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Investigation of the Effect of Turbulence Models for CFD Simulations of a Moving Airfoil

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Anahtar Kelimeler

Çırpan Kanat
Türbülans Modeli
Basınç Dağılımı
Sinüzoidal Hareket

Graphical/Tabular Abstract (Grafik Özet)

The aerodynamic behavior of a NACA 0012 airfoil undergoing sinusoidal pitching motion is evaluated using various transition turbulence models. The study focuses on dynamic flow characteristics, boundary layer dynamics, and flow separation processes. / Sinüzoidal çırpma hareketi yapan bir NACA 0012 kanat profilinin aerodinamik davranışı çeşitli geçiş türbülans modelleri kullanılarak değerlendirilmiştir. Çalışma dinamik akış özellikleri, sınır tabaka dinamikleri ve akış ayırma süreçlerine odaklanmıştır.

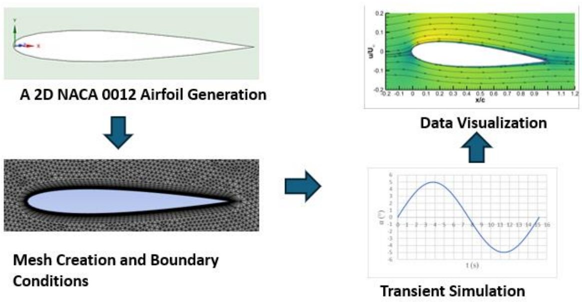

***Figure A**: Simulation workflow for pitching NACA 0012 airfoil /**Şekil A:** Çırpan NACA 0012 kanat profili için simülasyon iş akışı*

Highlights (Önemli noktalar)

- *SST, SST with intermittency, and Transition SST models are compared to capture boundary layer separation and transition for pitching NACA 0012 airfoil. / SST, aralıklı SST ve Geçiş SST modelleri, çırpma hareketi yapan NACA 0012 kanat profili için sınır tabaka ayrılmasını ve geçişini yakalamak amacıyla karşılaştırılmıştır.*
- *Significant hysteresis effects were observed in the pressure coefficient distributions during the pitch-up and pitch-down phases. / Yukarı ve aşağı çırpma aşamalarında basınç katsayısı dağılımlarında önemli histerezis etkileri gözlemlenmiştir.*
- *The results suggest that Transition SST models offer the most accurate predictions of unsteady flow behavior. / Sonuçlar, Geçiş SST modellerinin dinamik akış davranışının en doğru tahminlerini sunduğunu önermektedir.*

Aim (Amaç): *To investigate the aerodynamic response of a NACA 0012 airfoil undergoing sinusoidal pitching motion using different turbulence models. / Farklı türbülans modelleri kullanarak sinüzoidal pitching hareketi yapan bir NACA 0012 kanadının aerodinamik tepkisini araştırmak.*

Originality (Özgünlük): *This study provides new insights into the dynamic flow behavior of airfoils under pitching motion, comparing the effectiveness of different turbulence models in capturing boundary layer dynamics. / Bu çalışma, çırpma hareketi altında kanatların dinamik akış davranışına yeni bakış açıları sunmakta ve sınır katmanı dinamiklerini yakalamada farklı türbülans modellerinin etkinliğini karşılaştırmaktadır.*

Results (Bulgular): *The results demonstrate that advanced turbulence models, such as SST with intermittency and Transition SST, provide more accurate representations of boundary layer separation and transition in dynamic flows compared to the standard SST model. / Sonuçlar, SST ile kesiklilik ve Geçiş SST gibi gelişmiş türbülans modellerinin, standart SST modeline kıyasla dinamik akışlarda sınır katmanı ayrılma ve geçişini daha doğru bir şekilde temsil ettiğini göstermektedir.*

Conclusion (Sonuç): *The study finds that modeling dynamic flows, like boundary layer separation and vortex interactions, requires advanced transition models for accuracy in unsteady conditions. / Çalışma, dinamik akışların doğru modellenmesinin ileri geçiş modellerini gerektirdiğini göstermektedir.*

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Abstract

This study presents a numerical investigation into the aerodynamic behavior of a pitching NACA 0012 airfoil under dynamic conditions. The analysis was carried out using a sliding mesh method in Fluent, incorporating sinusoidal pitching motion with various turbulence models, including SST, SST with intermittency, and Transition SST. The effects of different turbulence models on the aerodynamic performance of the airfoil at various angles of attack (AoA) were studied, focusing on the pressure coefficient (C_p), flow structure, and laminar separation bubble (LSB) formation. Additionally, the results for pitch-up and pitch-down motions were compared to evaluate the hysteresis effects and dynamic flow behaviors. The study found that the SST model exhibited inviscid flow characteristics, while the SST with intermittency and Transition SST models captured the boundary layer behavior more effectively, including the separation and reattachment processes. Significant differences were observed in the C_p distribution and turbulence characteristics, with pitch-down motion resulting in higher C_p values and more complex flow phenomena. The results contribute to the understanding of aerodynamic behavior during dynamic motions, offering insights into the role of turbulence models on airfoil performance.

Hareketli Bir Kanat Profilinin CFD Simülasyonları İçin Türbülans Modellerinin Etkisinin Araştırılması

