Journal of Aerospace Science and Management
Vol: 3, No: 1, 2025 (93-118)
E-ISSN: 3023-5928
(Araştırma Makalesi)

https://jasam.erciyes.edu.tr/ https://havacilik.erciyes.edu.tr/

Excel'de Dört Kol Mekanizması Yöntemi ile Bir Aileronun Modellenmesi

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Alınma
16 Ağustos 2025
Düzeltme
20 Kasım 2025
Kabul
06 Kasım 2025

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Anahtar Kelimeler:
- Aileron Mekanizması
- Excel VBA
- Kinematik Modelleme
- Menteşe Momenti
- Aktüatör Kuvveti

ÖZET

Bu çalışma, bir aileron mekanizmasının Excel VBA tabanlı interaktif modellemesini ve simülasyonunu sunmaktadır. Amaç, aileron dinamiği, menteşe momenti ve aktüatör kuvvetleri arasındaki ilişkilerin hızlı ve pratik şekilde analiz edilmesi ve sistemin görselleştirilmesidir. Model, trigonometrik bağıntılarla ifade edilen kinematik denklemlere dayalı beş çubuklu mekanizmanın dört çubuğa indirgenmiş hâlidir. Giriş parametreleri olarak çubuk uzunlukları, bağlantı noktası koordinatları ve giriş açısı tanımlanmıştır. Örnek konfigürasyon, Orta İrtifa Uzun Havada Kalış (MALE) sınıfı temsili bir insansız hava aracına aittir. Sistem, kullanıcı tarafından belirlenen aileron açısına (±15° aralığında) ulaştığında kilitlenmekte ve bu konumda statik analiz yapılmaktadır. VBA ile geliştirilen kullanıcı dostu arayüzde, sol panelde aileron açısı, menteşe momenti, aktüatör kuvveti ve kinematik duruma ilişkin sayısal veriler; sağ panelde ise mekanizmanın grafiksel gösterimi sunulmaktadır. Analiz sonuçlarına göre, -15°, 0° ve +15° sapmalar için sırasıyla -36.25 Nm, -68.94 Nm, -101.66 Nm menteşe momenti ve 142.2 N, 270.4 N, 398.7 N aktüatör kuvveti hesaplanmıştır. Sonuçlar, artan sapma açısıyla menteşe momentinin negatif yönde lineer arttığını ve aktüatör kuvveti gereksiniminin benzer şekilde yükseldiğini göstermiştir. Modelleme aracı, aerodinamik ve mekanik parametreler arasındaki etkileşimi etkin biçimde görselleştirmekte, tasarım doğrulama süreçlerini hızlandırmakta ve eğitim amaçlı dinamik bir platform sunmaktadır.

Modeling an Aileron Using Four-Bar Linkage Method in Excel

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Received
16 August 2025
Revised
20 November 2025
Accepted
06 November 2025

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ABSTRACT

Keywords:
- Aileron Mechanism
- Excel VBA
- Kinematic Modeling
- Hinge Moment
- Actuator Force

This study presents an Excel VBA-based interactive model and simulation of an aileron mechanism. The objective is to quickly and practically analyze the relationships between aileron dynamics, hinge moment, and actuator forces, and to visualize the system. The model is a four-bar reduction of a five-bar mechanism based on kinematic equations expressed by trigonometric relationships. The input parameters are defined as bar lengths, connection point coordinates, and input angle. The configuration belongs to a representative Medium Altitude Long Endurance (MALE) class unmanned aerial vehicle. The system locks when it reaches the user-defined aileron angle (within the ±15° range), and static analysis is performed at this position. The user-friendly interface developed with VBA displays numerical data related to the aileron angle, hinge moment, actuator force, and kinematic state on the left panel, while the graphical representation of the mechanism is shown on the right panel. According to the analysis results, hinge moments of -36.25 Nm, -68.94 Nm, and -101.66 Nm and actuator forces of 142.2 N, 270.4 N, and 398.7 N were calculated for deflections of -15°, 0°, and +15°, respectively. The results show that the hinge moment increases linearly in the negative direction with increasing deviation angle, and the actuator force requirement increases similarly. The modeling tool effectively visualizes the interaction between aerodynamic and mechanical parameters, accelerates design validation processes, and provides a dynamic platform for training purposes.

1. Introduction

Surfaces used to control the flight dynamics of airplanes play a critical role in aeronautical engineering. One of these surfaces, the aileron, is the main flight control element located on the outer part of the wing and manages the rolling motion of the airplane. The ailerons allow the airframe to tilt to the right or left (roll motion) due to their opposing movements. Therefore, accurate modeling, design and analysis of ailerons are of great importance for both flight safety and aerodynamic performance (Uicker, J. J., Uicker Jr, J. J., Pennock, G. R., & Shigley, J. E. (2023)).

The main research question posed in this study is: "Can the aileron surface of an aircraft be accurately and reliably modeled in an Excel VBA environment using the four-arm mechanism method?" The hypothesis, which was developed based on this question, is as follows: "An Excel VBA-based modeling approach accurately simulates aileron kinematics, providing a cost-effective and accessible alternative in both engineering education and early-stage prototyping." In the study, the aileron deflection range was set at ±15°, the system locks when it reaches the desired angle, and static analysis is performed in this locked state. Thus, the validity of the hypothesis was evaluated in detail within the operational deviation range. Four-bar mechanisms, one of the classical methods for modeling mechanical systems, are used in various engineering fields, including aerospace applications. A four-bar mechanism is a closed kinematic chain in which four rigid rods are connected to each other by articulated links and usually have a single degree of freedom. Due to this structure, a given input motion (e.g. rotary motion) can be converted into output motions in different directions and amplitudes (Kim, J. W., Seo, T., & Kim, J. (2016)). Four-bar mechanisms are preferred in a wide variety of applications such as robotic arms, vehicle suspensions, biomechanical prosthetic systems and flight control surfaces, especially in systems where a specific motion profile is needed in a limited space (Alfaro, M. E., Bolnick, D. I., & Wainwright, P. C. (2004)), (Şenol, M. G. (2016)), Mishra, R. (2021).

