TRANSITION ONSET PREDICTIONS FOR HIGH-LIFT CONFIGURATIONS

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Abstract

A new approach that employs an innovative implementation of results of linear stability theory and modeling of transitional flows is used to predict onset and extent of transition on multi-element airfoils at high angles of attack. It is based on the k-ζ. transitional/turbulence model. The approach is validated by calculating flows past the multi-element McDonnell Douglas landing configuration at two angles of attack, 8 and 16 degrees. Comparisons involve pressure distribution, velocity profiles, transition onset, and Reynolds shear stresses. In general, good agreement with all measurements is indicated. Some differences (less than 3%) are noted in the prediction of the extent and penetration of the slat wake at the higher angle of attack.

Introduction

The prediction of confluent boundary layers past high lift configurations is an extremely difficult problem that proved to be a challenge to existing CFD codes. Such flows are characterized by multiple interactions of free- and wall-bounded shear layers. These interactions are viscous in nature. Moreover, their behavior is strongly dependent on the onset of transition on each element.

The inability of traditional Reynolds-averaged Navier-Stokes (RANS) [1-3] to predict high lift flows are a result of two important limitations: the first pertaining to the inability of calculating wall bounded shear flows and free shear layers using the same set of model constants [4]. This is important for confluent boundary layers. The second is the absence of transitional models capable of predicting onset and extent of transition. Evidently, methods based on stability theory, such as e^n method or methods based on the Parabolic Stability Equation (PSE), have proven to be ineffective for such flows. Moreover, Bertelrud [5] has shown that none of the existing transition prediction correlations provide reliable onset prediction criteria for high lift devices.

Recent successes at calculating such flows were demonstrated by Czerwiec et al. [6, 7]. Their model, which is based on a formulation, by Warren and Hassan [8], demonstrated that reliable and inexpensive predictive methods can be developed for high lift flows. The approach of Ref. 8 addresses the shortcomings of existing models. Thus, it employs the k-ζ turbulence model [9, 10], which was derived from the exact equations that govern *k*, the kinematic energy of the fluctuation and ζ, the enstrophy or variance of vorticity. It has been demonstrated that the model reproduces the growth rates of free shear layers, and other wall bounded shear flows, using the same set of model constants. Moreover, transitional flows were treated in a manner similar to that of turbulent flows and the eddy viscosity in the transitional region was deduced from results of linear stability theory. Transition onset is determined, as part of the solution, by choosing it to correspond to minimum skin friction or other more appropriate criterion.

Results of calculations for two angles of attack at 8 and 16 degrees will be presented and compared with experiments that were carried out over a span of five years in the NASA Langley Low Turbulence Pressure tunnel

(LTPT). These experiments involve pressure distribution, velocity profiles, transition onset, and Reynolds stresses [11-14]. The k-ζ transitional model is incorporated into CFL3D which is a widely used NASA code. The code was used by a number of investigators to calculate [1-3] some of the test conditions from the extensive experimental state base [11-14].

Formulation of the Problem

Approach

Traditionally, the transition problem has been treated as a combination of two problems. The first deals with transition onset while the second deals with extent given the onset. There are a number of ways that are being used to specify transition onset: experimental measurements, empirical correlations or, use of stability theory. One of the methods employed in calculating the extent is to replace the turbulent viscosity by

$$\Gamma \mu_t$$

when μ_t is the turbulent viscosity and Γ is the intermittency, or the fraction of time the flow is turbulent at a given location. Γ varies from 0, at onset, to 1 when the transition to turbulence is complete. Γ can be chosen as a step function or, the expression developed by Dhawan and Narasimha [15], or some other expression. Even when the transition onset is specified, above procedure does not work well. This is because the procedure does not account for the nonturbulent fluctuations that exist in the flow. As a result, the above choice is replaced by

$$(1-\Gamma)\mu_{nt} + \Gamma\mu_t$$

where μ_{nt} represents the contribution of the non-turbulent fluctuations. In this work, μ_{nt} is deduced from linear stability theory.