Makale Bilgisi

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Öz

Bu çalışma, dinamik koşullar altında çırpan bir NACA 0012 kanat profilinin aerodinamik davranışına ilişkin sayısal bir araştırma sunmaktadır. Analiz, SST, aralıklı SST ve Geçiş SST dahil olmak üzere çeşitli türbülans modelleriyle sinüzoidal çırpma hareketini birleştiren Fluent'te kayan bir ağ yöntemi kullanılarak gerçekleştirilmiştir. Farklı türbülans modellerinin, çeşitli hücum açılarında kanat profilinin aerodinamik performansı üzerindeki etkileri, basınç katsayısı (K_b), akış yapısı ve laminer ayrılma kabarcığı (LAK) oluşumuna odaklanılarak incelenmiştir. Ek olarak, yukarı ve aşağı çırpma hareketlerinin sonuçları, histerezis etkilerini ve dinamik akış davranışlarını değerlendirmek için karşılaştırılmıştır. Çalışma, SST modelinin görünmez akış karakteristikleri sergilediğini, aralıklı SST ve Geçiş SST modellerinin ise ayrılma ve yeniden bağlanma süreçleri dahil olmak üzere sınır tabakası davranışını daha etkili bir şekilde yakaladığını bulmuştur. K_b dağılımında ve türbülans özelliklerinde önemli farklılıklar gözlemlendi. Aşağı çırpma hareketi daha yüksek K_b değerleri ve daha karmaşık akış fenomenleriyle sonuçlandı. Sonuçlar dinamik hareketler sırasında aerodinamik davranışın anlaşılmasına katkıda bulunarak, kanat profili performansında türbülans modellerinin rolüne dair açılımlar sunar.

1. INTRODUCTION (GİRİŞ)

The demand for efficient aerodynamic designs is ever-increasing in fields such as renewable energy and aerospace engineering. Wind turbines, as a significant source of renewable energy, and modern aircraft, crucial for reducing fuel consumption and environmental impact, rely heavily on advanced aerodynamic performance. Achieving such a performance requires a deep understanding of complex aerodynamic phenomena, particularly the behaviors of airflow in unsteady, dynamic conditions [1-3]. Accurately predicting flow phenomena is essential for designing systems that are both efficient and sustainable.

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The process of laminar-to-turbulent transition is a fundamental aspect of aerodynamic analysis, influencing the performance of airfoils in various applications [4,5]. In static conditions, transition models can effectively capture the onset of turbulence and the separation of flow over the surface of an airfoil. However, under dynamic conditions, particularly when the airfoil undergoes a pitching motion, the complexity of the flow increases substantially [6]. The interaction between the changing angle of attack and the flow characteristics creates a much more intricate scenario, where the LSBs behave differently compared to static conditions. These bubbles, which are typically formed in regions of adverse pressure gradients, may grow, move, or collapse as the airfoil pitches, leading to highly dynamic and often unpredictable aerodynamic effects [7]. Kim and Chang [8] investigated the aerodynamic behavior of a sinusoidally pitching NACA 0012 airfoil at low Reynolds numbers between 2.0×10^4 and 5.0×10^4. Smoke-wire flow visualization revealed the formation of trailing-edge vortices and complex wake structures, with hysteresis loops in the lift and pressure drag coefficients showing significant variation with Reynolds number. The results indicated that increasing Reynolds number led to earlier occurrences of boundary-layer events, such as laminar separation and transition, affecting the overall aerodynamic performance. The experimental study examined boundary layer transition on a rectangular wing experiencing unsteady pitching motions, with tests conducted at chordwise Mach numbers ranging from 0.2 to 0.6 and sweep angles of 0°, 15°, and 30° using surface hot-film sensors under different pitch rates and compressibility effects [9]. During sinusoidal pitching motions, the transition point shifts forward with increasing pitch rate and moves aft as the pitch rate decreases. At higher reduced frequencies, a pronounced hysteresis of up to 3.6° occurs between the transition and relaminarization angles, with this effect being more prominent between x/c = 0.15-0.30 than near the leading edge.

As the airfoil pitches, the pressure distribution over the surface changes, which causes the boundary layer to react accordingly. The dynamic nature of pitching introduces additional factors such as vortex shedding, fluctuating separation points, and rapid changes in the reattachment of the flow [10]. These factors interact with the transition process, altering the timing and location of transition onset and making it much more difficult to model. The transition process itself may become more erratic, with the boundary layer experiencing periods of stability followed by sudden breakdowns due to the fluctuating pressure gradients. Hain et al. [11] examined the LSB on an SD7003 airfoil at Re = 66,000, focusing on dominant transition frequencies and bubble flapping using high-resolution time-resolved particle image velocimetry (TR-PIV). Unlike conventional PIV, TR-PIV effectively identifies different flow modes and vortex interactions, highlighting their role in turbulence generation. Observations showed vortex amplification in the shear layer above the bubble, driven by Kelvin-Helmholtz instabilities, which exhibited limited spanwise coherence. Eventually, these vortices transitioned to a three-dimensional turbulence breakdown as part of the transition process.

In static conditions, the airflow around an airfoil can be described as relatively stable, with steady-state separation and reattachment occurring in predictable patterns. Transition models, such as the Menter SST model [12], have been extensively validated in these conditions and are able to simulate the flow transition with reasonable accuracy. However, when an airfoil is subjected to pitching oscillation, the flow becomes time-dependent and highly unsteady [13]. Lian et al. [14] presented a combined numerical and experimental investigation of flow behavior around a pitching-plunging SD 7003 airfoil at Re=0.6 x 10^5. Chen et al. [15] examined the behavior of transitional flows over a pitching-up cambered thin airfoil at low Reynolds numbers using an unsteady RANS (Reynolds-averaged Navier–Stokes) approach with the k-ω SST γ-$Re_{\theta t}$ turbulence transition model. For a stationary airfoil, short LSBs form near the leading edge, with bubble length increasing as the angle of incidence rises. In dynamic cases, trailing-edge separation dominates at low incidences, but as the angle increases, LSBs emerge near the leading edge, displaying significant variations in lift perturbations between different Reynolds numbers. At lower Reynolds numbers, vortex dynamics within LSBs cause greater lift disturbances, whereas higher Reynolds numbers yield more stable LSB behavior and reduced lift variations. Rezaei and Taha [16] addressed the non-linear lift response of a pitching airfoil under conditions where linear behavior is typically expected, using a validated $\gamma-Re_{\theta}$ transition model coupled with the k−ω SST turbulence model. The findings demonstrate that laminar-to-turbulent transition induces significant pressure variations near the trailing edge, leading to non-linear effects on lift dynamics and bound circulation. These insights provide a foundation for enhancing potential flow-based methods to better capture the non-linearities in lift dynamics caused by transitional flow behavior.