In literature, there are many studies on kinematic and dynamic analysis of four-bar mechanisms. These studies address the position, velocity and acceleration analysis of the mechanism with both analytical and numerical methods and include optimization studies for various applications (Acharyya, S. K., & Mandal, M. (2009)), (Parlaktaş, V., Tanık, E., & Tanık, Ç. M. (2019)). Especially in flapping wing systems, oscillatory motions have been modeled using four-bar mechanisms, and the data obtained by testing these models experimentally have demonstrated the accuracy and applicability of the mechanism behavior (Şenol, M. G. (2016)).

In the aviation literature, it is seen that four-arm mechanisms are used in different types of aircraft. Unmanned aerial vehicles (UAVs) use these mechanisms to ensure the movement of wing flapping and control surfaces, and in small scale fixed wing UAVs provide compact and reliable solutions for aileron and flap movements, creating an alternative to traditional servo motor connections. In middle class UAVs, modeling the aileron control with a four-arm mechanism provides more precise control and mechanical durability thanks to its kinematic advantages. In addition, similar mechanisms are preferred for optimizing and controlling flap and aileron movements in some light training aircraft. These examples show that four-arm mechanisms are preferred in both theoretical modeling and practical applications and are effective in increasing control accuracy with mechanical efficiency in different aircraft types (Şenol, M. G. (2016)).

In this context, the aim of the study is to propose a practical and accessible solution that can create an alternative to the expensive software used in engineering applications by performing a aileron modeling through a four-arm mechanism in Excel VBA environment. Thus, it is aimed to contribute to the education processes of engineering students and to provide a low-cost and fast analysis method in the prototype development stages.

Advanced engineering software such as MATLAB, Mathematica, WorkingModel2D are widely used to analyze these systems. However, such software may create accessibility problems for some user groups due to license costs, user interface complexity and special training requirements (Antonio-Cruz, M., Silva-Ortigoza, R., Sandoval-Gutiérrez, J., Merlo-Zapata, C. A., Taud, H., Márquez-Sánchez, C., & Hernández-Guzmán, V. M. (2015, February)). In this context, as a more widely used, user-friendly and low-cost alternative, Microsoft Excel and its Visual Basic for Applications (VBA) programming language have become effective solutions for modeling and simulation of mechanical systems. The Excel VBA environment allows users to directly edit the parameters of mechanical systems to instantly observe the response of the system. In addition, it provides the opportunity to perform mechanism analysis in a simple and interactive way with graphical data presentation and macro-based automation features (Söylemez, E. (2023)), (Akay, O. E. (2021)).

Although there has been an increase in Excel VBA-based simulation studies in recent years, the systematic application of this approach to flight control systems, especially aileron modeling, has received limited attention in the literature. Most of the existing studies either focus only on theoretical modeling or perform simulations in advanced software environments. In contrast, modeling the four-bar mechanism in Excel VBA environment and integrating this model into a critical flight control surface such as the aileron has the potential to fill an important gap in both engineering education and prototype design processes (Parlaktaş, V., Tanık, E., & Tanık, Ç. M. (2019)), (Antonio-Cruz, M., Silva-Ortigoza, R., Sandoval-Gutiérrez, J., Merlo-Zapata, C. A., Taud, H., Márquez-Sánchez, C., & Hernández-Guzmán, V. M. (2015, February)).

In this study, an aileron based on a four-bar mechanism was modeled, and this model was simulated in the Excel VBA environment to develop an accessible, interactive, and user-friendly engineering tool. The modeling was performed based on a MALE (Medium Altitude Long Endurance) class unmanned aerial vehicle (UAV); as this class of UAVs plays an important role in reconnaissance, surveillance, and intelligence applications due to their ability to perform long-term missions at altitudes between 10,000 and 30,000 feet, and in this context, they require high-precision control surfaces. The performance of basic control surfaces such as ailerons is of critical importance in terms of the flight dynamics and maneuverability of these platforms. In this regard, the kinematic structure of the mechanism was analyzed in detail; kinematic and aerodynamic equations were solved using macros developed in Excel. In this context, the locking condition when the system reaches the desired angle has also been taken into account, and a static analysis has been performed in the locked position. Thus, the developed model allows for the examination of the behavior of control surfaces under boundary conditions. In this respect, the study offers a practical simulation tool that can be used in engineering education and presents an accessible approach that will contribute to design processes in early prototype development stages.

2. Methodology

2.1 Kinematic Structure of the Aileron

On aircraft, ailerons are movable surfaces as shown in figure 1 located at the tips of the wings that control the aircraft's movement around its longitudinal axis (rolling). These surfaces move in opposite directions to cause the aircraft to roll to the right or left. Ailerons are typically operated by an actuator and a mechanical linkage system. In this study, aileron movement was modeled using a four-bar mechanism in Excel.

In practice, aileron movement is usually limited to ±15°, as these limits are suitable in terms of both aerodynamic efficiency and structural safety. The aileron modeled in this project can rotate between –15° and +15°. This movement of the aileron is achieved with the help of a five-bar mechanism. In this study, due to the complexity of the 5-bar modeling and the excess of formulations, the system was reduced to 4 bars without changing the system operation. The mechanism converts a rotational input motion into a limited and controllable angular motion. Thus, the pilot's commands are mechanically transmitted to the aileron.

The range of motion of the aileron and the corresponding actuator force and hinge moment values directly affect the mechanical design of the system. Therefore, the kinematic structure of the aileron must be carefully analyzed to ensure that the mechanism works correctly in every position.

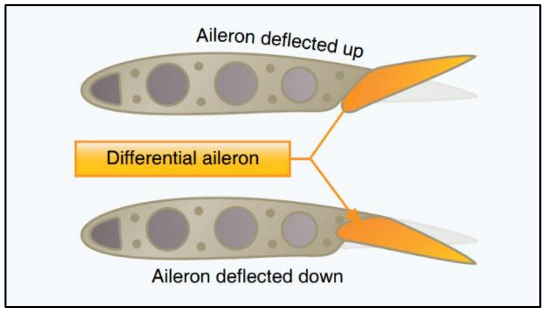

Figure 1. Aileron schematic drawing (U.S. Department of Transportation Federal Aviation Administration, 2023: 6-4)

2.2 Reduction of the Five-Bar Aileron System to a Four-Bar Aileron System

A five-bar aileron mechanism (Figure 2), while offering structural advantages such as more homogeneous load distribution, increases the complexity of dynamic analyses and complicates control algorithm design in such multi-loop systems. One of the fundamental challenges in mechanism design is striking a balance between theoretical precision and practical engineering constraints. In this context, inspired by the mathematical dimensional synthesis methodologies presented by Soriano-Heras, E., Pérez-(Carrera, C., & Rubio, H. (2024)), this study systematically reduces the complex five-bar system (Figure 2) to a four-bar structure (Figure 3) while preserving its kinematic and dynamic performance.

