Research Article
Investigation on Improved Correlation of CFD and EFD for Supercritical Airfoil

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Abstract: It is necessary to improve the correlation between CFD and EFD through the correction of EFD results and validation of CFD method, thus investigating the aerodynamic characteristics of supercritical airfoil perfectly. In this study, NASA SC (2) -0714 airfoil is numerically simulated and compared with NASA corrected experimental results to validate the CFD method. The Barnwell-Sewell method is applied to correct sidewall effects for experimental results of typical supercritical airfoil CH obtained in NF-6 wind tunnel. It is shown that there was large disparity between CFD and uncorrected EFD results, while CFD and EFD compared well after correction. The CFD method is validated and the Barnwell-Sewell method is feasible for sidewall effects correction. The correlation of EFD and CFD improved after the correction of EFD results and validation of CFD method.

Keywords: CFD, correlation, EFD, supercritical airfoil

INTRODUCTION

Aerodynamic characteristics of airfoil which reflect the basic performance of an aircraft could be obtained in wind tunnel test. However, there is three-dimensional flow around the test model and the blockage at high attack angle is unacceptable, which would make results unreliable for the supercritical airfoil wind tunnel test; meanwhile, there is shock-induced separation on the upper surface of supercritical airfoil which is difficult to simulate through numerical method. So, CFD (Computational Fluid Dynamics) and EFD (Experimental Fluid Dynamics) are combined to conduct the related research. However, EFD and CFD usually correlate poorly due to the shortage of CFD and the sidewall effects of EFD which would affect real Mach numbers. In wind tunnel test, the sidewall of test-section would affect the flow of the middle area. According to reference (Barnwell, 1978), the sidewall effect is called blockage, which would affect the Mach numbers. So, it is necessary to improve their correlation through the correction of EFD results and validation of CFD method, thus investigating the aerodynamic characteristics of supercritical airfoil perfectly. Experimental data for selected test conditions were corrected for wall effects (Rivers and Wahls, 1994), but this correction to the Mach numbers is suitable for slotted wall only. The Barnwell-Davis-Moore method is limited for the correction of attack angle, which is unfeasible for supercritical airfoil (Hess *et al*., 1989).

In this study, wind tunnel test and numerical simulation were combined to study improved correlation of CFD and EFD for supercritical airfoil CH. For the EFD, airfoil test was conducted in NF-6 wind tunnel; and the results of Mach numbers and pressure coefficient affected by the sidewall boundary-layer were corrected by Barnwell-Sewell (B-S) method. For the CFD, NASA SC (2) -0714 airfoil was simulated and compared with NASA corrected experimental results to validate the CFD method. Then, CH airfoil was simulated with the validated CFD method and compared with EFD result which was corrected by B-S method. It is shown that there was large disparity between CFD and uncorrected EFD results, while CFD and EFD compared well after correction. The correlation of EFD and CFD improved after the correction of EFD results and validation of CFD method.

BASIC RESEARCH METHODOLOGY

EFD method: The airfoil test was conducted in NF-6 wind tunnel, whose test-section size was 0.8×0.4×3 m (height × width × length), with sidewalls solid and others porous. The total pressure of test-section was from 0.5×10^5 to 5.5×10^5 Pa.

The test model was a typical supercritical airfoil CH (Liu *et al*., 2011). On the upper surface, the curvature was quite small. The airfoil chord length was 0.25 m. In order to measure the surface pressure

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Table 1: CH airfoil simulation states

	State
Ma	0.74, 0.76, 0.82
Re	3×10^6, 5×10^6, 8×10^6, 10×10^6, 20×10^6, 30×10^6, 40×10^6, 50×10^6
α [°]	-4, -2, 0, 2, 3, 4, 5, 6, 7

distribution, there are 56 pressure orifices on the upper surface and 24 pressure orifices on the lower surface.

Wind tunnel test was conducted with fixed transition which is 7% airfoil chord length far from leading edge, with Mach numbers ranging from 0.6 to 0.8, the Reynolds number based on airfoil chord from 3×10^6 to 10×10^6. The pressure distribution was obtained through pressure orifices.

CFD method: For the CFD method, two dimensional discrete N-S equations were conducted by finite volume method; viscosity coefficient was obtained based on the Sutherland's formula. The Spalart-Allmaras (S-A) turbulent model was applied in this study, in order to simulate shock-induced separation correctly. The S-A model is one equation model, suitable for the boundary-layer flow which has middle separation.
The simulate states were given in Table 1.

Improved methods: The improvement of correlation of CFD and EFD in this study is conducted with two ways. On the one hand, the sidewall boundary-layer effects was corrected to make the Mach number and pressure coefficient more reliable; On the another hand, the reliability of numerical simulation was enhanced by comparing of CFD simulation results with corrected experiment results of NASA SC (2) -0714 airfoil.