The eddy viscosity μ_{nt} is set as

$$\mu_{nt} = c_\infty \rho k \, \tau, \qquad c_\mu = 0.09 \tag{1}$$

where k is the fluctuation kinetic energy per unit mass, ρ is the density and τ is a time scale characteristics of the type of instability considered. For transitions resulting from Tollmien-Schlicting (T-S) waves, τ is chosen as

$$\tau = a/\omega \tag{2}$$

Where ω is the frequency of the first mode disturbance having the maximum amplification rate and a is a model constant the depends on the freestream tubulent intensity, Tu, defined as

$$Tu = 100\sqrt{\frac{2}{3}\frac{k_\infty}{q_\infty^2}} \tag{3}$$

Where k_∞ and q_∞ are the freestream kinetic energy of the fluctuations and magnitude of freestream velocity. As was indicated in Ref. 6 a has the form

$$a = 0.095(Tu - 0.138)^2 + 0.0112 \tag{4}$$

The frequency ω was correlated by Walker [16] in terms of the displacement thickness. However, because CFL3D has no provision for calculating boundary layer quantities, a new correlation, derived in Ref. 6 is chosen. This correlation can be written as

$$\frac{\omega \nu}{q_e^2} = 0.48\,\mathrm{Re}_x^{-.65} \tag{5}$$

Where q_e is the edge velocity, ν is the kinematic viscosity, and Re_x is the Reynolds number based on a distance measured from the stagnation point

Intermittency and Onset Criterion

The Dhawan and Narasimha expression is given by

$$\Gamma = 1 - \exp(-0.412\xi^2) \tag{6}$$

with

$$\xi = \max(x - x_t, 0)/\lambda \tag{7}$$

where λ is a characteristic extent of the transitional region. An experimental correlation between λ and x_t is [16]

$$\mathrm{Re}_{\lambda} = 9.0\,\mathrm{Re}_{x_t}^{.75} \qquad (8)$$

where α_t being the location where turbulent spots first appear. This point can also be chosen as the location of minimum skin friction or minimum heat flux if the pressure gradient is zero. In this work, a criterion first developed in Ref. 17, which selects x_t as the first location where the relation

$$\frac{1}{c_{\mu}} \frac{\nu_{nt}}{\nu} = 1 \qquad (9)$$

is satisfied, is employed. Experimentally [13], characteristics of hot films were used to infer transition on high-lift configurations. These characteristics could not be related directly to any of the flow properties calculated by traditional CFD codes. In spite of this, it is shown in Ref. 6 that Eq. (9) appears to be a viable criterion for determining transition onset.

Results and Discussion

The results presented here are for the McDonnell Douglas 30P-30N landing configurations for angles of attack, α, of 16 and 8 degrees, freestream Mach number, M_{∞}, of 0.2 and a Reynolds number of 9×10^6. The model was tested in the Langley Low Turbulence Pressure Tunnel (LTPT). It has a stowed chord, c, of 0.5588 m. The slat and flap settings are: for the slat, deflection of 30°, gap of 2.95% c, and overhang of – 2.5% c; for the flap, deflection of 30°, gap of 1.27% c, and overhang of – 25% c. The layout is shown in Fig. 1, which shows, in addition, locations where some of the comparisons are made. The grid used is the four-zone free air grid first employed in Ref. 2.

1. Comparison for α = 16 degrees

Tunnel wall suction was employed for this angle of attack in order to approximate two-dimensional flow. Figure 2 compares computed pressure distributions with experiment. As seen from the figure, the pressure distributions are accurately predicted.

Transition prediction for all elements is shown in Fig. 3. There was no attempt to probe the cove regions and the aft portion of the flap [13]. The circles in the figures indicate the start and end (when indicated) of measured transition region, the squares indicate computed onset predictions, and the crosses indicate locations where the computed values of Γ = 1/2. In general, good agreement with experiment is indicated. The apparent disagreement with experiment on the lower surface of the main airfoil is not as severe as it appears because the maximum value of μ_T / μ_{∞} in the region below the main airfoil is less than 100.

Figure 4 displays velocity profiles at eight stations on the main airfoil and flap. The quantity d/c appearing in the figure is the ratio of the surface-normal distance to the wing chord length. As is seen from the figure, the penetration of the main airfoil wake is well-captured. Departures in the penetration and magnitude of the slat wake deficit are noted in the figure. However, the differences between peak measured and calculated values divided by peak measured value is less than 3%. The cause of this discrepancy is not wall understood: it can be a result of unsteadiness, measurement accuracy, or limitations of the present model.

