through wind tunnel tests or flight tests, it can estimate transition location. However, since we only have a few data for the transition N value in three-dimensional supersonic flow, we can not predict it at present. Therefore the best way to analyze transition characteristics is to investigate the qualitative characteristics of transition locations corresponding to several typical N values.

After several iterative design processes, the desired NLF wing was designed at a design point of M=2.0, C_L=0.1 and 15,000 m in altitude[2, 3]. Fig.1 shows estimated chordwise N characteristics at a typical spanwise station of the NLF wing. The SALLY code estimates two kinds of N value, one is for Tollmien-Schlichting (T-S) instability and another is for crossflow (C-F) instability. As is shown in this figure, the growth of N value due to C-F instability at the front part of the wing was completely suppressed. Fig.2 shows estimated transition locations corresponding to typical transition N values. If N=20~25 is a transition N value, we suppose a large laminar region on the upper surface at supersonic speed. The validity of this selection will be discussed later.

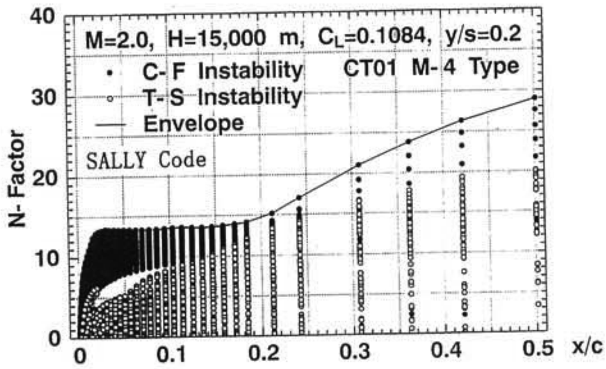

Figure 1. N characteristics estimated by SALLY code at 20% semi-spanwise station of the designed NLF wing

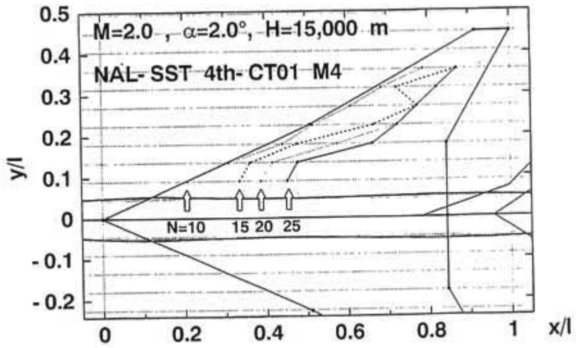

Figure 2. Estimated transition locations of the NLF wing by SALLY code

In this work, we have advanced the transition analysis to establish this NLF wing design concept completely by solving the following problems.

(1) We have never confirmed that the step function type target Cp distribution for the NLF wing design is optimum.

(2) Since the SALLY code was formulated on an incompressible stability theory, we must investigate the effect of compressibility.

(3) In general, any current three-dimensional e^N method has not been completely established yet, because of the following problems, how to select the integral path of amplification rate, how to specify any relations among components of complex wave number vector, and how to understand the influence of higher mode (Mack mode) instability on transition process.

(4) The laminar velocity profile near the leading edge estimated by boundary layer approximation is relatively inaccurate, because of the strong streamline curvature.

(5) We have only a few experimental data on transition N value in supersonic flow.

(6) In addition, we must also investigate the possibility of transition due to attachment-line contamination.

This paper describes some trials on them.

RECONSIDERATION OF TARGET Cp DISTRIBUTION

The present target Cp distribution[3)] for the NLF wing was derived under the following consideration. To suppress C-F and T-S instabilities, a pressure distribution with narrow accelerated region near the leading edge and no adverse pressure gradient from mid to rear chord is very effective. Therefore we specified the target Cp distribution with a shape like "step function" shown in Fig.3 in achieving the NLF design. The detail was described in Refs.2-3.

