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Araştırma Makalesi / Research Article

Impacts of Tapered Wingtip on Lateral-Directional Stability Coefficients of a Morphing Fixed-wing UAV

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Abstract

Recent developments in unmanned aerial vehicle (UAV) technologies have shown the possibility of morphing applications to provide improvement in various performance metrics in the desired manner. In rotary-wing UAVs, applications mainly focused on propeller blades and rotor arms, while efforts on fixed-wing UAVs mainly concentrated on the main wing and tail geometries. Although every morphing design has its own advantages and disadvantages, all of the applications have similar common purposes to have improved aerodynamics, flight performance, control responses, or a combination of such objectives. In that context, new morphing design attempts require a precise investigation of their pros and cons. Thus, in this study, a new morphing scenario of tapering morphing wingtip is applied to ZANKA-I fixed-wing UAV and investigated in terms of lateral-directional stability considerations. The lateral dynamic model of the aircraft is constituted and necessary aerodynamic, geometric, and inertial assessments are numerically and analytically performed. The lateral-directional stability coefficients are discussed and an improvement in lateral stability is obtained, while directional stability is found to be affected negatively by the morphing application.

Keywords: Morphing, Unmanned aerial vehicle, Lateral stability, Directional stability.

Başkalaşabilen Sabit Kanatlı bir İnsansız Hava Aracında Sivrilen Kanat Ucunun Yanal ve Yön Kararlılık Katsayılarına Etkisi

Öz

Son dönemlerde insansız hava aracı (İHA) teknolojilerindeki gelişim, başkalaşım uygulamalarının çeşitli hava aracı performans parametrelerinde iyileştirme elde edebilmek adına potansiyelini ortaya koymaktadır. Döner kanatlı İHA'larda uygulamalar genellikle pervane pal geometrisi ve rotor kolları üzerine odaklanmışken, sabit kanatlı İHA'larda ise girişimler özellikle kanat ve kuyruk geometrilerinde yoğunlaşmıştır. Her başkalaşım tasarımının kendine özgü avantaj ve dezavantajları olduğu bilinse de tüm uygulamaların aerodinamik, uçuş performansı, kontrol tutumu veya bunların bir kombinasyonu olan benzer ortak amaçlar çevresinde buluştuğu görülmektedir. Bu çerçevede, yeni başkalaşım tasarımı girişimlerinin özenli şekilde avantaj ve dezavantajlarının değerlendirilmesi gerekmektedir. Buradan hareketle, bu çalışmada, yeni bir başkalaşım senaryosu olarak ZANKA-I İHA kanat ucu konikleşme kabiliyetine sahip şekilde yeniden tasarlanmış ve yanal-yön kararlılığı açısından değerlendirilmiştir. Hava aracının yanal dinamik modeli oluşturulmuş ve bu süreçte ihtiyaç duyulan aerodinamik, geometrik ve ataletsel değişkenler analitik ve sayısal yöntemlerle elde edilmiştir. Yanal-yön kararlılığı katsayıları değerlendirildiğinde ise uygulamanın yanal kararlılıkta bir gelişme sağladığı görülmüş, fakat yön kararlılığında olumsuz etkilerin baskın olduğu görülmüştür.

Anahtar Kelimeler: Başkalaşım, İnsansız hava aracı, Yanal kararlılık, Yön kararlılığı.

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1. Introduction

The recent development in materials science encourages scientists for innovative attempts at aircraft design and paved the way for morphing applications which have been frequently discussed lately in the scientific literature. “Morphing” could be defined as the ability of an aircraft component or part to change in shape with the aim of an improvement in various performance parameters that offer significant potential for both fixed-wing or rotary-wing aerial vehicles (Oktay and Kose, 2019). The main purpose of these applications could be an improvement in aerodynamic performance, flight performance, trajectory tracking quality, or various combinations of these (Barbarino et al., 2019).