Figure 5 compares Reynolds shear stresses in streamline coordinates at four stations. As may be seen from the figure, the stations closest to the flap gap are not as well predicted as stations away from the gap. Again, this may be a result of unsteadiness.

2. Comparisons for α = 8 degrees

A third-order accurate Roe solver was used in generating the results for the α = 16 degrees. For the α = 8 degrees, the scheme resulted in an oscillation over the slat which was infered from the movement of the predicted transition onset on the upper surface of the slat over 10-12 grid points. The oscillations disappeared when a second-order Roe solver was employed. Figure 6 compares the role of the numerical dissipation on the pressure distribution. As is seen from the figure, the pressure distributions in the slat's cove region are different, with the second-order results agreeing better with experiment. Further, it is seen from Fig. 6 that pressure measurements on the slat suggest that the flow is unsteady. All subsequent results employ the second-order Roe solver.

As is seen from Fig. 7(a), the current model predicts delayed transition on the upper surface of the slat with Γ remaining below1/2. Moreover, transition is predicted in the lower surface of the slat. As was indicated earlier, no attempt was made to probe the cove region. Figure 7(b) and 7(c) indicate that predictions are in good agreement with experiment. Although the model predicts transition in the lower surface of the flap, Γ remains less than1/2 there.

Figure 8 compares velocity profiles. Data is shown for three stations on the main airfoil and two stations on the flap. It is indicated in Ref. 2 that the offset velocity difference between computation and experiment shown in Fig. 8 (a) was probably a result of improper calibration of experimental data at this station. Thus, discounting the first station, good agreement is indicated with the maximum error on the main airfoil being less than 3%. The penetration of the wake of the main airfoil over the flap is slightly underpredicted. Overall, results indicate that the slat wake is diffuse beyond x/c = 0.45, in good agreement with experiment. This case was calculated in Ref. 2 where transition onset was specified. Their results do not show the diffuse nature of the slat wake. Moreover, they indicated that no upper surface slat transition onset provided satisfactory slat-wake profiles that agreed well with experiment.

Figure 9 compares Reynolds stress measurements. In general the agreement is similar to that for α = 16. Differences can be a result of unsteadiness, gap setting, and inadequacy of transitional/turbulence model being used.

It is to be noted that a number of calculations were carried out in which transition onset was assumed, in order to improve slat wake predictions. We were unable to determine a set of transition points, including those that were measured by experiment, that improved upon the velocity profiles generated when the model was allowed to seek transition onset. This is especially true for α = 8 degrees. This finding suggests that Eq. (9) is a viable criterion for determining transition onset for natural transition.

Comparison of the pressure distribution for the two cases considered here reveals that as α increases the loading shifts from the flap to the slat. This behavior is consistent with observations involving three-element airfoils.

Concluding Remarks

The present approach presents a viable and economical method for calculating transitional flow over multi-element airfoils at high angles of attack without user interface. Comparisons involving pressure distribution, transition onset, velocity profiles and Reynolds stresses are, in general, in good agreement with experiment. The only exceptions are the profiles of the slat wake, where depth tends to be overpredicted.

The level of overall agreement suggest that the k-ζ transitional model captures the essence of the complex flow physics of this problem. Although traditional techniques of stability theory are not used in this work, results of linear stability theory played a major role in the success of the present work.

Acknowledgements

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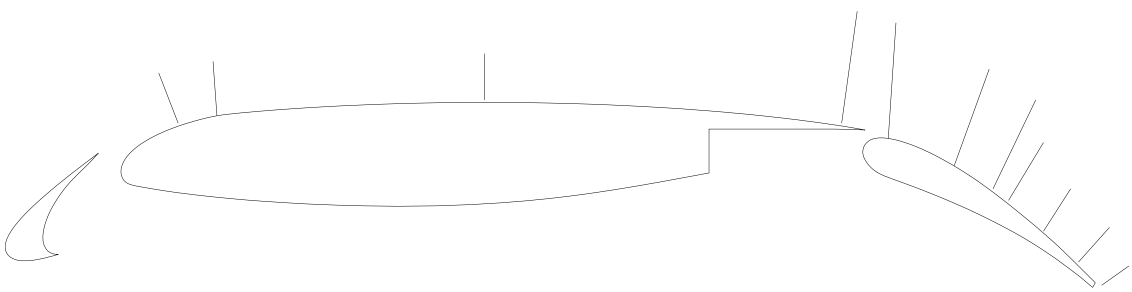