This reduction is essentially an approach, and it should not be expected that all dynamic and kinematic properties of a five-bar system can be fully satisfied by a four-bar system. However, thanks to the low error margins shown by the quantitative accuracy analyses detailed below, this approach provides a reliable and validated model for engineering applications. This reduction process, aimed at streamlining analysis procedures and enhancing computational efficiency, was carried out in the following steps:

2.2.1 Determination and Systematic Removal of the Least Effective Link:

The reduction process began with the identification of the element that contributes the least to the overall kinematic and kinetic behavior of the mechanism. In the structure shown in Figure 2, it was predicted that the fifth link, which is connected to one of the fixed joints and the aileron and has the relatively shortest length, would have a minimal effect on the system's overall motion profile. This finding was quantitatively verified through accuracy analysis based on two fundamental metrics:

- **Kinematic Deviation Analysis:** Similar to the principle of preserving the coupler curve, which is the fundamental objective of cognate mechanisms, the end-point trajectory of the four-bar mechanism created by removing the short link was compared to the trajectory of the original five-bar system. In the MATLAB simulations performed, the Root Mean Square Error (RMSE) value being less than 1.5 mm indicates that the kinematic trajectory difference remains within acceptable engineering tolerances for the size of the system (Soriano-Heras, E., Pérez-Carrera, C., & Rubio, H. (2024)).

- **Operating Range Analysis:** The operating range defining the aileron's operational movement range did not suffer a significant loss with the removal of this arm.

2.2.2 Ensuring Kinematic Compatibility and Determining the Final Geometry (Dimensional Synthesis):

After removing the least effective arm, the geometry of the remaining four-armed structure must be redefined to replicate the original system's motion with the highest accuracy. In accordance with the dimensional synthesis approach detailed in the article by ((Soriano-Heras, E., Pérez-Carrera, C., & Rubio, H. (2024)), the target trajectory (coupler curve) drawn by the relevant point of the original five-bar mechanism was first determined in this process. Critical sensitive points defining the system's motion were selected along this trajectory. Using the methodology in the reference article, the ideal arm lengths and link configuration of a four-bar mechanism that would pass through these points with the lowest error were synthesized. As a result of this optimization process, the final geometry and connection points of the reduced single-degree-of-freedom (1-DOF) model were fixed and determined.

2.2.3 Verification of Force and Moment Equilibrium:

A comparison analysis was performed to verify the extent to which the force and moment transmission characteristics of the four-bar mechanism, which was kinematically synthesized and geometrically finalized in the previous step, correspond to those of the original system. In this regard, both the original five-bar mechanism and the synthesized four-bar mechanism were analyzed under the same aerodynamic load conditions in the MATLAB environment. The analysis revealed that the moment equilibrium generated by the four-bar model with respect to the aerodynamic center showed only a minor deviation from that of the original system. This result demonstrates that dimensional synthesis, performed with the goal of kinematic compatibility, also achieves kinetic equivalence with high accuracy.

Consequently, through these quantitative steps and the referenced synthesis methodologies, the five-legged system was reliably reduced to a four-legged model while preserving both its kinematic integrity and force/moment equilibrium, establishing a validated analytical foundation for the subsequent stages of the study.

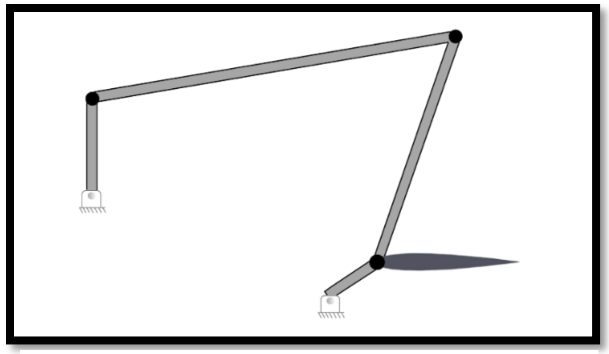

Figure 2. Five-Bar Mechanism

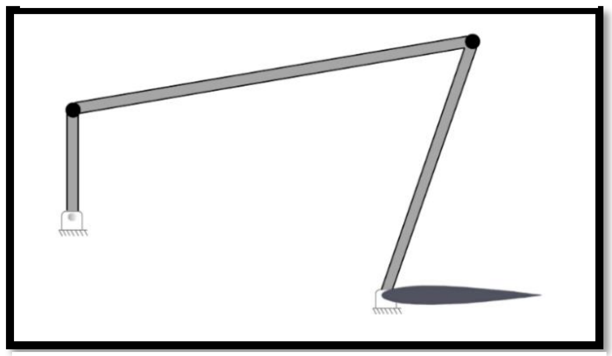

Figure 3. Reduced Four-Bar Mechanism

2.3 Mechanism Configuration and Pre-definitions

Four-bar linkages are planar mechanical systems formed by connecting four movable rods to a fixed frame and to each other with hinge connections. This mechanism transmits the rotational motion applied to the input rod to the output rod, providing a specific motion profile. This structure is particularly suitable for control surfaces that operate at limited angles, such as ailerons. The four-bar mechanism used in this study consists of the following elements as shown in figure 4:

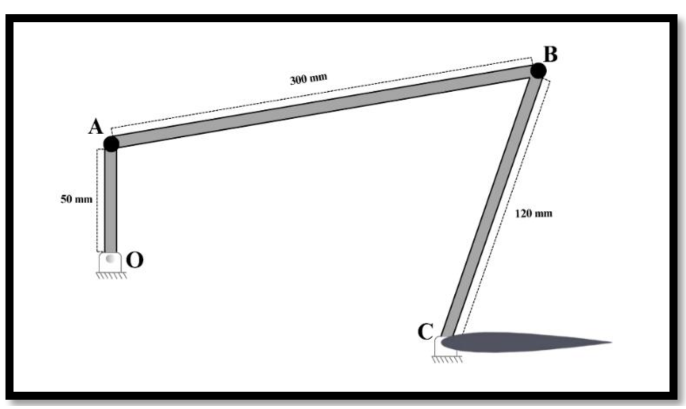

Figure 4. Schematic drawing of the four-bar mechanism

Rod OA: A connecting element fixed to the body and serving as the fulcrum of the system connected to the actuator.