As a result, transition models that work well under steady conditions often fail to predict the unsteady behavior of the flow under dynamic conditions. The dynamic movement of the airfoil, especially at high frequencies or large amplitudes, introduces additional non-linearities into the flow that are not typically accounted for in steady-state transition models. This discrepancy between static and dynamic behavior highlights a significant gap in the current understanding of aerodynamic performance, particularly for applications like wind turbines or aircraft that experience varying and unsteady loading conditions during operation.

This study tackles the critical challenges associated with modeling dynamic flow phenomena, focusing on the behavior of LSB under unsteady conditions induced by pitching motion of a NACA 0012 airfoil. Unlike many previous studies that primarily investigate static or simplified flow scenarios, this research systematically evaluates the performance of advanced transition models (SST k-ω, SST k-ω with intermittency, and Transition SST) in capturing the intricate dynamics of LSB formation during oscillatory motion. By comparing these models in a dynamic framework, this study not only identifies their relative strengths and weaknesses but also sheds light on the limitations of existing transition modeling approaches in replicating real-world unsteady aerodynamic behavior. The novelty of this work lies in its detailed exploration of how dynamic flow conditions affect the interaction between transition mechanisms and aerodynamic performance, particularly the pressure distribution. Additionally, the results provide a comprehensive benchmark for transition models under conditions that closely resemble operational environments in wind energy systems and aerospace applications. This research bridges a significant gap in the literature by offering new insights into dynamic LSB behavior and proposing pathways to enhance the fidelity of computational tools for designing and optimizing systems subjected to unsteady aerodynamic loads.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Geometry and Mesh Structure (Geometri ve Mesh Yapısı)

In this study, the aerodynamic performance of a NACA 0012 airfoil subjected to sinusoidal pitching motion was analyzed using computational fluid dynamics (CFD) simulations. The computational domain was carefully selected to ensure an accurate representation of the flow physics [17-20], particularly in capturing the boundary layer dynamics, LSB formation, and transition behavior in the region of the airfoil. The airfoil used in the study is a NACA 0012 with a chord length of 1 meter, which provides a manageable environment for numerical simulations.

The computational domain was set up with the airfoil placed in a flow field. The inlet boundary was positioned at a distance of 10 times the chord length (10c) upstream of the airfoil, ensuring that the flow conditions were fully developed before encountering the airfoil [21-23]. Similarly, the outlet boundary was placed at 20 times the chord length (20c) downstream of the airfoil. This choice of domain size helps in minimizing the influence of boundary effects on the solution, ensuring that the flow is adequately captured both before and after the airfoil.

A triangular grid was employed in the numerical domain. To accurately resolve the boundary layer, 50 inflation layers were applied near the surface of the airfoil with growth rate. The number of inflation layers was chosen such that the near-wall mesh cells would maintain y+ values well below 1, ensuring that the flow is properly resolved in the viscous sublayer and avoiding the need for wall functions. The detailed mesh structures were presented in Figure 1.

The overall mesh quality was thoroughly checked to ensure good orthogonality and smooth transitions in the grid spacing. The mesh was refined in the region of interest, particularly around the airfoil, where boundary layer phenomena and flow separation would occur, while the far-field mesh remained coarser to reduce computational expense. The final mesh consisted of approximately 200,000 elements.

2.2. Boundary Conditions, Solver Settings, Turbulence Models And Dynamic Motion (Sınır Koşulları, Çözücü Ayarları, Türbülans Modelleri ve Dinamik Hareket)

For the simulations, the inlet velocity (U_∞) was set to 4.14 m/s, corresponding to a chord-based Reynolds number of 250,000. The flow was assumed to be incompressible, with constant density and viscosity, and the turbulent viscosity was modeled using various transition models to assess their impact on the flow under transient conditions. The stationary and rotating parts of the domain related to non-conformal interface boundary condition and no-slip wall were defined for airfoil surface (Figure 2).

The study focused on capturing the dynamic behavior of the airfoil as it underwent sinusoidal

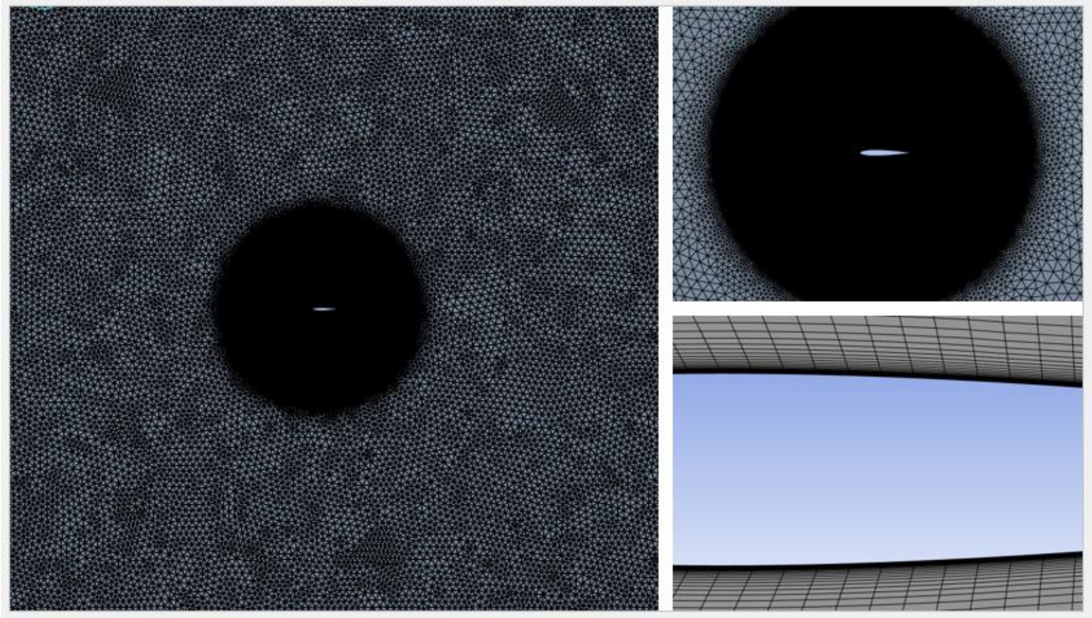


Figure 1. The mesh structure in the stationary region, rotating region and near to airfoil surface (Sabit, dönen ve kanat profili yüzeyine yakın bölgedeki ağ yapısı)