EFD correcting method: The correcting method of sidewall effects changed with different tunnel test-sections. The width of NF-6 wind tunnel was 0.4 m and the CH airfoil chord was 0.25 m, thus the aspect ratio of test model was 1.6. So, the B-S method which was suitable for small ratio has been applied in this study.

B-S method is created by Richard Barnwell in the subsonic flow (Barnwell, 1980), developed by William Sewell in transonic test (Sewall, 1982). The basic correcting theory of B-S method was that sidewall boundary-layer changed the Mach numbers in test-section. After Mach numbers and pressure coefficient correction, the flow with sidewall boundary-layer has been changed to the ideal flow without sidewall boundary-layer.
The Mach numbers correction formula:

$$\frac{M_{MAC}}{(1-M_{MAC}^2)^{3/4}} = \frac{M_\infty}{\overline{\beta}^{3/2}} \qquad (1)$$

The pressure coefficient correction formula:

$$C_{p,MAC} = \frac{\overline{\beta}}{\sqrt{1-M_{MAC}^2}} C_p \qquad (2)$$

Table 2: Corrected and uncorrected results (the same reynolds number)

Re	$M\infty$ (uncorrected)	M_{MAC} (corrected)	C_{FACTOR}
10×10^6	0.60	0.584	1.018
10×10^6	0.70	0.683	1.017
10×10^6	0.75	0.733	1.016
10×10^6	0.80	0.782	1.015
10×10^6	0.85	0.833	1.014

Table 3: Corrected and uncorrected results (the same mach number)

Re	$M\infty$ (uncorrected)	M_{MAC} (corrected)	C_{FACTOR}
4×10^6	0.74	0.720	1.018
6×10^6	0.74	0.721	1.017
10×10^6	0.74	0.723	1.016
15×10^6	0.74	0.724	1.015
20×10^6	0.74	0.724	1.014
30×10^6	0.74	0.725	1.014
40×10^6	0.74	0.726	1.013
45×10^6	0.74	0.726	1.013

Table 4: 0714 airfoil numerical simulation states

State	Ma	Re	α [°]
1	0.7055	35×10^6	0.5202
2	0.7400	35×10^6	2.0000

where, $\overline{\beta}$ in Eq. (1) and (2) is:

$$\overline{\beta} = \sqrt{[1 - M_\infty^2 + \frac{2\delta^*}{b}(2 + \frac{1}{H} - M_\infty^2)]} \qquad (3)$$

According to B-S method, the displacement thickness of sidewall boundary-layer δ^* and shape factor of velocity profile H were needed, to calculate equivalent test section width, equivalent Mach numbers M_{MAC} and pressure coefficient affecting factor:

$$C_{FACTOR} = \overline{\beta} / \sqrt{1-M_{MAC}^2}$$

According to parameters of the NF-6 wind tunnel and Eq. (1) and (2) some results with and without corrections were presented in Table 2 and 3.

CFD reliability investigation: In order to validate CFD method, NASA SC (2) -0714 airfoil was simulated and compared with corrected results (Renaldo, 1989). NASA Langley center corrected wall interference effects in 0.3 m-TCT and then compared CFD with corrected EFD results (Rivers and Wahls, 1994).

In this study, two typical states of NASA SC (2)-0714 airfoil were numerically simulated (Table 4). The comparison with NASA's results was shown in Fig. 1.

In Fig. 1a, CFD results in this study were compared with CFD and EFD results of NASA. The two CFD results have good agreement on the pressure distribution after the shock wave, but the shock wave location has a slight disparity (maybe caused by different turbulent model). The results of CFD and EFD compared much better on the lower surface but there was a slight disparity on the upper surface in the
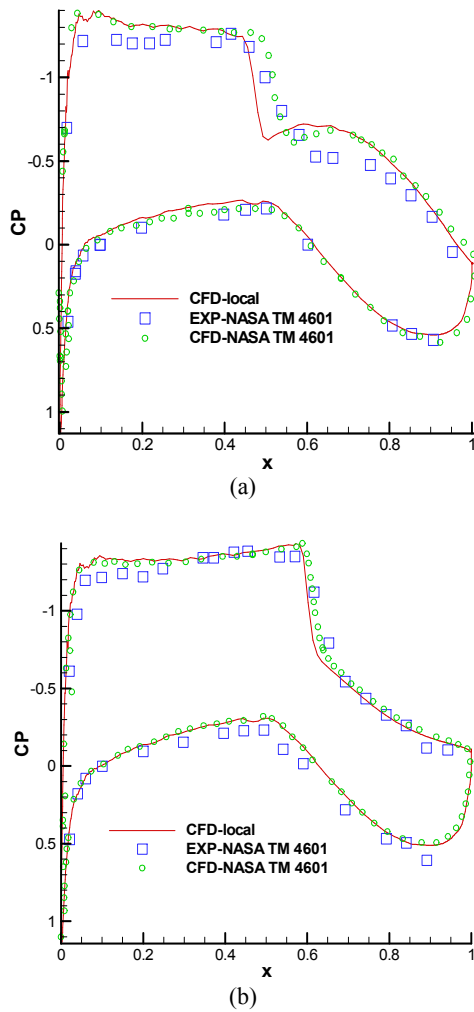
(a)

