Numerical Simulation of the Flow Separation on a 2-D Airfoil Using a Compact Difference Scheme

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The flow simulations of the sound wave propagation problem need high accuracy and high resolutions, since the energy of sound is weak compared with the kinetic energy. We propose the new spectral-like 3-point Combined Compact Difference (CCD) Scheme. This new scheme has the eighth-order accuracy and spectral-like resolution for first derivatives. Using this scheme, we analyze the acoustic effect for the flow separation on a 2-D airfoil with the Mach number 0.1 and 0.05. The simulations show the new scheme give excellent results compare with the previous spectral methods.

Key Words: Combined Compact difference, Acoustic excitation, Flow separation, Separation bubble

1. Introduction

Several experiments have demonstrated that the tendency toward the separation in the flow on an airfoil is reduced by an acoustic excitation [1-3]. The separation phenomena and the effect of excitation have been noted to be different dependency on the Reynolds number and the frequency of excitation. Recently we successfully reproduce these phenomena by numerical simulation on the airfoil at M=0.23. While the experimental results show that the amplification of the imposed perturbation takes place primarily in the downstream shear layer after the separation point, the numerical results shows the vorticity of the laminar boundary layer become large and the separation point moves to the leading edge. There are different conditions between the experiment and the numerical calculation. The Mach number difference of them is large: 0.012 in the experiment and 0.23 in the numerical simulation. Due to this difference, the large amplitude acoustic excitations are used in the numerical calculation and we get larger responses in the view of the lift coefficients. In order to calculate the lower Mach number flow and to reproduce these phenomena of the experiment, we must use the high accurate calculation since the kinetic energy of the flow is smaller than the internal energy and the acoustic energy is still smaller than the kinetic energy. We propose the new scheme with high accuracy and high resolution and analyze the detailed flow field.

2. Compact Difference Scheme

The numerical simulation of the flow field with the acoustic waves requires higher accuracy and higher resolution. The trend toward highly accurate finite difference schemes has recently led to a renewed interest in compact difference schemes in the computational aerodynamics. Standard finite difference methods obtain an approximation of a derivative of a grid function from a weighted average of the values of the function on a stencil. There are at least two features of these finite difference methods that are troublesome. First, the stencil has to be at least one point wider than the approximation order. Second, explicit finite difference schemes give a suboptimal representation of the dispersion relation with respect to the stencil width. This problem is emphasizes as the distinction between "accuracy "(order of approximation) and "resolution". Generally these criteria are not equivalent.

In the calculation, we use the new "spectral-like" combined compact different (CCD) scheme for the convective terms, in which the first derivative has 8-th order accuracy. Chu and Fan[4] propose a three-point combined compact difference scheme, in which the implicit finite different schemes of the first, the second and the third derivative are combined:

$$
\begin{aligned}
f_i' &= a_1(f_{i+1} - f_{i-1}) + a_2(f_{i+1}' + f_{i-1}') \\
&\quad + a_3(f_{i+1}'' - f_{i-1}'') + a_4(f_{i+1}''' + f_{i-1}''') \\
f_i'' &= b_1(f_{i+1} + f_{i-1} - 2f_i) + b_2(f_{i+1}' - f_{i-1}') \\
&\quad + b_3(f_{i+1}'' + f_{i-1}'') + b_4(f_{i+1}''' - f_{i-1}''') \\
f_i''' &= c_1(f_{i+1} - f_{i-1}) + c_2(f_{i+1}' + f_{i-1}') \\
&\quad + c_3(f_{i+1}'' - f_{i-1}'') + c_4(f_{i+1}''' + f_{i-1}''')
\end{aligned}
$$

We choose the values of a's , b's and c's for the new scheme to have the 8th order accuracy for the first derivative, the 6th order accuracy for the second derivative, the 4th order derivative for the third derivative and the spectral-like resolution to 2.6/(Δx). These second and third derivative accuracies are lower than those of the original, but the resolution become much higher. In the explicit part of the approximate factorization method for the compressible Navier-Stokes equations, we use this new spectral-like scheme and use the 6-order Compact scheme in the implicit parts. The scheme also has the second order accuracy in time by using Adans-Bashforth method.