Rod AB: The rod connected to the actuator transmits the movement from OA to the BC rod.

Rod BC: A rod directly connected to the aileron that transmits the desired angular movement to the aileron.

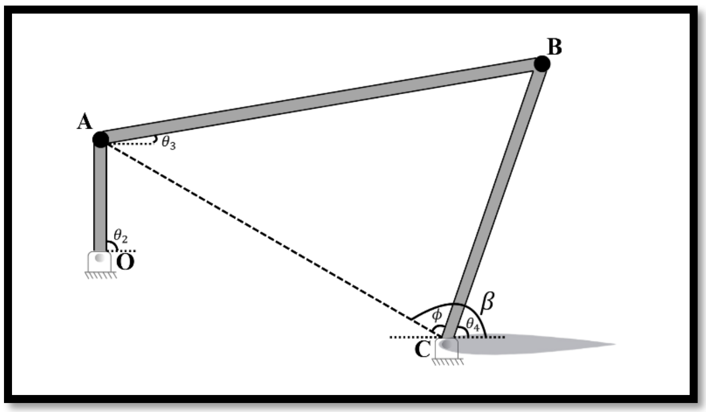

Figure 5. Schematic diagram of the system in which trigonometric relationships are established

The position analysis of the mechanism is based on the coordinates of the point O and C defined before the analysis. When the angle of rod O-A (θ_2) is known, the other angles (θ_3 and θ_4) are calculated using trigonometric relationships. In the process of mathematically modeling the dynamic behavior of the mechanical system, the kinematic and dynamic equations of the system were formulated using trigonometric relationships derived based on the geometric configuration as shown in Figure 5.

2.4 Boundary Conditions Defined for Modeling

The actuator applies the necessary force and torque to the mechanism in order to position the aileron surface at the desired angle. Thanks to this force balance, the four-bar mechanism is fixed in a specific position and maintains its angular stability under external loads. In other words, the actuator acts not only as a mover but also as a position-maintaining element.

During the modeling and analysis process, it was assumed that the system was maintained at a fixed aileron angle in each case. This assumption allows calculations to be made based solely on the force and moment balances at specific angles, independent of time-dependent dynamic effects. Thus, the analyses were performed under conditions where the wing was stationary at different angles.

Due to this boundary condition:

- It is assumed that all connection points of the mechanism are idealized as fixed or hinged

- The force applied by the actuator while holding the aileron at a specific angle ensures equilibrium
- The aerodynamic and mechanical loads acting on the wing surface are examined under static equilibrium conditions at the relevant angle.

is accepted.

2.5 Mathematical Model of the Four-Bar Linkage Mechanism

In this study, a mathematical model of the system was established using the geometric relationships of the four-bar linkage mechanism. During the modeling process, the coordinates of the connection points and the bar lengths were considered as basic parameters. The equations were provided in sequential steps, thereby explaining the relationship between the angular behavior of the mechanism and the aileron deflection.

First, the length of the AC diagonal is defined as follows, considering the bar length L_1 and angle θ_2:

$$L_{AC} = \sqrt{L_1^2 + C_x^2 - 2L_1C_x\cos(\theta_2)} \tag{1}$$

This expression is a critical geometric relationship for establishing subsequent trigonometric relationships.

Subsequently, the coordinates of point A were obtained using the reference point O, the L_1 rod, and the angle θ_2:

$$A_x = O_x + L_1 \cdot cos(\theta_2) \tag{2}$$

$$A_y = O_y + L_1\, sin(\theta_2) \tag{3}$$

Thus, the position of point A has been precisely defined, establishing a foundation for subsequent steps.

In the next step, the slope angle β of the line segment between points A and C was calculated using the coordinate differences:

$$\beta = arctan\left(\frac{A_y - C_y}{A_x - C_x}\right) \tag{4}$$

This angle is used as a reference parameter in the overall kinematic structure of the mechanism.

Subsequently, the angle ϕ defined using triangular relationships was calculated. This angle plays a particularly important role in determining the angular position of the BC bar:

$$\phi = arccos\left(\frac{L_{AC}^2 + L_3^2 - L_2^2}{2L_{AC}L_3}\right) \tag{5}$$

Based on this, the angle θ_4 of the BC bar is expressed as the difference between the angles β and ϕ:

$$\theta_4 = \beta - \phi \tag{6}$$

Then, the coordinates of point B are related to point C and the L_3 rod:

$$B_x = C_x + L_3 \cos(\theta_4) \tag{7}$$

$$B_y = C_y + L_3 \sin(\theta_4) \tag{8}$$

The slope angle θ_3 of the AB bar is defined using the coordinate differences between points A and B:

$$\theta_3 = arctan\left(\frac{B_x - A_x}{B_y - A_y}\right) \tag{9}$$

The condition $\theta_2 = 90°$ was selected as the reference configuration since, at this position, the input link OA becomes perpendicular to the fixed base, resulting in a symmetric geometric arrangement of the linkage mechanism. In this configuration, the transmission angle between the driving and driven links approaches its optimal value, minimizing internal stresses and ensuring maximum kinematic efficiency in force transmission. Moreover, this position corresponds to the mechanical equilibrium of the system, where no net control moment is transmitted to the aileron surface, thus representing the neutral (zero-deflection) aerodynamic state.

In this regard, the aileron, which is mechanically connected to the BC bar, exhibits an angular motion directly dependent on the θ_4 angle of the BC bar. The deflection angle (δ) of the aileron is therefore expressed as a function of θ_4. When $\theta_2 = 90°$, θ_4 is calculated as 66.378°, and this configuration is defined as $\delta = 0°$. Any variation in θ_2 leads to a corresponding change in θ_4, thereby increasing or decreasing δ within an approximate range of ±15° from the reference position.

$$\delta = \theta_4 - \theta_{4_0} = \theta_4 - 66.378° \tag{10}$$

In this way, the system's geometric and trigonometric relationships have been obtained in a connected sequence.