pitching motion. The sinusoidal motion was defined in terms of the angle of attack, with a mean angle of attack (α_0=0°), an amplitude of (α_1=5°) and a reduced frequency ($k=\omega c/2U_\infty$) of 0.05. The equation describing the motion is given below;

$$\alpha(t) = \alpha_0 + \alpha_1 \sin(\omega t) \quad (1)$$

where α is pitching angle, α_0 is mean angle of attack, α_1 the amplitude of the oscillation, ω is the angular frequency of the oscillation, and t is time. The pitching angle variation of sinusoidal motion with time was illustrated in Figure 3.

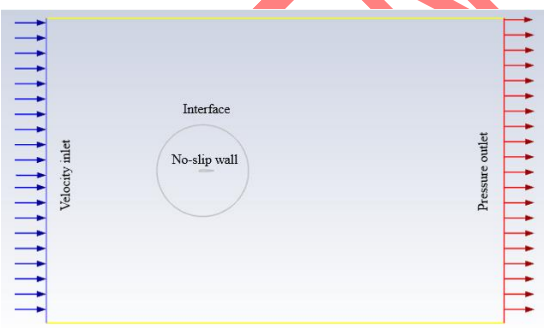


Figure 2. Boundary conditions in the numerical domain (Sayısal alandaki sınır şartları)

For the dynamic simulations involving pitching motion, each of the transition models was applied to capture the complex interaction between the moving airfoil and the unsteady flow field. The dynamic effects of pitching motion are expected to cause time-varying boundary layer separation, reattachment, and transition processes, making it crucial to select the appropriate model for each case. The transition models selected include:

- **SST k-ω model (SST)** is anticipated to provide a more accurate representation of the boundary layer, especially in regions with complex separation, but may require additional modifications to better handle dynamic transitions.
- **SST k-ω with intermittency (SSTI)** will be crucial in capturing the intermittency of transition during dynamic motion, as it accounts for the time-varying nature of flow separation and transition.
- **Transition SST (TSST)** model is expected to provide the most accurate predictions for transition, as it incorporates additional equations that account for both the onset of transition and the intermittency factor. This model is particularly suited for dynamic, time-varying flows like those encountered in pitching airfoils.

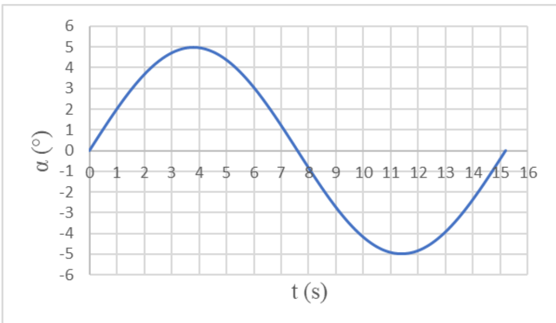


Figure 3. The variation in AoA over time (Zaman içindeki AoA değişimi)

2.3. Numerical Solver And Time Step Size
(Sayısal Çözücü ve Zaman Adımı Boyutu)

The simulations were conducted using the commercial CFD software ANSYS Fluent. The solver used was a coupled, pressure-based solver, which ensures that the pressure-velocity coupling is handled efficiently for unsteady flows. The governing equations for mass, momentum, and turbulence were solved using a second-order upwind scheme, providing a balance between accuracy and stability in the solution.

For the dynamic simulations involving pitching motion, a transient approach was used with a time step size of 0.005. The time step size was selected based on the frequency of the pitching motion, ensuring that the solution could capture the oscillatory behavior of the flow without introducing numerical instability. The total simulation time was long enough to capture several cycles of the pitching motion, allowing for the analysis of the flow characteristics over multiple oscillations.

3. RESULTS (BULGULAR)

In this section, the results obtained from various turbulence models for a pitching NACA 0012 airfoil undergoing sinusoidal motion are presented. The analysis focuses on pressure coefficient (C_p) distributions, non-dimensionalized velocity (u/U_∞) contours, and turbulence kinetic energy (TKE) contours at specific angles during the motion. These results provide insights into the aerodynamic performance, boundary layer behavior, and flow separation characteristics under dynamic conditions, allowing for a detailed evaluation of capability of each turbulence model in capturing the complex unsteady flow phenomena associated with sinusoidal pitching.

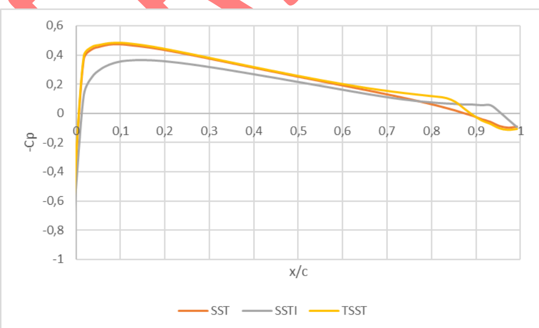


Figure 4. The pressure coefficient for AoA=1° and pitch-up position (AoA=1° ve yukarı çırpma pozisyonu için basınç katsayısı)

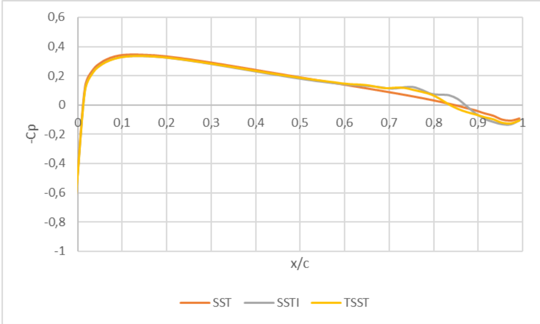


Figure 5. The pressure coefficient for AoA=-1° and pitch-down position (AoA=-1° ve aşağı çırpma pozisyonu için basınç katsayısı)