Morphing applications on fixed-wing aerial vehicles are especially concentrated on the main wing due to its being the main lifting surface maintaining flight. In the literature, there are several studies focused on morphing in terms of planform, out-of-plane, or airfoil geometries of the main wing. For instance, Eguea et al. designed a wingtip mechanism for a fixed-wing aerial vehicle capable of morphing in terms of dihedral and sweep angles of the main wing that provides an enhancement in range, endurance, maneuverability, and total flight performance up to 25% (Eguea et al., 2021). A morphing wingtip is applied on a conventional regional jet aircraft by Afonso et al., which provided lateral stability and range improvement (Afonso et al., 2017). A camber morphing winglet design presented by Dimino et al. (Dimino et al., 2021) provided a decrease in structural loads. Liu et al. proposed a wing design capable of morphing in terms of both airfoil and planform geometries. Their design provided an enhancement of up to 24% in aerodynamic performance for both subsonic and hypersonic flight regimes (Liu et al., 2022). Parancheerivilakkathil et al. proposed a multiple morphing application that includes an active wing span increment and passively wing pitch angle alteration and provided improvement in aerodynamic performance and bending moment (Parancheerivilakkathil et al., 2022). RQ-7a Shadow unmanned aerial vehicle is redesigned with a camber morphing airfoil by Jo and Majid and they obtained aerodynamic performance improvement of up to 60% (Jo and Majid, 2023). Such studies in the literature emphasize the importance of investigating new morphing scenarios and designs in terms of stability, control, or aerodynamic considerations and discovering their potential.

The traditional aircraft design procedure is composed of conceptual design, preliminary design, and advanced design steps respectively, and finalizes with the construction step (Raymer, 2012). The morphing aerial vehicle design procedure only involves the integration of an additional morphing scenario to this conventional methodology. It is inevitable to have aerodynamic, geometrical, and inertial alterations due to the integrated morphing application. Therefore, it is critical to assess the effects of the morphing scenario on aircraft flight dynamics and corresponding stability considerations.

In this study, the effects of a morphing scenario of tapering are investigated in terms of lateral-directional stability considerations on ZANKA-I fixed-wing unmanned aerial vehicle. For that purpose, the aircraft lateral dynamic model is presented in parametric state-space representation, and later on the aerodynamic, geometrical, and inertial effects of the tapering wingtip are numerically and analytically investigated. In last, the effects of the morphing scenario on lateral and directional stability coefficients are evaluated.

2. Materials and Method

2.1. The Morphing Scenario

In this paper, a morphing scenario is applied to a fixed-wing unmanned aerial vehicle produced at Erciyes University, named ZANKA-I. The required parameters and detailed information about the original design could be achieved from (Oktay et al., 2016). The morphing scenario in this study is applied as shown in Figure 1 by separating the main wing of the vehicle into two sections as morphing and rectangular planforms. The taper ratio of the morphing section (λ_2) is able to vary between 0.2 to 1, while rectangular planform has a constant taper ratio (λ_1=1). The chord lengths along the spanwise locations are also given with abbreviations c_1, c_2, and c_3, where c_3 is able to morph and correspondingly change the wingtip taper ratio, λ_2, while others are constant. The morphing application takes place in both the leading and trailing edges of the wing symmetrically so as not to move the aircraft's center of gravity, and the wing area is preserved constantly not to have a loss in lifting surface.