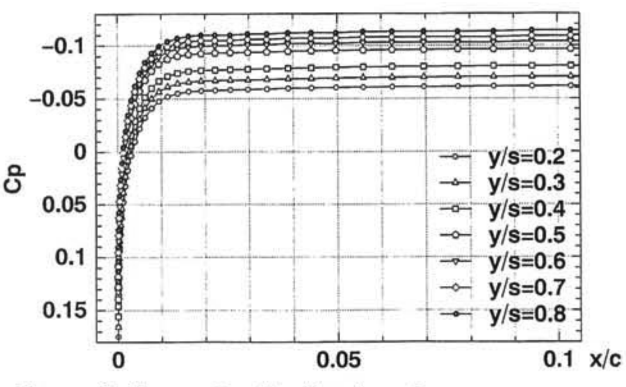

Figure 3. Target Cp distributions for supersonic NLF wing design at M=2.0, C_L=0.1

To investigate the validity of this target Cp, we made a model of Cp distribution schematically shown in Fig.4. The major parameters characterizing it are pressure gradient (m_1) between $\xi = 0$ and ξ_1, width of the accelerated region (ξ_2), flat Cp level (Cp_2) and pressure gradient ($m_2 = \tan\phi$). The combination corresponding to the target Cp was named as "case No.0" in Fig.5 and other 20 combinations of those parameters listed in Table 1 were generated. Fig.5 shows typical candidate distributions and N characteristics of these 21 combinations were evaluated by the SALLY code.

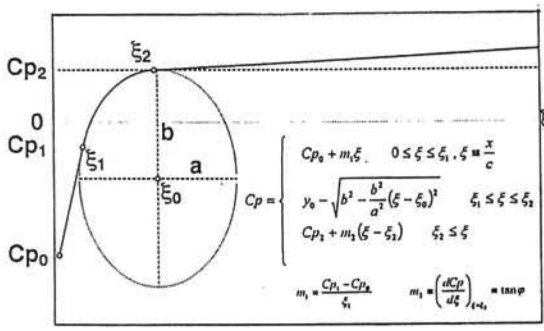

Figure 4. A model of the target Cp distribution for the NLF wing design

Table 1. Combinations of parameters on candidate target Cp distributions

	Parameters of Model Cp						
No.	Cp_0	ξ_1	Cp_1	m_1	ξ_2	Cp_2	ϕ
0	0.165	0.0010	0.030	-135.00	0.016	-0.065	-0.0595
1	0.165	0.0050	0.030	-27.00	0.016	-0.065	-0.0595
2	0.165	0.0005	0.030	-270.00	0.016	-0.065	-0.0595
3	0.165	0.0010	0.030	-135.00	0.016	-0.030	-0.0595
4	0.165	0.0010	0.030	-135.00	0.016	-0.100	-0.0595
5	0.165	0.0010	0.030	-135.00	0.008	-0.065	-0.0595
6	0.165	0.0010	0.030	-135.00	0.024	-0.065	-0.0595
7	0.165	0.0050	0.030	-27.00	0.016	-0.030	-0.0595
8	0.165	0.0050	0.030	-27.00	0.016	-0.100	-0.0595
9	0.165	0.0005	0.030	-270.00	0.016	-0.030	-0.0595
10	0.165	0.0005	0.030	-270.00	0.016	-0.100	-0.0595
11	0.165	0.0020	0.030	-67.50	0.016	-0.065	-0.0595
12	0.165	0.0020	0.030	-67.50	0.016	-0.030	-0.0595
13	0.165	0.0020	0.030	-67.50	0.010	-0.065	-0.0595
14	0.165	0.0020	0.030	-67.50	0.010	-0.030	-0.0595
15	0.165	0.0020	0.050	-57.50	0.016	-0.065	-0.0595
16	0.165	0.0020	0.050	-57.50	0.016	-0.030	-0.0595
17	0.165	0.0020	0.050	-57.50	0.010	-0.065	-0.0595
18	0.165	0.0020	0.050	-57.50	0.010	-0.030	-0.0595
19	0.165	0.0040	0.030	-33.75	0.020	-0.030	-0.0595
20	0.165	0.0040	0.030	-33.75	0.020	-0.065	-0.0595

Fig.6 shows qualitative feature of estimated transition locations corresponding to typical N values. If we pay attention to N=25 for natural transition similar to the design process, the target Cp (case No.0) is found to be nearly optimum comparing with other cases. Therefore we think present target Cp distribution is effective for the NLF wing design.