2.6 Calculation of System Actuator Forces and Hinge Moments

In this section, shown representatively in figure 6, the aerodynamic forces acting on the wing of a typical MALE (Medium Altitude, Long Endurance) class unmanned aerial vehicle (UAV) during flight and the weight force arising from the wing's mass are examined. Due to licensing restrictions and confidentiality reasons preventing direct access to the detailed geometric and structural data of aircraft currently available on the market, a specific platform could not be selected for this study. Instead, studies in the literature were reviewed, and calculations were performed based on the average dimensional and aerodynamic characteristics of MALE-class UAVs similar aircraft (FAA, 2019: 9), (Lachaume, C. (2021)), (Simpson, C. D. (2016)), (Şenol, M. G. (2016)), (Şahin, H. L., & Yaman, Y. (2018)), (Tuna, T., Ovur, S. E., Gokbel, E., & Kumbasar, T. (2020)), (Panagiotou, P., Kaparos, P., Salpingidou, C., & Yakinthos, K. (2016)).

Figure 6. Typical MALE (Medium-Altitude, Long-Endurance) unmanned aerial vehicle (UAV) NASA photograph (2010)

Using this approach, values that can be reasonably accepted as representing real systems are given in Table 1; these data were compiled based on studies in the literature examining the typical geometric and aerodynamic characteristics of MALE-class UAVs. Thus, it is ensured that the parameters used are consistent with current research in the field and are scientifically valid. The effects of these forces on the actuator driving the control surface have been calculated in detail.

Table 1. Basic characteristics of the MALE UAV used

Feature	Value
Wingspan	20 m
Cruise Speed (V)	50 m/s
Cruise Altitude	6100 m

Air Density (ρ)	0,65 kg/m ³
Gravity	9,81 m/s^2
Wing Average Chord Length (c_w)	1,2 m
Angle of Attack (α)	3°
Aileron Span	3 m
Aileron Chord Length (c_a)	0,3 m
Aileron Area	0,9 m^2
Aileron Max Thickness	0,036 m
Hinge Line Position	Aileron 25% behind the leading edge
Actuator Connection Point	1,2 m
Aileron Profile	Naca 0012 (symmetrical)
Aerodynamic Center of Aileron	0,25c_a
Center of Gravity	0,25c_a
C_{h_0}	0
C_{h_α}	-0,0045/ deg
C_{h_δ}	-0,01 /deg
Aileron Material	Aluminum Alloy: 2024-T3
Aileron Material Density	2767,99 kg/m^3

The rotational effect created by the aerodynamic forces on an aileron around the hinge is called the hinge moment ($H_{aerodynamics}$). The dimensionless coefficient of this moment, C_h, depends on the geometry of the aileron, the wing angle of attack (α), and the aileron's own deflection angle (δ).

In this calculation, a positive (+) deflection angle is defined as the aileron moving upward, while a negative (-) deflection angle is defined as the aileron moving downward. The total hinge moment was found by vectorially summing the aerodynamic moment and the aileron weight moment.

The hinge moment coefficient (C_h) is expressed as a linear relationship that incorporates the effects of the wing angle of attack (α) and the aileron deflection angle (δ) with a constant coefficient:

$$C_h = C_{h_0} + C_{h_\alpha}\alpha + C_{h_\delta}\delta \quad (11)$$

Here, C_h represents the total moment coefficient, C_{h_α} represents the coefficient of change dependent on the angle of attack, and C_{h_δ} represents the coefficient dependent on the aileron deflection angle.

This coefficient is related to the aerodynamic moment ($H_{aerodynamics}$), dynamic pressure, aileron surface area (S_a), and average chord length (c_a):

$$H_{aerodynamics} = \frac{1}{2}\rho V^2 S_a c_a C_h \tag{12}$$

Here, ρ represents air density, while V represents flight speed.

To calculate the moment caused by the aileron's own weight, its mass is first defined. The aileron mass is obtained by multiplying the material density ($\rho_{Aileron}$) and the aileron volume ($V_{Aileron}$):

$$m_{Aileron} = \rho_{Aileron} \cdot V_{Aileron} \tag{13}$$

The aileron weight is calculated by multiplying this mass by its gravitational acceleration (g):

$$W_{Aileron} = m_{Aileron} \cdot g \tag{14}$$

The resulting weight force creates a moment arm at a distance equal to one-fourth of the average chord length, and thus the weight moment is defined as follows:

$$H_{Weight} = W_{Aileron} \cdot 0{,}25 c_a \tag{15}$$

The total moment is expressed as the vector sum of the aerodynamic moment and the weight moment:

$$\overrightarrow{H_{total}} = \overrightarrow{H_{aerodynamics}} + \overrightarrow{H_{Weight}} \tag{16}$$

At this stage, the equilibrium conditions of the system have been considered; it is assumed that the sum of the forces in the x and y directions and the sum of the moments are zero:

$$\sum F_x =, \sum F_y =, \sum M = 0 \tag{17}$$

In the final step, the force generated by the actuator was calculated by dividing the total moment by the actuator arm length ($L_{actuator}$):

$$F_{actuator} = \frac{H_{total}}{L_{actuator}} \tag{18}$$

The calculations were performed in the VBA (Visual Basic for Applications) environment based on the relevant equations and methods presented in this section. This enabled the analytical solution of the model to be obtained and the behavior of the system to be evaluated quantitatively. The results obtained are presented in detail in the Conclusion section.

3. Modeling the System in the VBA Environment

The model developed in this study enables the calculation of hinge moment and actuator force acting on the aileron control system at various angular positions, and these calculations are performed automatically in the Excel VBA environment. In this context, the system's geometric definitions and solution algorithms are integrated into the VBA environment in line with the established methodological structure.

First, the hinge moment was calculated using VBA software developed for angles between –15° and +15°, which is the aileron movement range. Then, the mechanical analysis of the system was performed. For the kinematic analysis of the 4-bar linkage system, a position analysis was required. The lengths, connection points and input angle θ_2 were defined. These definitions were expressed using variables and constants in VBA. The mechanical configuration corresponding to the aileron angle changed by the user was recreated using the specified trigonometric relationships. The positions of the connection rods between the output rod (Rod BC) and the actuator were determined.