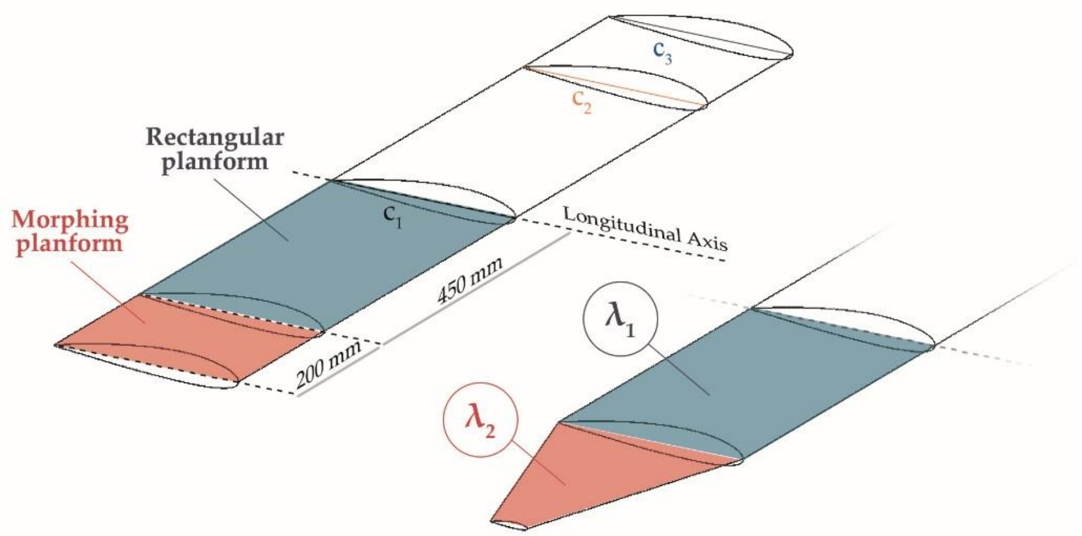

Figure 1. Morphing scenario and separated planforms

2.2. Aircraft Dynamic Modeling

Dynamic model of an aircraft could be defined as mathematical equations deciding the stability and controllability qualities of the vehicle. When a morphing scenario is conducted to the aerial vehicle design, these equations and considerations become more complicated than conventional ones. Correspondingly, constructing an accurate model plays a critical role on obtaining desired performance parameters for different disciplines.

In Equation 1, the aircraft lateral dynamic model is given in parametric state-space representation, and detailed information about equations and variables could be achieved from (Nelson, 1998).

$$\begin{bmatrix}\Delta\dot{v}\\ \Delta\dot{p}\\ \Delta\dot{r}\\ \Delta\dot{\phi}\end{bmatrix}=\begin{bmatrix} Y_v & Y_p & -(u_0-Y_r) & -g\cos(\theta_0)\\ L_w^*+\frac{I_{xz}}{I_x}N_v^* & L_p^*+\frac{I_{xz}}{I_x}N_p^* & L_r^*+\frac{I_{xz}}{I_x}N_r^* & 0\\ N_v^*+\frac{I_{xz}}{I_z}L_v^* & N_p^*+\frac{I_{xz}}{I_z}L_p^* & N_r^*+\frac{I_{xz}}{I_z}L_r^* & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta v\\ \Delta p\\ \Delta r\\ \Delta\phi\end{bmatrix}+\begin{bmatrix} 0 & Y_{\delta_r}\\ L_{\delta_a}^*+\frac{I_{xz}}{I_x}N_{\delta_a}^* & L_{\delta_r}^*+\frac{I_{xz}}{I_x}N_{\delta_r}^*\\ N_{\delta_a}^*+\frac{I_{xz}}{I_z}L_{\delta_a}^* & N_{\delta_r}^*+\frac{I_{xz}}{I_z}L_{\delta_r}^*\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\delta_a\\ \Delta\delta_r\end{bmatrix}$$

(1)

As it is exampled for L_p in Equation 2, in order to estimate lateral dynamic model of the aircraft, there are various variables that should be determined such as x-axis area moment of inertia (I_x), dynamic pressure (Q), wing area (S), wing span (b), lift curve slope ($C_{l\alpha}$), wing taper ratio (λ), airspeed (u_0) and some unitless stability coefficients (i.e. C_{lp}). With the aim of determining these stability coefficients, it is required to obtain related aerodynamical, geometrical and inertial terms as clearly seen in Equation 3.

$$L_p=\frac{QSb^2C_{l_p}}{2I_xu_0} \tag{2}$$

$$C_{l_p}=-\frac{C_{l_\alpha}}{12}\frac{1+3\lambda}{1+\lambda} \tag{3}$$

2.3. Aerodynamic, Geometrical and Inertial Effects of the Morphing Scenario

It is inevitable to have geometric and correspondingly aerodynamic and inertial alterations on morphing aerial vehicle. In order to preserve the lifting surface area constant, the change in taper ratio will lead to alteration in wing span naturally. Wingtip taper ratio could be determined from c_3 and c_2 chord lengths via Equation 4, and wing aspect ratio could be estimated from wing area and wing span via Equation 5. The total taper ratio of the wing (λ) and mean aerodynamic chord length (*MAC*) could be obtained with Equation6 and Equation 7, respectively.

$$\lambda_2 = \frac{c_3}{c_2} \tag{4}$$

$$AR = \frac{b^2}{S} \tag{5}$$

$$\lambda = \frac{0,45\lambda_1 + 0,2 * \lambda_2}{0,65} \tag{6}$$

$$MAC = \left(\left(\frac{c_1 + c_2}{2} \right) * 0.45 + \left(\frac{c_2 + c_3}{2} \right) * 0.2 \right) / 0.65 \tag{7}$$