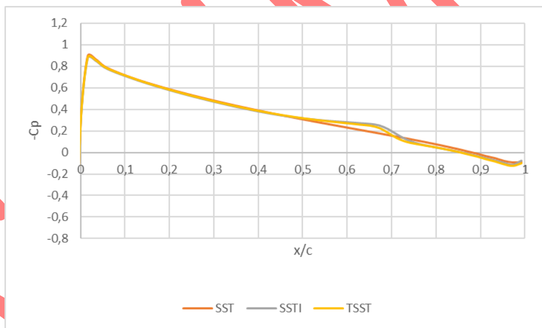


Figure 6. The pressure coefficient for AoA=3° and pitching-up position (AoA=3° ve yukarı çırpma pozisyonu için basınç katsayısı)

The pressure coefficient distributions for angles of 1°, 3°, and -1° were analyzed (Figure 4, Figure 5, Figure 6). At all three angles, the SST model exhibited C_p curves resembling those of inviscid flow, indicating limited resolution of boundary layer dynamics. In contrast, the SST with intermittency model and the Transition SST model provided more detailed solutions for boundary layer behavior and successfully captured flow separations. The case at 3° was further investigated using velocity contours normalized by the freestream velocity (u/U_∞), which supported the observations from the C_p curves. In the SST solution, the flow remained attached to the surface throughout the chord. However, the analysis with the SST with intermittency model revealed multiple discrete laminar separation bubbles along the chord. Meanwhile, the Transition SST model results showed a longer laminar separation region near the trailing edge. These findings highlight the varying capabilities of the models in capturing separation phenomena and boundary layer transitions as seen Figure 7a and 7b. It was observed that the transition occurs normally in the SST model results, there are different dynamics in the transition with bubble effect in the other two models when TKE contours were considered. (Figure 8).

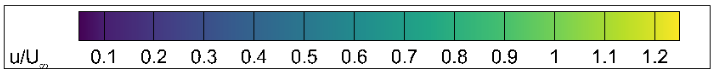
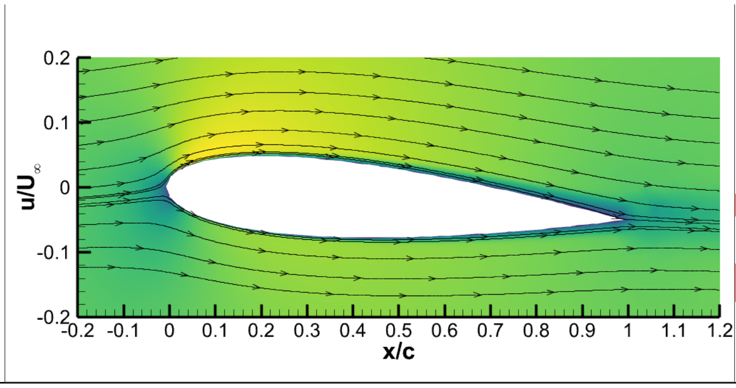
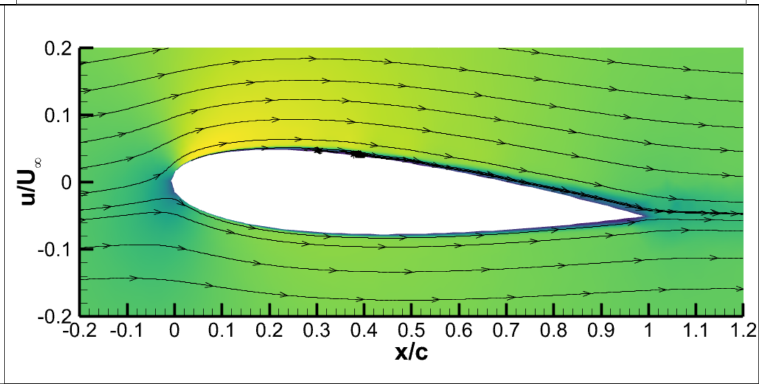
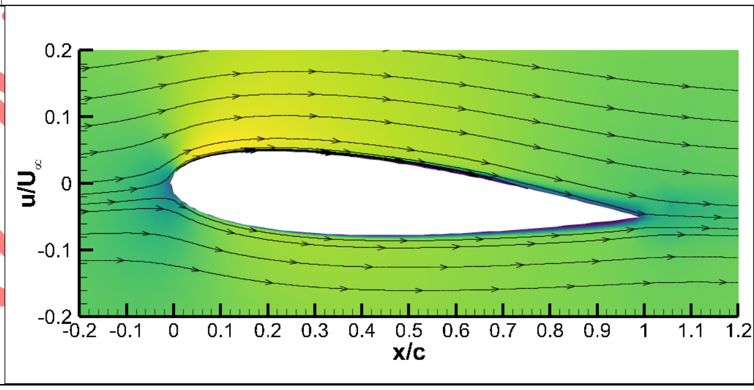
Model	u/U∞
	
SST k-ω	
SST k-ω with intermittency	
Transition SST	

Figure 7a. The dimensioned velocity contour for AoA=3° and pitch-up position (AoA=3° ve yukarı çırpma pozisyonu için boyutlandırılmış hız konturu)