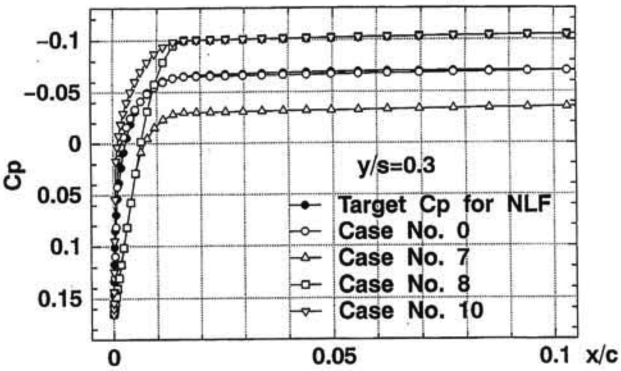

Figure 5. Some candidate target Cp distributions

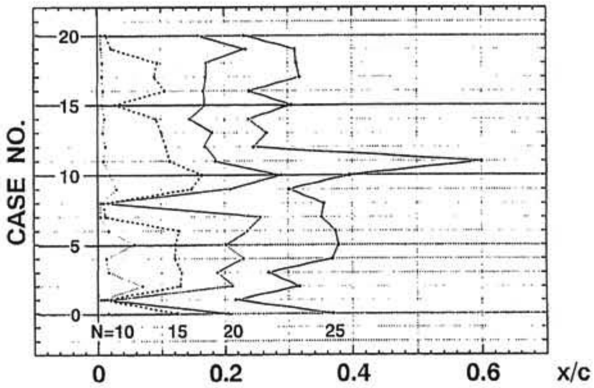

Figure 6. Estimated transition characteristics on candidate target Cp distributions

EFFECT OF COMPRESSIBILITY

Because we did not have any practical compressible code based on an e^N method, we originally developed a compressible code named "LSTAB" according to the formulation derived by El-Hady[7] and Mack[8], taking account of the problems mentioned above. The remarkable assumptions of this code are as follows.

(1) In the formulation, simple plane wave disturbances were assumed as follows:

$$\{u',v',w',p',T',\rho',\mu'\} \equiv q'(x,y,z,t) = \tilde{q}(y)\exp[i(\alpha x+\beta z-\omega t)]$$

Here (x,y,z) are coordinates in streamwise direction, boundary layer thickness direction and spanwise direction. (u,v,w) are velocities in (x,y,z) direction components. (p,T,ρ,μ) are pressure, temperature, density and viscosity. And ω is circular frequency (real) and (α,β) are components of wave number vector (complex).

(2) A local streamline direction was selected as an amplification direction.

(3) The angles of wave number vector and amplification vector $\psi,\bar{\psi}$ defined below were treated as parameters; namely any auxiliary relation on them was not specified.

$$\psi \equiv \tan^{-1}\left(\frac{\beta_r}{\alpha_r}\right),\ \bar{\psi} \equiv \tan^{-1}\left(\frac{\beta_i}{\alpha_i}\right)$$

$$\textit{where}\ \alpha \equiv \alpha_r + i\alpha_i\ ,\ \beta \equiv \beta_r + i\beta_i$$

(4) The N value corresponding to transition was assumed to be an envelope of N values at several parameter conditions as follows.

$$N = \underset{\psi}{Max}\ \underset{\bar{\psi}}{Max}\ \underset{f}{Max}\left[\int_{x_0}^{x}(-\alpha_i)_{\psi,\bar{\psi},f}\,dx\right]$$

Here $-\alpha_i$ is an amplification rate, which is an eigenvalue solution of a stability equation. f is dimensional frequency of the plane wave disturbance.

The detail of the present formulation and some validations were described in Ref.9, and a few applications were mentioned in Ref.10.

In applying this code to the transition analysis of the NLF wing, a large parameter space for $\psi,\bar{\psi}$ is necessary. To reduce calculation time, first of all, we investigated an influence of $\bar{\psi}$ on the amplification rate at a typical Reynolds number and frequency. Fig.7 shows the result of eigenvalue solutions at 20% semi-spanwise station of the designed NLF wing. We can find that maximum amplification rate is realized in the condition of $\psi \cong 70°$ and $\bar{\psi} = 0°$ in this figure. Through the similar analysis at other Reynolds numbers and frequencies, we found the condition of $\bar{\psi} = 0°$ was almost dominant and enough for estimating maximum amplification rate as an envelope. Therefore we applied this condition in all analysis.