The aerodynamic and inertial effects of morphing can be obtained by numerical methods. In an aerodynamic manner, XFLR5 is a powerful tool providing admissibly accurate results during the conceptual design of aerial vehicles (Millard et al., 2022). In this paper, the main wing of ZANKA-I is modelled on XFLR5 and investigated using 3D panel method in terms of lift coefficient (C_L), drag coefficient (C_D), lift curve slope ($C_{L\alpha}$), drag curve slope ($C_{D\alpha}$) and Oswald efficiency (e). For that purpose, firstly grid independence analysis is performed and results are given in Figure 2.

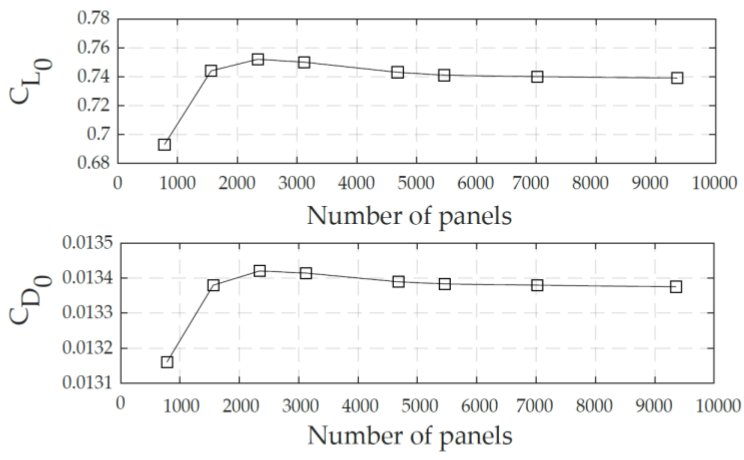

Figure 2. Grid independence results for reference lift and drag coefficients

The grid independence analyses are performed for level flight at 60 km/h airspeed and sea-level conditions, and both lift and drag coefficients are found to be converged at 5000 panels, and become constant for the higher number of panels.

On the other hand, inertial effects of morphing scenarios are investigated numerically, rather than analytical methods to have more accurate results. The wing model is constructed on XFLR5 and the numerical estimations of area moment of inertia terms (I_x, I_z and I_{xz}) various morphing scenarios are performed.

2.4. Lateral and Directional Stability Coefficients

Lateral and directional stability coefficients have critical role on aircraft flight dynamics as mentioned before. These coefficients could be categorized in three group as y-axis force derivatives ($C_{Y\beta}$, C_{Yp}, C_{Yr}, $C_{Y\delta r}$), rolling moment derivatives ($C_{l\beta}$, C_{lp}, C_{lr}, $C_{l\delta a}$, $C_{l\delta r}$) and yawing moment derivatives ($C_{n\beta}$, C_{np}, C_{nr}, $C_{n\delta a}$, $C_{n\delta r}$). The equations for determination of each derivative are given in Table 1 related with angular rates (p, q, r) in radian per second, rudder and aileron deflections (δr, δa) and sideslip angle (β) in radians (Nelson, 1998).