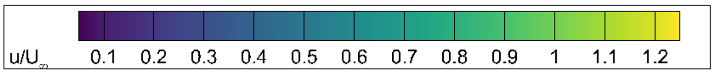
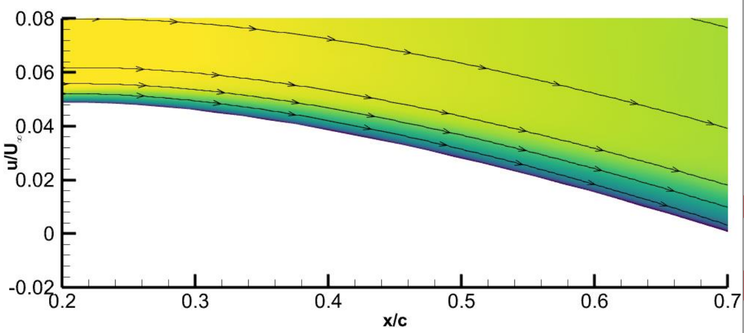
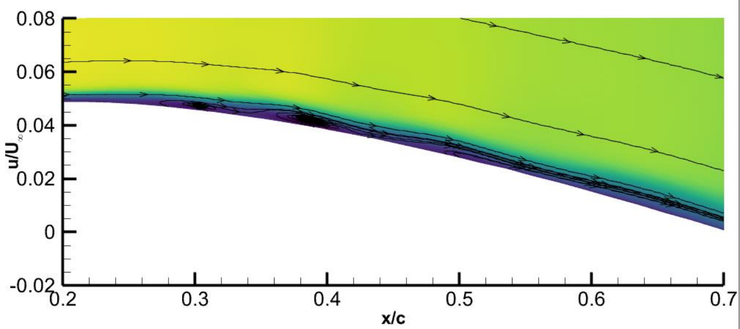
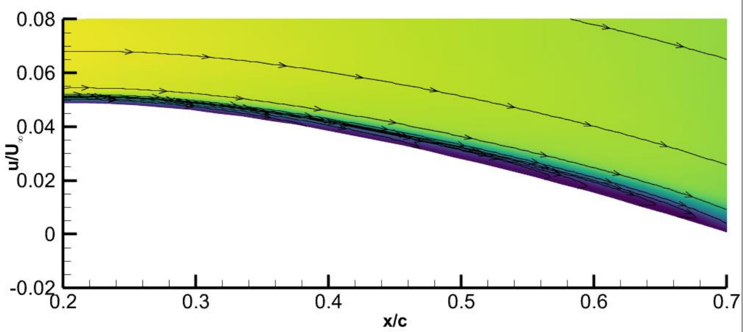
Model	**u/U∞ (focused)**
	
SST k-ω	
SST k-ω with intermittency	
Transition SST	

Figure 7b. The dimensioned velocity contour for AoA=3° and pitch-up position (focuced) (AoA=3° ve yukarı çırpma pozisyonu için boyutlandırılmış hız konturu (odaklanmış))

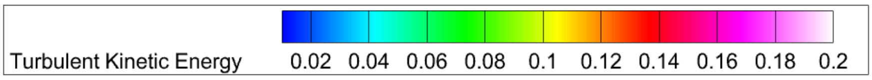
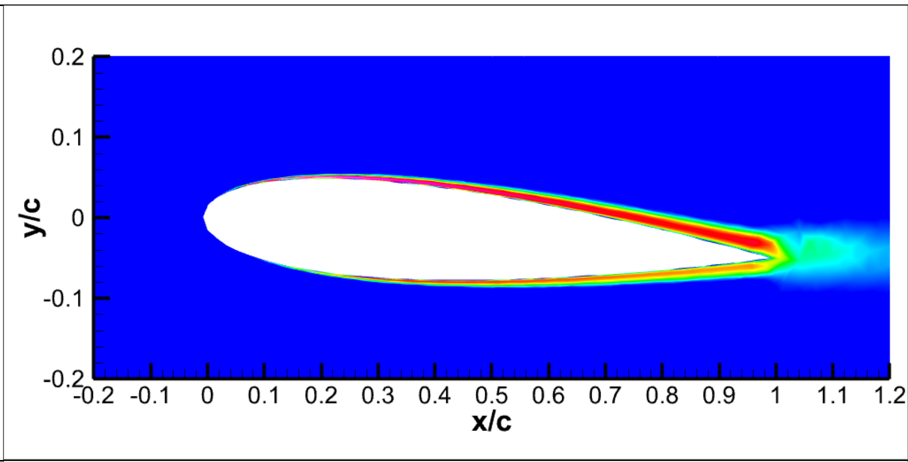
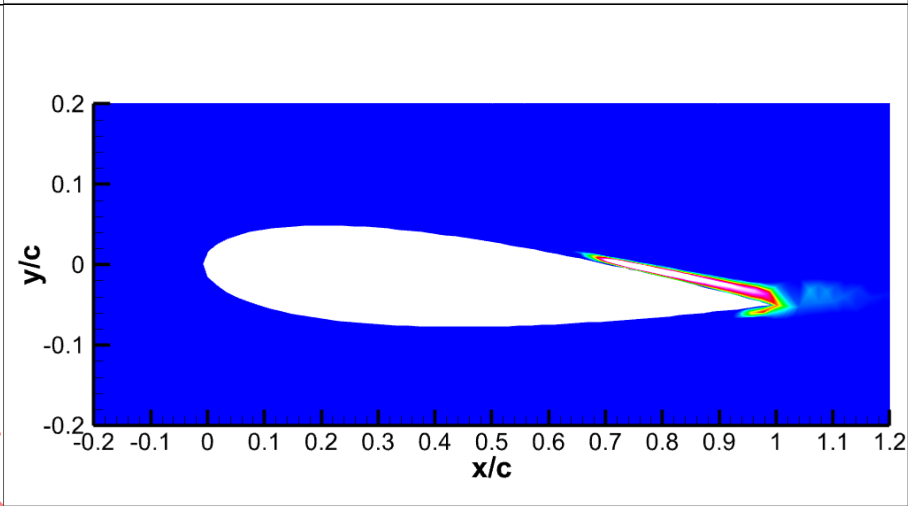
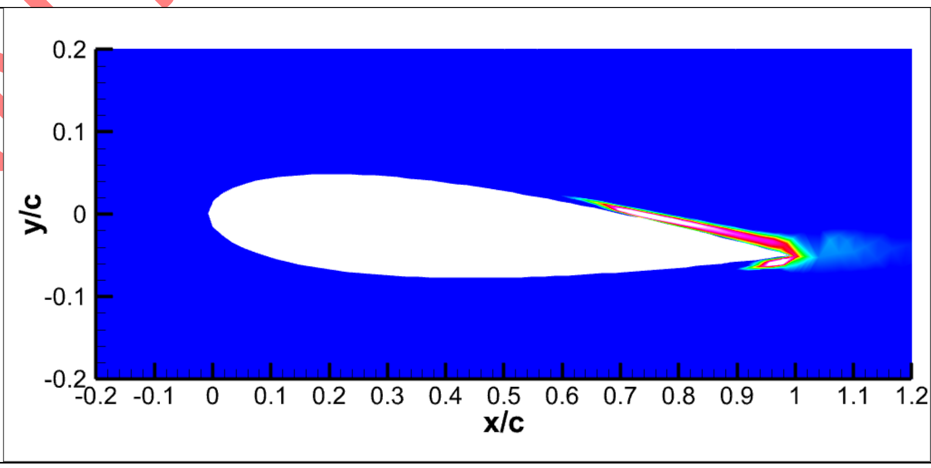
Model	Turbulent kinetic energy
	