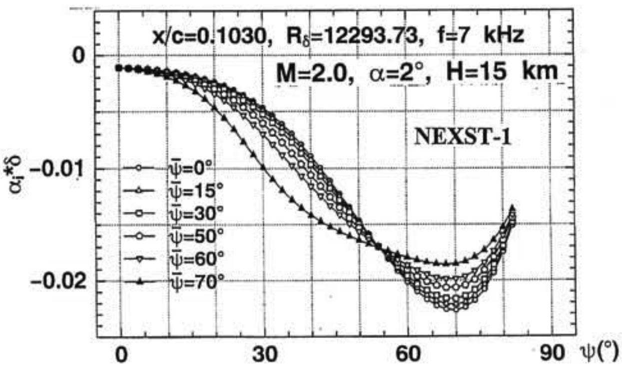

Figure 7. Influence of $\bar{\psi}$ on amplification rate

Fig.8 and 9 show some neutral stability curves and envelope of N values corresponding to each ψ at 20% semi-spanwise station. It was found in both figures that large ψ corresponding to C-F instability was dominant near the leading edge. By taking account of compressibility effect, unstable disturbances with very high frequencies near the leading edge was obtained as shown in Fig.8. It was also found that the behavior of the N curve in Fig.9 was qualitatively similar to one in Fig.1 except the mid-chord region. Fig.9 indicates that the NLF wing completely suppresses the growth of the N value due to both C-F and T-S instabilities at the front and mid-chord.

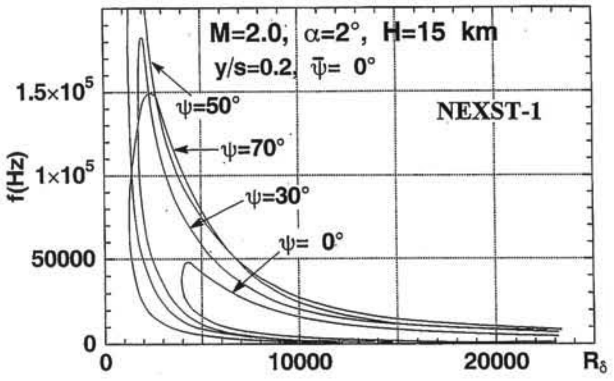

Figure 8. Neutral stability curve at 20% semi-spanwise station of the NLF wing

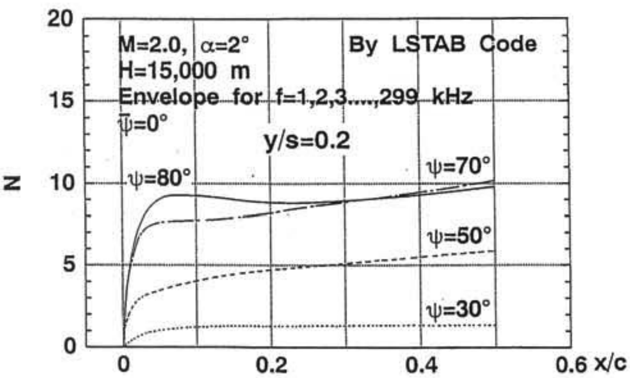

Figure 9. N characteristics estimated by LSTAB code at 20% semi-spanwise station of the designed NLF wing

Then Fig.10 shows estimated transition locations corresponding to each typical transition N value. The qualitative feature was similar to one in Fig.2 for transition N values about a half of them by the SALLY code. In general, such reduction of N value due to compressibility is well known to be valid[11].

As was mentioned above, we do not have any clear transition N value in such a crossflow-dominant case at supersonic speed. However, NASA recently found out N=14 as the transition N value through the transition experiment on F-16XL airplane using supersonic low-disturbance tunnel at Langley[12]. If it is assumed to be valid and universal, we can expect very large laminar region on the upper surface of the designed NLF wing. This must be verified at any future experiment. Therefore we confirmed present compressible transition analysis indicated the validity of the NLF wing design. Naturally this result must be verified by any future experiment.