Table 1. Lateral and directional stability coefficients

Y-force derivatives	Yawing moment derivatives	Rolling moment derivatives
$C_{y_\beta} = -\eta \frac{S_v}{S} C_{L_{\alpha_v}} (1+\frac{d\sigma}{d\beta})$	$C_{n_\beta} = C_{n_{\beta_{wf}}} + \eta_v V_v C_{L_{\alpha_v}} (1+\frac{d\sigma}{d\beta})$	$C_{l_\beta} = (\frac{C_{l_\beta}}{\Gamma})\Gamma + \Delta C_{l_\beta}$
$C_{y_p} = C_L \frac{AR+\cos\Lambda}{AR+4\cos\Lambda} \tan\Lambda$	$C_{n_p} = -\frac{C_L}{8}$	$C_{l_p} = -\frac{C_{L_\alpha}}{12}\frac{1+3\lambda}{1+\lambda}$
$C_{y_r} = -2(\frac{l_v}{b})(C_{y_\beta})_{tail}$	$C_{n_r} = -2\eta_v V_v (\frac{l_v}{b}) C_{L_{\alpha_v}}$	$C_{l_r} = \frac{C_L}{4} - 2\frac{l_v}{b}\frac{z_v}{b} C_{y_{\beta_{tail}}}$
$C_{y_{\delta_r}} = \frac{S_v}{S} \tau C_{L_{\alpha_v}}$	$C_{n_{\delta_\alpha}} = 2KC_{L_0} C_{l_{\delta_\alpha}}$	$C_{l_{\delta_\alpha}} = \frac{2C_{L_\alpha}\tau}{Sb}\int_{y1}^{y2} cy\,dy$
	$C_{n_{\delta_r}} = -V_v \eta_v \tau C_{L_{\alpha_v}}$	$C_{l_{\delta_r}} = \frac{S_v}{S}(\frac{z_v}{b})\tau C_{L_{\alpha_w}}$

It is clear from the equations of y-force derivatives that C_{y_β} highly depends on the term dσ/dβ which is the sidewash angle due to alteration in sideslip angle. On the other hand, C_{y_p} alters critically with wing aspect ratio and sweep angle, while C_{y_r} and $C_{y_{\delta_r}}$ depends on wing span and wing area alterations, respectively.

Yawing moment derivatives point of view, static directional stability term C_{n_β} strongly relates with dσ/dβ and cross-coupling term C_{n_p} has direct relationship with lift coefficient. Yaw damping term C_{n_r} has inverse proportion with wing span, while $C_{y_{\delta_a}}$ is directly proportional with reference lift coefficient.

Rolling moment derivative C_{l_β} refers to dihedral effect and dominantly relates with dihedral angle ($\mathcal{Z}$) which is not changes in our morphing case. Another term roll damping C_{l_p} has a relationship with lift curve slope and wing taper ratio, which is critical for our morphing design. The coefficient C_{l_r} is the cross-coupling term both related with lift coefficient and wing span, while $C_{l_{\delta_a}}$is the lateral control power related with lift curve slope.

3. Results and Discussion

Within the scope of the morphing scenario, the alteration in wingtip taper ratio from its original value of 1 to 0.2 resulted geometrically in an increase in wing span (b), sweep angle (Λ), and aspect ratio (AR), while a decrease in mean aerodynamic chord length as their values are given for various wingtip taper ratios in Table 2.

Table 2. Geometric parameters of main wing with wingtip taper ratio

Variable	**Value**		
λ_2	1	0.6	0.2
$b\,(m)$	1.300	1.400	1.567
$MAC\,(m)$	0.25	0.236	0.226
AR	5.200	6.031	7.552
$\Lambda\,(rad)$	0	0.03569	0.06374

The alteration of the wingtip taper ratio aerodynamically led to an increase in reference lift coefficient, lift-curve slope, and Oswald efficiency factor for the entire taper ratio interval. The reference drag coefficient is diminished from original to mid wingtip taper ratio values and tended to increase for lower values of the interval. The reason behind this fluctuating behavior could be estimated as relating to the wing aspect ratio, where excessive values are known to affect the induced drag coefficient unfavorably (Chen and Katz, 2004). Furthermore, the aerodynamic performance (C_L/C_D) is also altered similar to the drag coefficient and has a peak value along the interval, which should be discussed separately as an optimization problem that is out of the scope of this study. On the other hand, the variation in inertial parameters is given in Table 4, where variables are totally decreased between whole wingtip taper ratio intervals.

Table 3. Aerodynamic parameters of main wing with wingtip taper ratio

Variable	Value		
λ_2	1	0.6	0.2
C_{L_0}	0.64949	0.6921	0.7429
C_{D_0}	0.013229	0.0120	0.0133
C_{L_α} (*1/rad*)	4.8242	5.1923	5.6522
C_{D_α} (*1/rad*)	0.1	0.0992	0.0953
e	1.013	1.0301	1.0322

Table 4. Inertial parameters of main wing with wingtip taper ratio

Variable	Value		
λ_2	1	0.6	0.2
I_{xx} (kgm^2)	0.09878	0.09309	0.08738
I_{yy} (kgm^2)	0.14219	0.13120	0.12932
I_{zz} (kgm^2)	0.22971	0.21637	0.20326
I_{xz} (kgm^2)	0.01276	0.0105	0.0089