SST k-ω	
SST k-ω with intermittency	
Transition SST	

Figure 8. The turbulent kinetic energy contour for AoA=3° and pitch-up position (AoA=3° ve yukarı çırpma pozisyonu için türbülans kinetik enerji konturu)

Considering analysis results, C_p curves for the same angle of attack were examined during both the pitch-up and pitch-down phases of the sinusoidal motion. This comparison highlights the hysteresis effects and differences in aerodynamic behavior between the two phases, providing an important understanding of how the dynamic motion influences the pressure distribution and overall flow characteristics around the airfoil.

For angles of attack of 1° and 3° results obtained using the SST model reveal that the C_p values are consistently higher during the pitch-down phase compared to the pitch-up phase as shown in Figure 9. This indicates a notable asymmetry in the aerodynamic response between the two phases. Additionally, in both angles, a sharper drop in C_p is observed during the pitch-down motion immediately after reaching the maximum value, suggesting a rapid change in pressure distribution. In contrast, the pitch-up phase exhibits a much smoother decline in C_p, indicating a more gradual adjustment of the flow to the changing angle of attack (Figure 9).

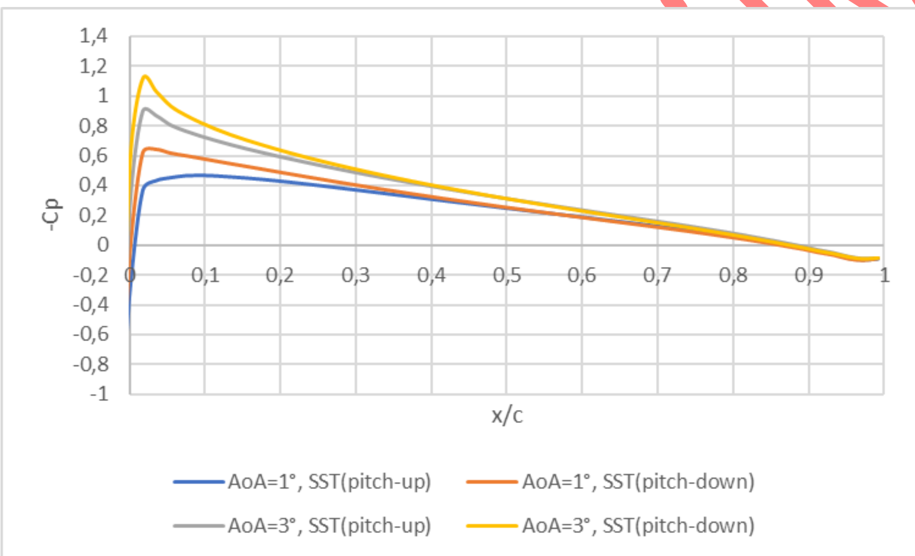


Figure 9. The pressure coefficient for AoA=1° and 3° with SST model under pitch-up and pitch-down positions (SST modeli ile aşağı ve yukarı çırpma pozisyonlarında AoA=1° ve 3° için basınç katsayısı)

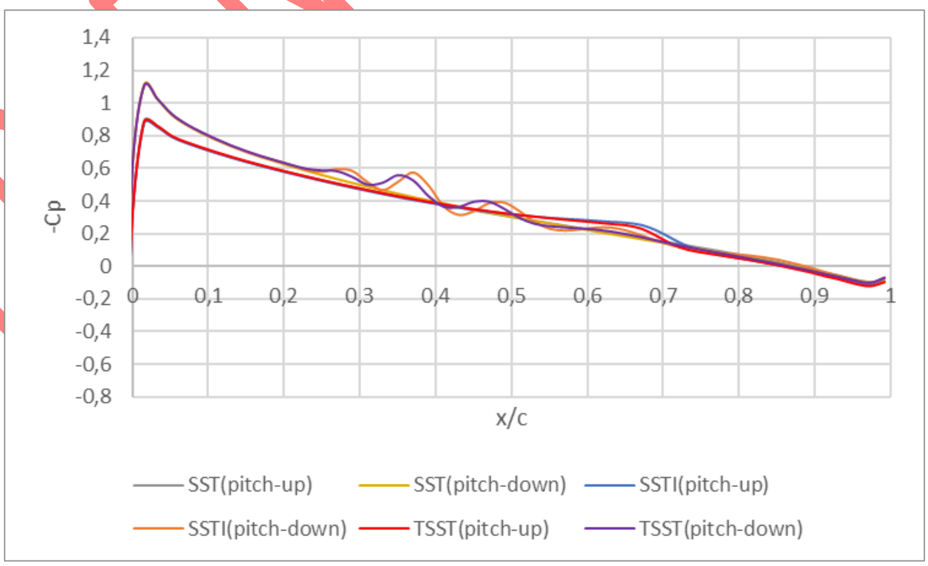


Figure 10. The pressure coefficient for AoA=3° with SST, SSTI, TSST models under pitch-up and pitch-down positions positions (SST, SSTI, TSST modelleri için aşağı ve yukarı çırpma pozisyonlarında AoA=3° için basınç katsayısı)