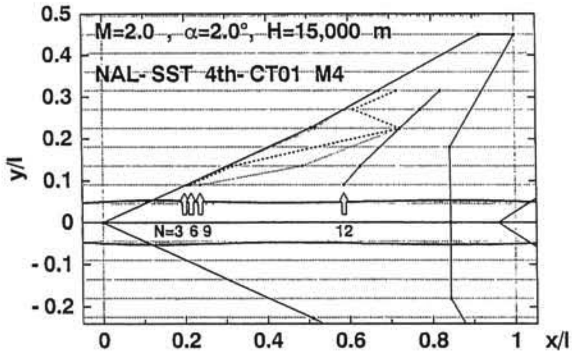

Figure 10. Estimated transition location of the NLF wing by LSTAB code

IMPROVEMENT OF LAMINAR PROFILES

In our transition prediction system, the laminar boundary layer profile was estimated by a compressible boundary layer code based on Kaups-Cebeci (K-C) method[13]. Although their method is very effective as a practical tool for high aspect ratio wings, it has some errors in the flow field with strong streamline curvature such as one near the leading edge. In general, the growth rate of the C-F instability depends on the precision of estimated laminar profiles. In order to improve the transition prediction, it is very effective to use laminar boundary layer profiles computed by a Navier-Stokes (N-S) code, because it is usually formulated on a general curvilinear coordinate system.

Fig.11 shows laminar velocity profiles computed by our N-S code[14]. We used a fine grid system that had about 50 points within a boundary layer. In general, careful selection of boundary layer edge is required in such an N-S calculation. After some trials on it, we assumed that the edge was placed in the height with 99% of maximum resultant velocity. Fig.12 shows the comparison of estimated laminar profiles computed by the N-S analysis (indicated by "CFD") and the K-C method (indicated by "BLT"). It was found that there was remarkable difference in the crossflow velocity profile (v) even though there was a little difference in the streamwise velocity (u) and temperature (T) profiles. The crossflow velocity was weakened by strong streamline curvature near the leading edge.

Fig.13 shows comparison of the N characteristics. We found that the N value based on laminar profiles computed by the N-S analysis were less than one by the K-C method. This consideration also leads to further improvement in the transition characteristics of our NLF wing design.