The lateral-directional stability coefficients are analytically estimated using the aerodynamical, geometrical, and inertial variables determined above, and the results are given in Table 5. Additionally, the extended data is given in Figure 3 to enable sensitive discussion on the tendencies of the variables along the wingtip taper ratio interval. The Y-force derivatives of lateral-directional stability coefficients are C_{y_β}, C_{y_p}, C_{y_r}, $C_{y_{\delta_r}}$, the rolling moment derivatives are C_{l_β}, C_{l_p}, C_{l_r}, $C_{l_{\delta_a}}$ and the yawing moment derivatives of lateral-directional stability coefficients are C_{n_β}, C_{n_p}, C_{n_r}, $C_{n_{\delta_a}}$ and $C_{n_{\delta_r}}$ as given in Table 1.

Y-force derivatives point of view, the increment in wing aspect ratio led to a decrease in the term $d\sigma/d\beta$, which is also dominant term for determination of the coefficient C_{y_β} that is diminished. Similarly, decrement in aspect ratio combined with increased sweep angle found to be resulted in increment in the term C_{y_p}. The higher wing span due to lower wingtip taper ratio found to be resulted in diminishment in the term C_{y_r}. The last force derivative $C_{y_{\delta_r}}$ is found to be remain constant due to the preserved area of the wing.

The yawing moment derivatives point of view, the static directional stability term C_{n_β} is found to be increased as desired with the help of the term $d\sigma/d\beta$ that refers to sidewash angle due to sideslip angle. The cross-coupling term C_{n_p} is found to be decreased in unfavorable manner which depends directly on lift coefficient that is increased with lower wingtip taper ratios. The yaw damping term

C_{n_r} is also increased unfavorably due to increased wing span at lower wingtip taper ratios. In addition, adverse yaw term $C_{n_{\delta_a}}$ also unfavorably decreased, while rudder power term $C_{n_{\delta_r}}$decreased as desired. In summary, the directional stability of the morphing scenario is found to be negatively affected from the morphing tapering wingtip application.

Rolling moment derivatives point of view, the dihedral effect term C_{l_β} strongly depend on dihedral angle of the wing, which is constant in our case and dependently the coefficient remains constant. The roll damping term C_{l_p} is found to be decreased due to increment in lift-curve slope and decrement in wing taper ratio, as desired. Similarly, cross-coupling term C_{l_r} is found to be increased by means of increment in lift coefficient despite the increased wing span, as desired. The term $C_{l_{\delta_a}}$is the lateral control power, which is found to be decreased in undesirable manner due to the wing span increment despite of the increased lift curve slope. In summary, the lateral stability of the morphing scenario is found to be improved in average.

Table 5. Lateral and directional stability coefficient results at various wingtip taper ratios

λ_2	1	0.6	0.2
C_{y_β}	-0.003001	-0.003021	-0.003058
C_{n_β}	-0.002154	-0.002145	-0.002127
C_{y_p}	0.000000	0.017326	0.035120
C_{n_p}	-0.081186	-0.086518	-0.092864
C_{l_p}	-0.804033	-0.837022	-0.875931
C_{y_r}	0.002546	0.002364	0.002113
C_{n_r}	-0.001226	-0.001139	-0.001018
C_{l_r}	0.162671	0.173293	0.185934
$C_{n_{\partial a}}$	-0.252228	-0.253597	-0.253564
$C_{l_{\partial a}}$	0.970870	0.915987	0.853279
$C_{y_{\partial r}}$	0.001057	0.001057	0.001057
$C_{n_{\partial r}}$	-0.000509	-0.000509	-0.000509
$C_{l_{\partial r}}$	0.013304	0.013296	0.012934