(b)

Fig. 1: Comparison result (a) state 1, (b) state 2

Table 5: Two typical states (uncorrected)

State	Ma	Re	α [°]
1	0.74	3.36×10^6	2
2	0.74	3.36×10^6	4

Table 6: Uncorrected and corrected EFD result

State	Re	Uncorrected		Corrected	
		Ma	CL	Ma	CL
1	10.4×10^6	0.60	0.4265	0.584	0.4305
2	10.4×10^6	0.60	0.6229	0.584	0.6313
3	3.36×10^6	0.74	0.4320	0.720	0.4368
4	3.36×10^6	0.74	0.6917	0.720	0.7082
5	10.2×10^6	0.80	0.6219	0.782	0.6319
6	10.2×10^6	0.80	0.6946	0.782	0.7039

(a)

(b)

Fig. 2: Initial correlation (a) state 1, (b) state 2

shock\boundary-layer disturbution area. For both CFD results, there was a separation bubble after the shock wave which could not be found in most NASA EFD results (Cahill and Conner, 1978).

The comparison result of state 2 was shown in Fig. 1b. Obviously, the CFD and EFD results compared much better than state 1.

As seen in Fig. 1, the CFD method in this study was validated.

IMPROVED RESULTS

Comparison between CFD and EFD results (uncorrected): CH airfoil was numerically simulated for two typical states as shown in Table 5. Initial compared results of CFD and uncorrected EFD results were shown in Fig. 2.

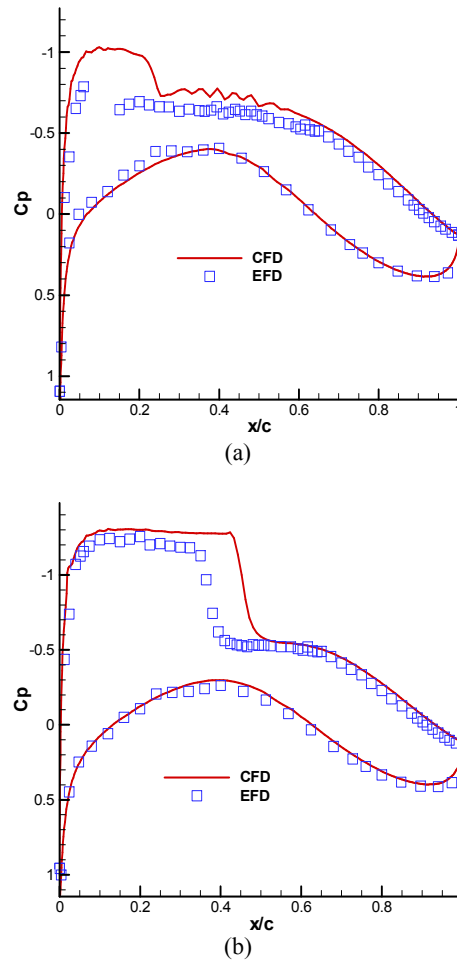In Fig. 2, there were large disparities between CFD and EFD results and initial correlation of CFD and EFD was poor.