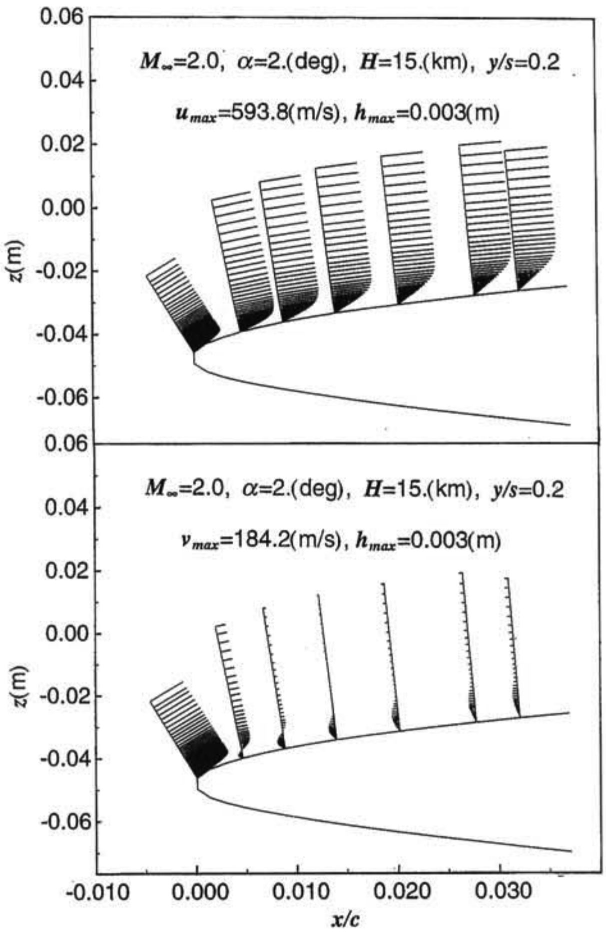

Figure 11. Laminar profiles estimated by N-S calculation

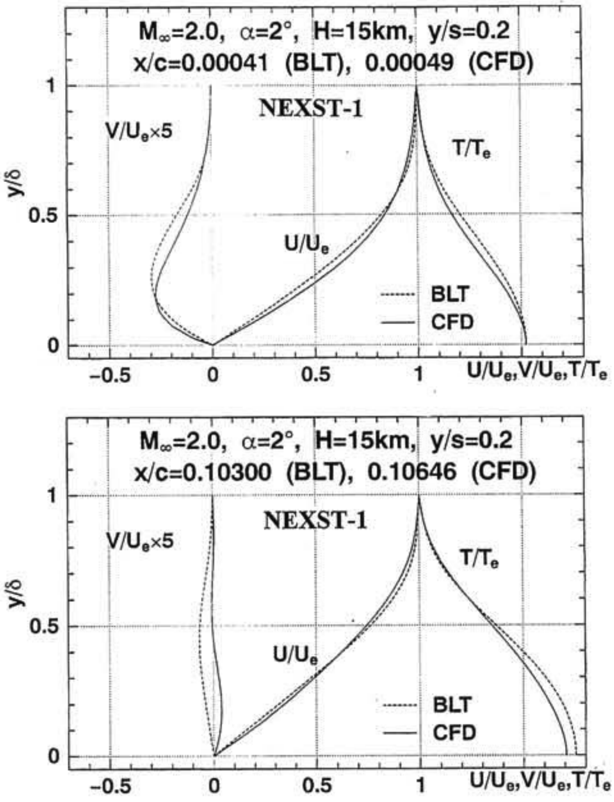

Figure 12. Comparison of laminar velocity profiles

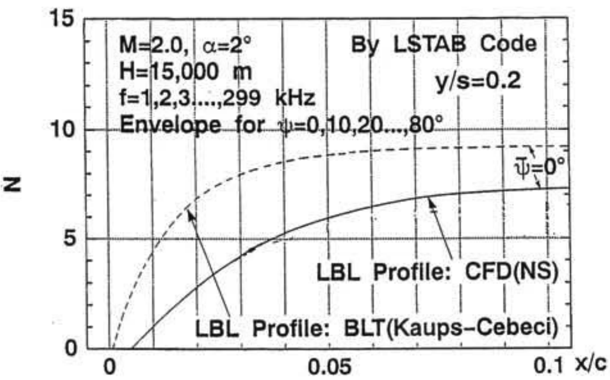

Figure 13. N characteristics estimated by LSTAB code with improved laminar profiles

INVETSIGATION OF ATTACHMENT-LINE CONTAMINATION

In a swept wing, it is well known that there is another transition mechanism, which is different from one due to T-S and C-F instability. This is transition due to attachment-line contamination originated in a turbulent boundary layer on the fuselage surface[10]. Although this process can not be analyzed theoretically, we well know that Poll's criterion[14] based on empirical database is very effective as a practical tool. Therefore we applied the criterion in this consideration.

Poll's criterion indicates that there is no possibility of transition due to attachment-line contamination if the special Reynolds number R^* is less than 245. In general, the R^* is related to the boundary layer characteristics of attachment-line flow, compressibility effect and radius of surface curvature near the leading edge.

Fig.14 shows spanwise distribution of estimated R^* in some wall temperature conditions. Here T_w and T_0 mean wall temperature and total temperature. It was found that all R^* was less than Poll's criterion 245, because our designed NLF wing had very small leading edge radius. Consequently we can expect no transition due to attachment-line contamination. Because this consideration is very rough, this problem must be experimentally investigated in the near future.

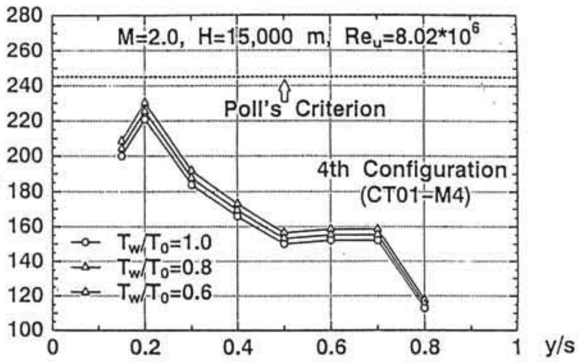

Figure 14. Result of consideration on attachment-line contamination

CONCLUDING REMARKS

We advanced transition analysis to verify the NLF wing concept incorporated in the aerodynamic design of the scaled supersonic experimental airplane. Using conventional incompressible and newly developed compressible transition prediction codes based on an e^N method, the NLF characteristics were well confirmed through the following results. (1) The step function type target Cp distribution applied in the NLF wing design was found to be optimum. (2) Comparing the transition N value estimated by the compressible code with experimental results obtained by NASA, wide laminar region of the NLF wing was expected. (3) Laminar boundary layer profiles estimated by a Navier-Stokes led to smaller N value than one by the compressible boundary layer code. (4) No transition due to attachment-line contamination was predicted. As a next step, we are planning some wind tunnel tests to validate these numerical results.

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