3. Results and Discussion

The flows past a 2-D wing with the acoustic excitation at M=0.1 and 0.05 are analyzed by using the new scheme. As the airfoil model, the NACA0012 airfoil is used. The angles of attack are 12 degrees. A C-type grid with 541x51 points is used. Acoustic waves are emitted from a speaker on the bottom boundary. The Thompson boundary conditions are used for incoming or outgoing sound waves. The excitation effects are investigated for different frequencies of the acoustic waves. The amplitude of the acoustic wave is 0.05% of the pressure on upwind boundary, of which the sound intensity is about $1x10^{-5}$ of the kinetic energy flux at infinity.

Figure 1 and 2 show the streamline and the vorticity deistribution at M=0.1 and Re=10^6 and $2x10^4$ without excitation, respectively. The flow in Fig.1 has the short separation bubble and the reattachment, while the flow does not have the reattachment.

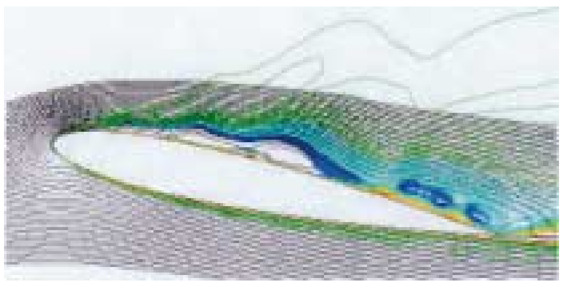

Figure 1. The flow past a wing with the attach angle 12 degree at M=0.1 and Re=10^6.

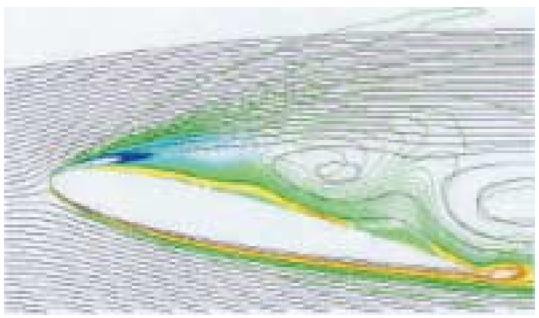

Figure 2. The flow past a wing with the attach angle 12 degree at M=0.1 and Re=10^5.

In Fig. 3, we show the flow field at M=0.1 and Re=$2x10^4$ with the acoustic excitation with the non-dimensional frequency 0.3. The figure shows the weak acoustic excitation change the flow field and the reattachment phenomena can be obtained.

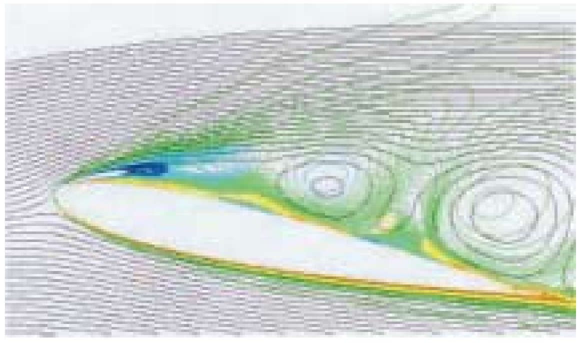

Figure 3. The flow past a wing with the attach angle 12 degree at M=0.1 and Re=$2x10^4$ with the acoustic excitation with f=0.3.

The effects of acoustic excitation with different frequencies on the flow past an airfoil are also obtained successfully. The following results are obtained. When the excitation frequency is around the natural shedding frequency, the separated flow re-attaches to an airfoil and the lift coefficient C_L increases. These frequency region at M=0.1 is wider than that of M=0.23, and the acoustic excitation with smaller amplitude changes the flow field at M=0.1. When the C_L has the larger value, the strength of vorticity in the laminar boundary layer becomes larger. In addition, the separation point shifts to the leading edge. These show that the study of flow near the laminar separation points as well as the flow in the down stream region, would be important in the acoustic control problem of an airfoil.

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