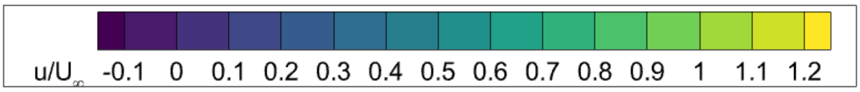
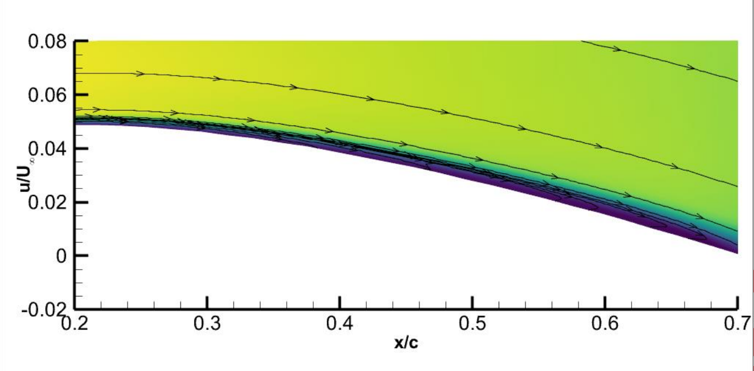
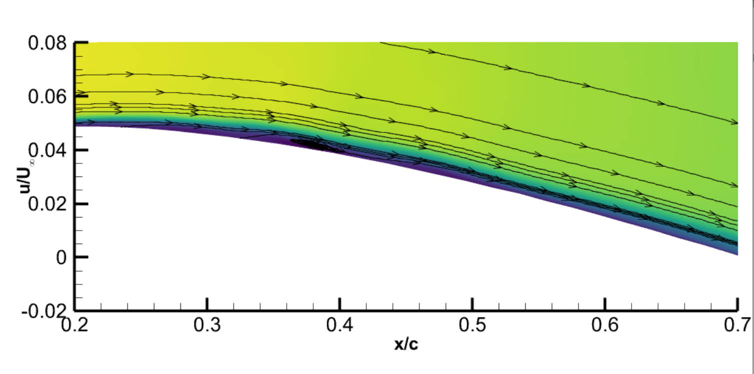
<table>
<tr><th>Position</th><th>u/U∞ (focused)
</th></tr>
<tr><td>Pitch-up</td><td></td></tr>
<tr><td>Pitch-down</td><td></td></tr>
</table>

Figure 11. The dimensioned velocity contour for AoA=3° with TSST model under pitch-up and pitch-down positions (TSST modeli ile AoA=3° için aşağı ve yukarı çırpma pozisyonlarında boyutlandırılmış hız konturu)

The C_p curves also display noticeable hysteresis along the chord length, which appears similar for both 1° and 3° illustrated by Figure 10. This hysteresis reflects the lag in the aerodynamic response due to the dynamic nature of the motion, where the flow field and pressure distribution are influenced by the airfoil's recent motion history. The results emphasize the sensitivity of pressure distribution to the phase of the pitching motion, particularly in dynamic conditions, and highlight the effectiveness of the SST model in capturing these intricate flow behaviors.

Figure 10 presents the C_p distributions for three turbulence models at an angle of attack of 3° during both pitch-up and pitch-down phases. During the pitch-up phase, all three models exhibit relatively stable C_p curves, reflecting a smooth pressure distribution along the chord. In contrast, during the pitch-down phase, fluctuations in the C_p curves are observed in the results of the SST with Intermittency and Transition SST models. Figure 11 illustrates the streamlines obtained from the Transition SST model, highlighting the complex flow structures observed during the pitching-down phase. The results reveal a more intricate flow pattern compared to the pitching-up phase.

These fluctuations are likely attributed to the interaction of the airfoil with vortices shed during its previous movements. As the airfoil moves downward, it encounters these residual vortices, which disrupt the flow and manifest as irregularities in the C_p distribution. On the other hand, the SST model shows a smoother trend during the pitch-down phase. This smoother response suggests a limitation in the SST model's ability to capture the physical interactions between the airfoil and the complex vortex structures in the wake. This result highlights the necessity of advanced transition models to accurately resolve such dynamic flow behaviors.

4. CONCLUSIONS (SONUÇLAR)

In this study, the aerodynamic performance of a NACA 0012 airfoil undergoing sinusoidal pitching motion was thoroughly analyzed using numerical simulations. The results demonstrated that the turbulence models played a crucial role in capturing the dynamic flow characteristics, especially during the transition from laminar to turbulent flow. The SST model provided an inviscid solution, while the SST with intermittency and Transition SST models were able to better resolve the boundary layer separation and reattachment, offering more accurate representations of the flow dynamics. The C_p distributions for both pitch-up and pitch-down motions revealed significant hysteresis effects, with pitch-down motion resulting in higher peak C_p values and sharper decreases in C_p along the chord. Streamline and velocity contour analysis further revealed the complexity of the flow in pitch-down conditions, with interactions between vortex shedding and the boundary layer contributing to more pronounced flow instabilities. These findings underscore the importance of considering dynamic effects in aerodynamic simulations, especially for applications where unsteady motion significantly influences performance. Future work will focus on refining the turbulence models to enhance the accuracy of dynamic flow predictions and extend the study to a wider range of airfoil shapes and motion profiles.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Sinem KESKİN: She conducted the numerical analysis, post-processed the results and performed the writing process.

Sayısal analizleri yapmış, sonuçları son işleme tabi tutmuş ve yazım sürecini gerçekleştirmiştir.

Mustafa Serdar GENÇ: He supervised the study and edited the draft.

Çalışmayı yönetmiş ve makaleyi düzenlemiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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