Figure 1: Surface normal profile x/c stations

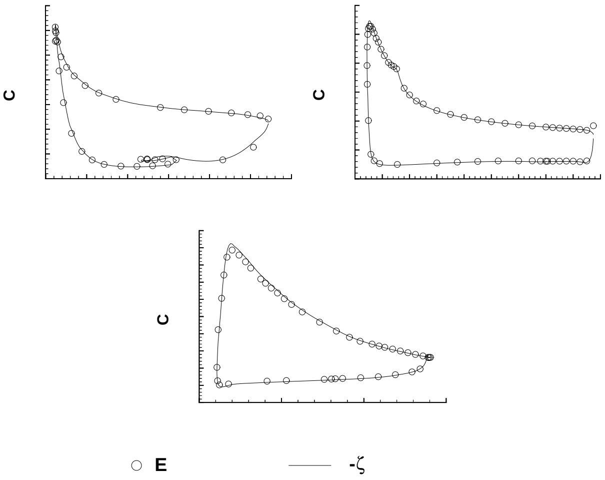

Figure 2: Pressure distributin for α = 16 degrees

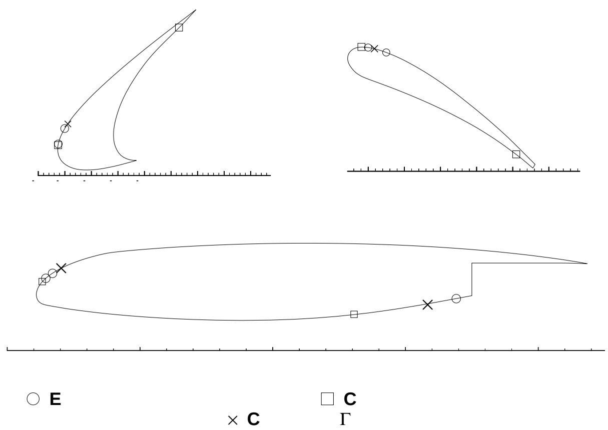

Figure 3: Transition locations for α = 16 degrees

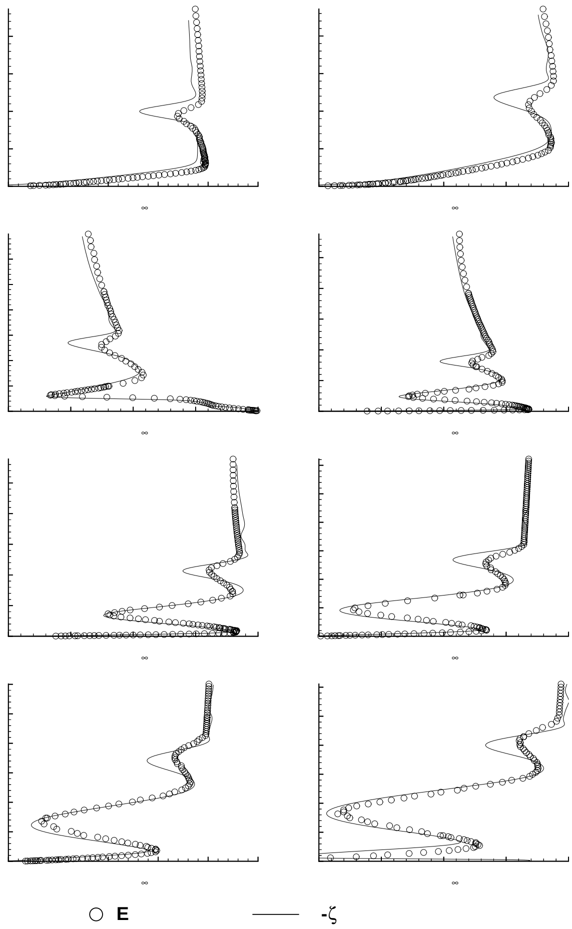