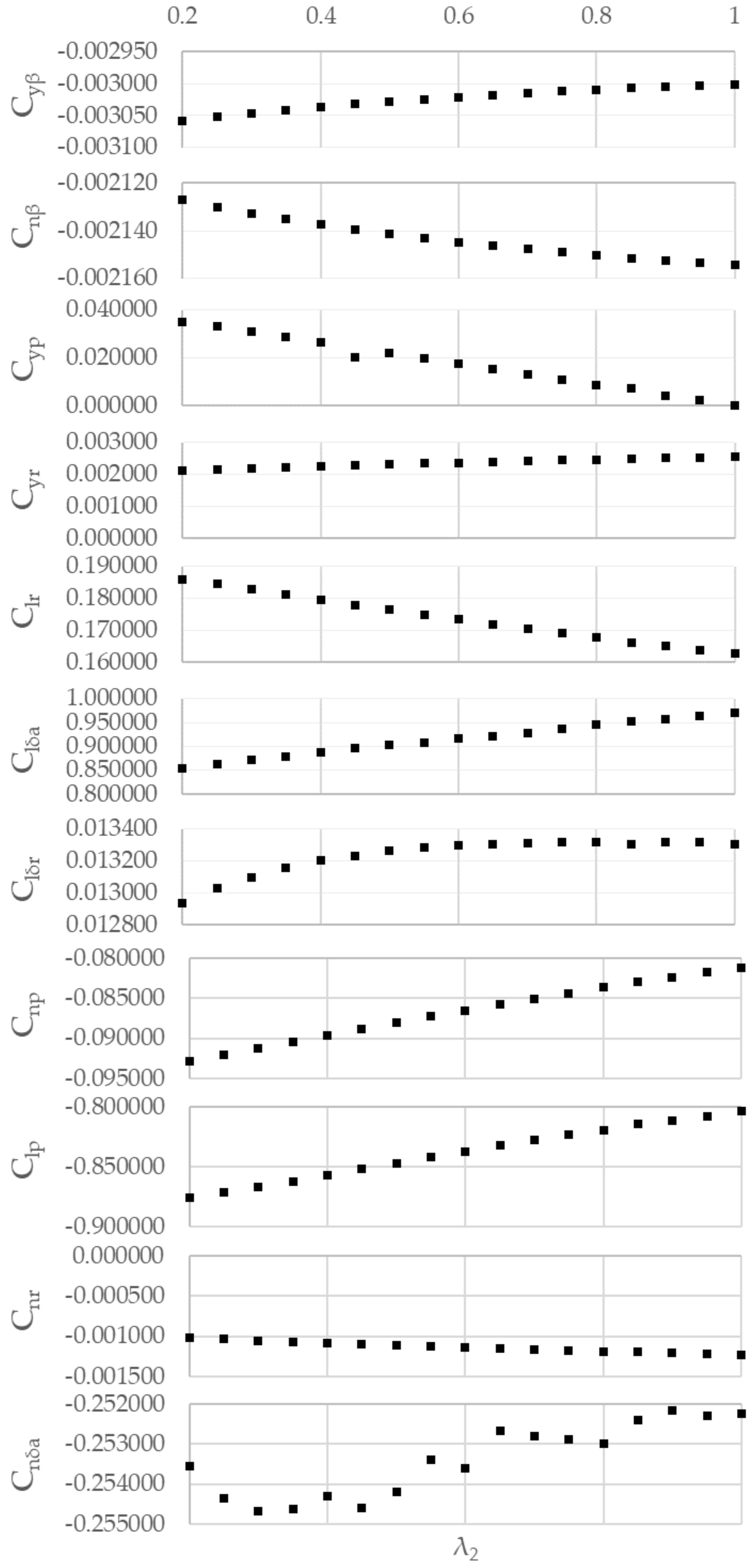

Figure 3. The alteration of lateral and directional stability coefficients with wingtip taper ratio

4. Conclusions

In this study, a morphing scenario with a tapering wingtip is applied on a fixed-wing unmanned aerial vehicle ZANKA-I, and investigated in terms of lateral-directional stability considerations. The main wing of the vehicle is separated into two planform sections and the wingtip section is designed as capable of morphing in terms of taper ratio within a determined interval. Within the context of the study, aircraft lateral dynamic model variables are first determined via numerical and analytical methods, and all of the obtained aerodynamic, geometrical, and inertial variables are used for the estimation of lateral-directional stability coefficients. The results of the coefficients shown that the tapering morphing wingtip design resulted in improved lateral stability, while a clear loss is found in directional stability. It is evident from the study that every design has pros and cons to be considered including morphing design attempts. This study could be extended to stability derivative calculation and associatively flight mode investigations as future work.

Authors' Contributions

All authors contributed equally to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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