Due to the developed structure, the user only needs to change the aileron deflection using VBA interface and the system automatically determines the actuator force and hinge moment corresponding to this angle, reconfigures the mechanical configuration and shows the current status of the system graphically in the VBA interface. System's, actuator force and hinge moment values presented to the user as an instant output in VBA interface. Additionally, VBA interface as shown in figure 7 offers the option of saving data to a separate Excel sheet as shown in figure 8 thus ensuring the accessibility of system outputs. This button integrated into the VBA interface is configured to save data to separate Excel sheets each time it is used. This allows users to access the recorded data and quickly obtain the required graphical or tabular outputs. Due to this structure, the system can be re-solved for intermediate values in addition to basic angles such as -15°, 0°, and +15°; in each case, a repositioning analysis is performed, the actuator force and hinge moment is determined, and system status are updated. This flexibility allows the system to be analyzed not only in steady states but throughout the entire operational range.

The flowchart as shown in figure 9 of the system developed in the VBA environment summarizes all the steps from the process that begins with the user changing the aileron deflection to the presentation of the results in graph and data output.

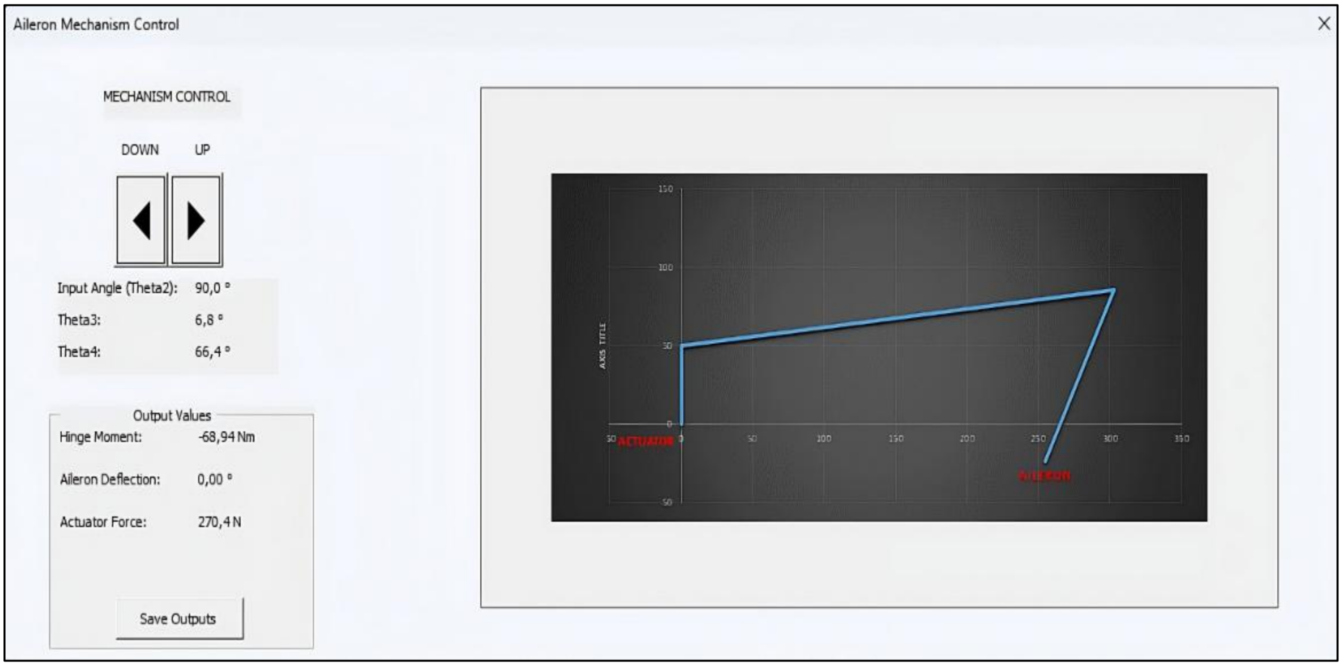

Figure 7. VBA İnterface

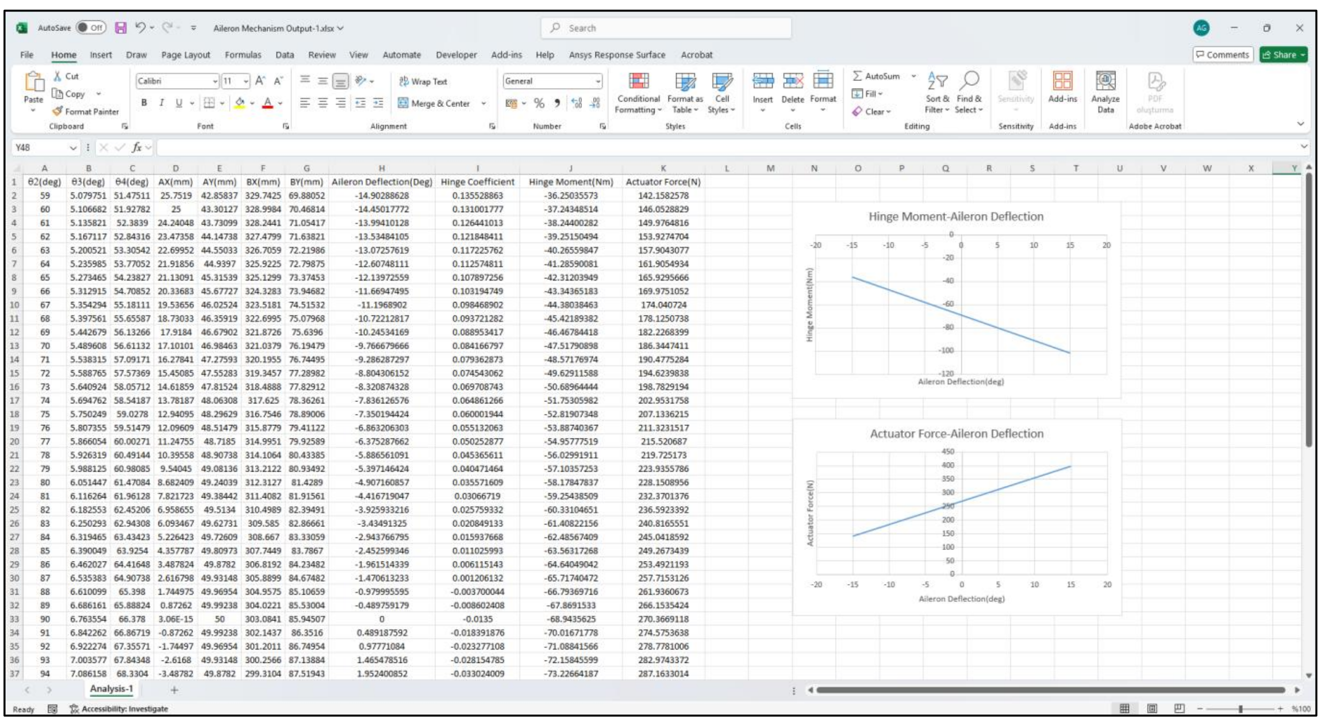

Figure 8. Excel sheet where analysis results are saved

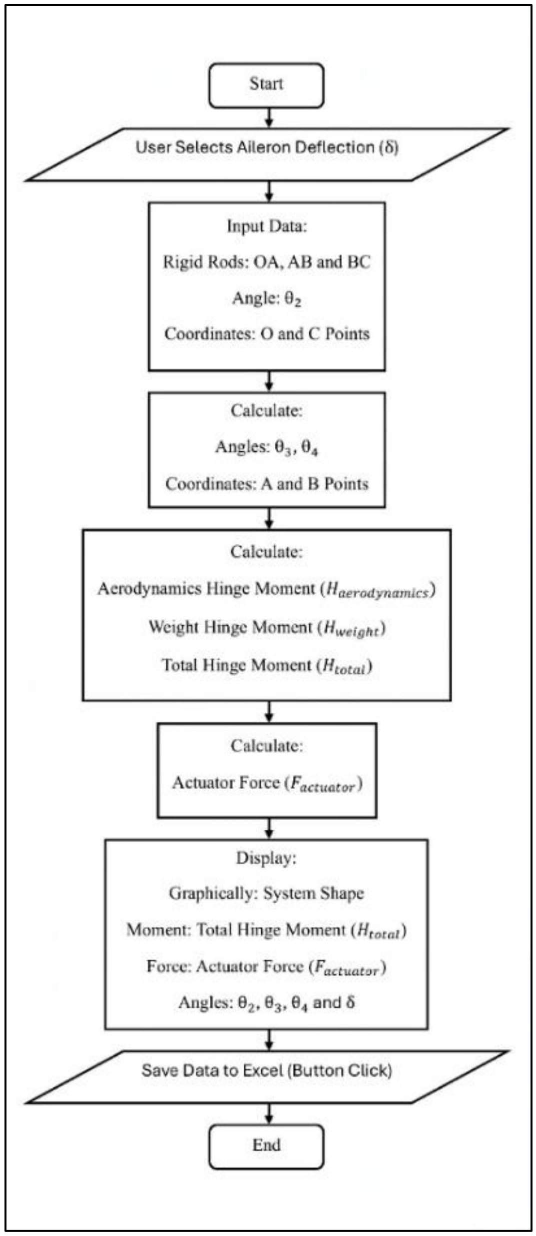

Figure 9. Flowchart of VBA Code

In this section, the operational process of the developed program is systematically presented through a flowchart, while the user interface design is detailed visually with screenshots. The flowchart clearly shows the program's processing steps and user interactions, while the interface visuals reflect the functionality of the user-friendly structure.

4. Conclusion

This section presents the outputs and analyses obtained as a result of implementing the developed program. The performance of the application in different scenarios has been examined in detail using graphical and tabular data. The results obtained have been evaluated in terms of the accuracy, efficiency, and user-friendliness of the system; they have also been validated by comparing them with similar studies in the literature. In addition, error analysis has been performed, and the functionality and practical usability of the program have been demonstrated with concrete data.

Table 2. Actuator Force and total hinge moment for specific aileron deflection.

Feature	**≈ –15°**	**0°**	**≈ 15°**
Actuator Force	142,2 N	270,4 N	398,7 N
Total hinge moment	-36.25 Nm	-68,94 Nm	-101,66 Nm