Figure 4: Velocity profiles for α = 16 degrees

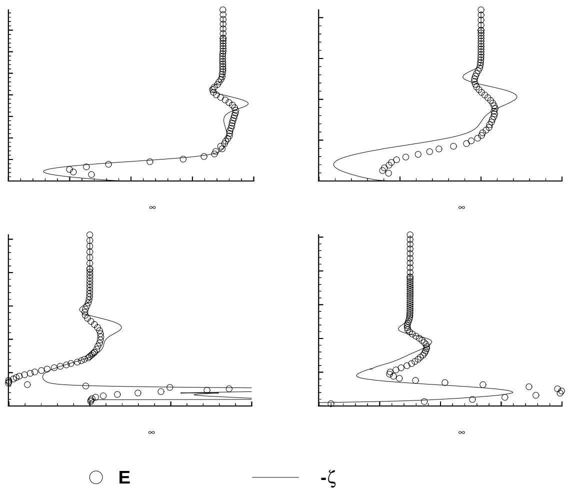

Figure 5: Streamwise Reynolds stress for α = 16 degrees

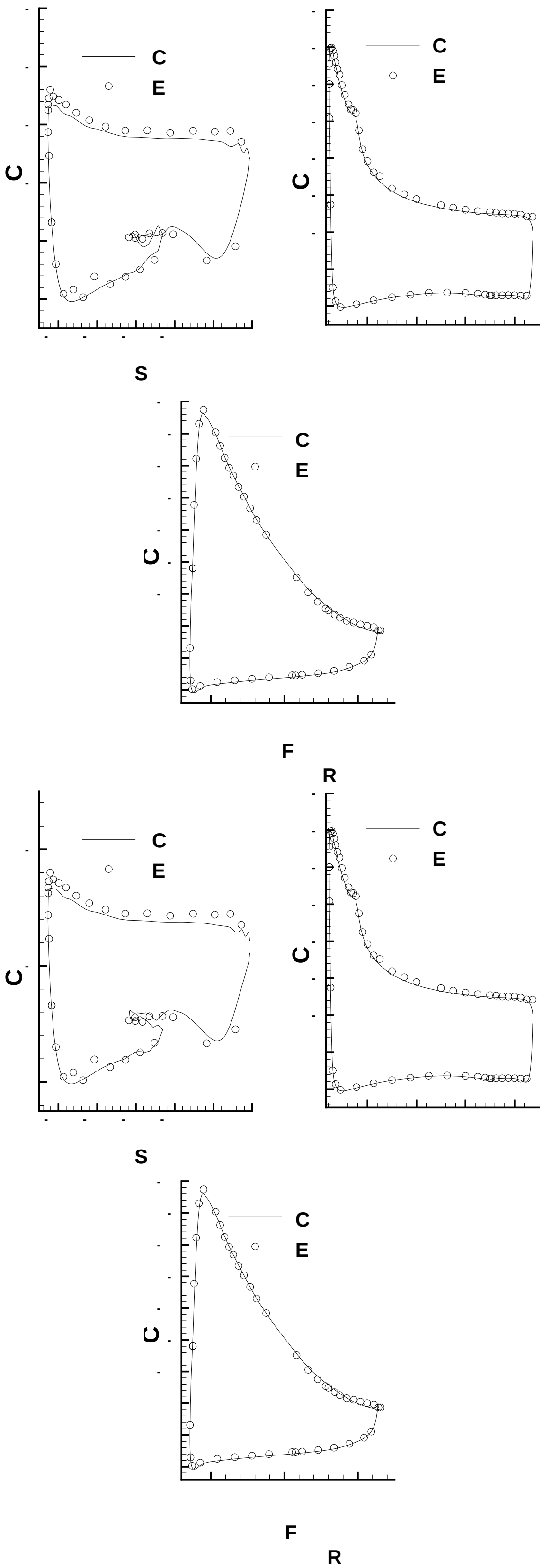

Figure 6: Pressure distributin for α = 8 degrees