Comparison between CFD and EFD result (corrected): The EFD results were corrected for sidewall effects in order to improve initial poor correlation of CFD and EFD. The B-S method was applied to the Mach numbers and pressure coefficient correction (Table 6). The CFD results have been compared with corrected EFD results. As shown in Fig. 3, the correlation of CFD and EFD for state 1 and 2 in Table 4 improved after correction. Other states in Fig. 3 also compared well.
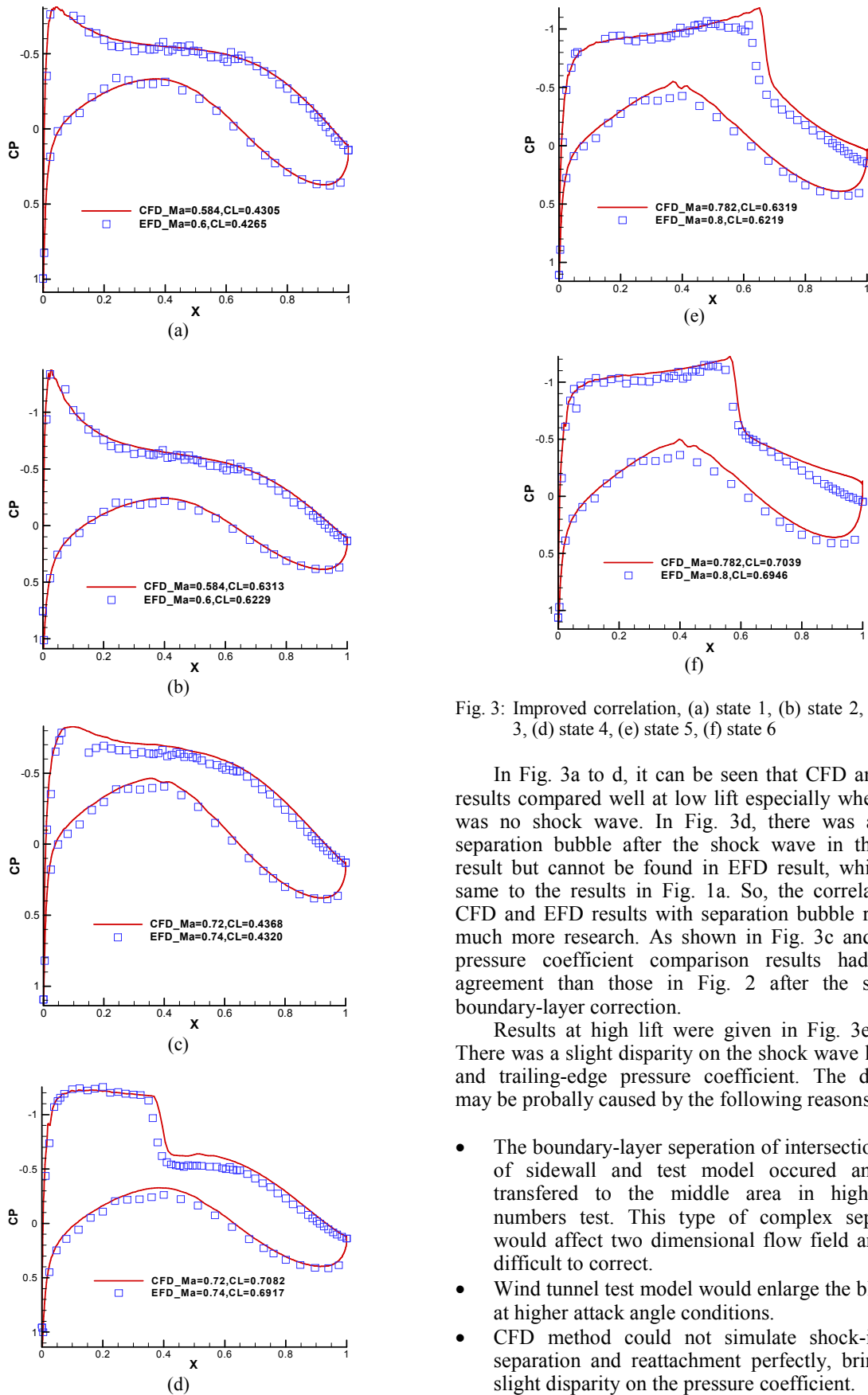
Fig. 3: Improved correlation, (a) state 1, (b) state 2, (c) state 3, (d) state 4, (e) state 5, (f) state 6

In Fig. 3a to d, it can be seen that CFD and EFD results compared well at low lift especially when there was no shock wave. In Fig. 3d, there was a small separation bubble after the shock wave in the CFD result but cannot be found in EFD result, which was same to the results in Fig. 1a. So, the correlation of CFD and EFD results with separation bubble required much more research. As shown in Fig. 3c and d, the pressure coefficient comparison results had better agreement than those in Fig. 2 after the sidewall boundary-layer correction.

Results at high lift were given in Fig. 3e and f. There was a slight disparity on the shock wave location and trailing-edge pressure coefficient. The disparity may be probally caused by the following reasons:

- The boundary-layer seperation of intersection areas of sidewall and test model occured and then transfered to the middle area in high Mach numbers test. This type of complex separation would affect two dimensional flow field and very difficult to correct.
- Wind tunnel test model would enlarge the blockage at higher attack angle conditions.
- CFD method could not simulate shock-induced separation and reattachment perfectly, bringing a slight disparity on the pressure coefficient.

CONCLUSION

- The CFD method in this study was proved to be reliable.
- There were large disparities between CFD and uncorrected EFD results; the initial correlation of CFD and EFD was poor.
- The correlation of EFD and CFD improved after the correction of EFD results and validation of CFD method.

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