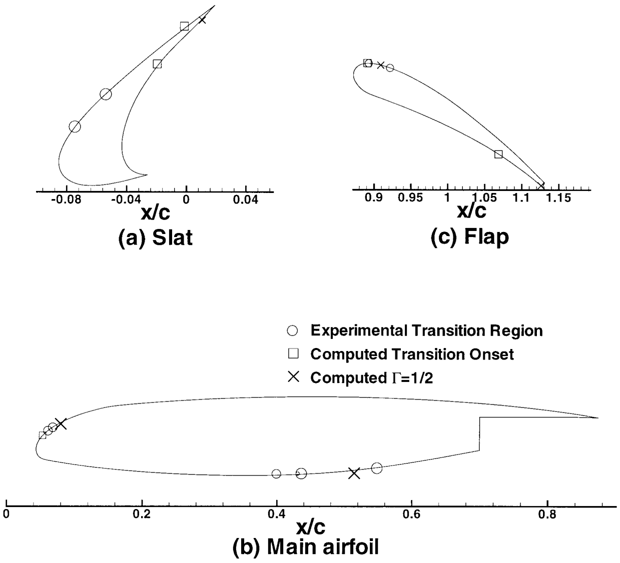

Figure 7: Comparison of transition points for α = 8 degrees

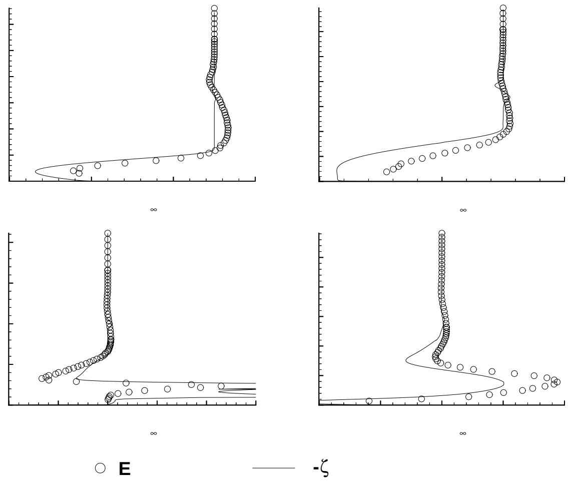

Figure 9: Slat cove vortices for α = 8 degrees

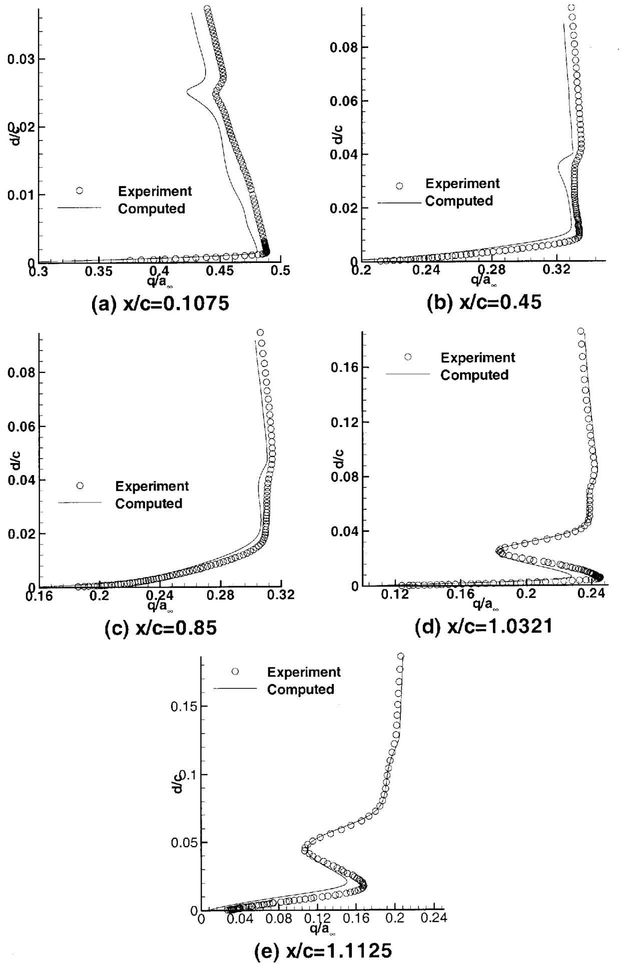

Figure 8: Velocity profiles for α = 8 degrees