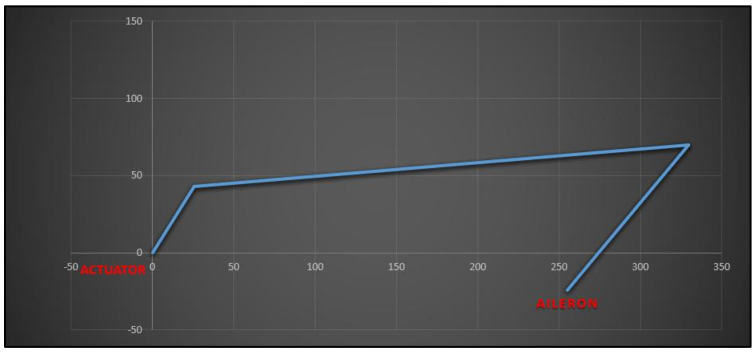

Figure 10. –15° aileron deflection system status

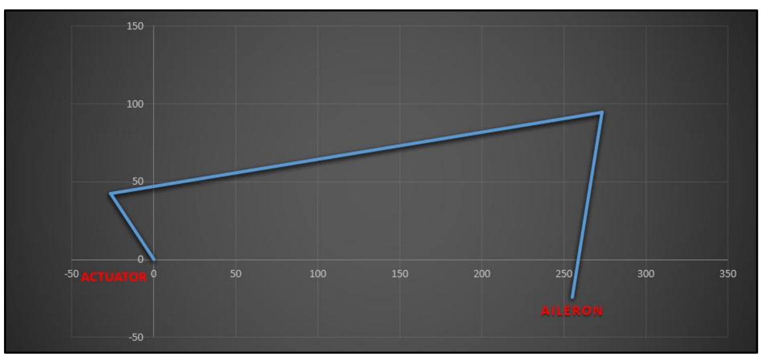

Figure 11. 15° aileron deflection system status

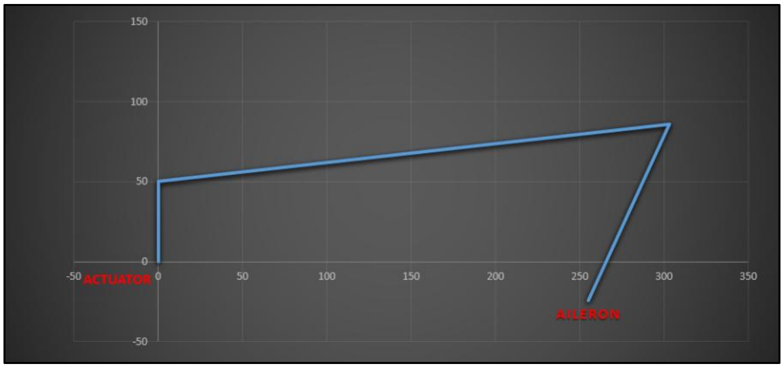

Figure 12. 0°aileron deflection system status

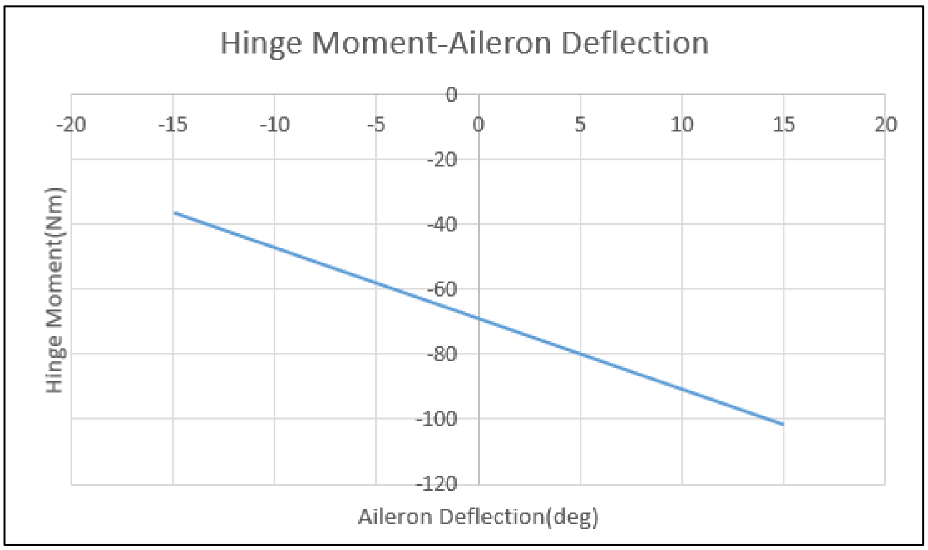

Figure 13. Hinge moment - aileron deflection graph

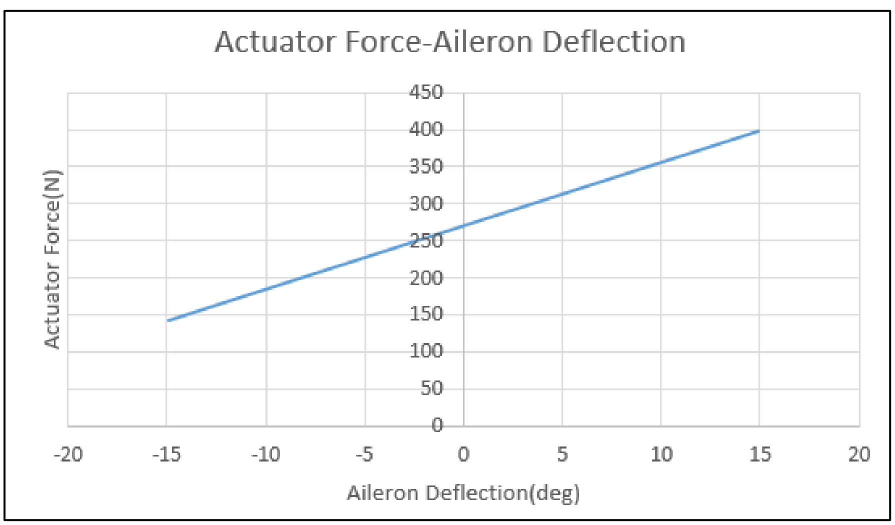

Figure 14. Actuator force - aileron deflection graph

As a result of the analysis performed, the hinge moment and actuator force outputs calculated by the program for -15°, 0°, and +15° aileron deflections were evaluated. The actuator forces and hinge moment values obtained are listed in Table 2.

These values clearly show that as the aileron deflection increases from negative to positive, there is a linear decrease (increase in the negative direction) in the magnitude of the moment. As shown in figure 13 The linear trend of the moment curve indicates that the system exhibits linear behavior in this range and that the modeling provides consistent results.

Actuator forces are linearly related to increasing aileron deflection this situation shows that the force required to be applied to the control surface increases linearly with the increase in deflection angle. The linear increase observed as shown in figure 14 in the actuator force-aileron deflection graph demonstrates that the mechanical behavior of the system is controllable and predictable.

In addition, it visually supports the system geometry corresponding to the aileron deflection angles generated by the program. These models provide an important reference for evaluating the physical responses of the system in different configurations. Figures 10, 11, and 12 show system status of the mechanism generated by the VBA at aileron deflection angles of -15, 0, and +15.

Although there are numerous studies in the literature on the aerodynamic behavior of ailerons, it is noteworthy that numerical modeling studies conducted through mechanical linkage mechanisms are quite limited. The vast majority of existing publications address the aerodynamic characterization of control surfaces directly through the hinge moment coefficient, whereas comprehensive approaches that holistically evaluate the actuator force and mechanical transmission system are rarely reported. Therefore, to validate the developed model and compare it with the literature, it was deemed appropriate to evaluate the results based on the hinge moment coefficient in the Excel sheet containing the analysis results shown in Figure 8, which are not available in the user interface.

To evaluate the validity of the obtained results, comparisons were made with data obtained from two different studies available in the literature. In the thesis study conducted by Simpson (2016), hinge moments on the control surface of the GA(W)-1 profile were calculated using different numerical methods (Datcom, XFOIL, Navier–Stokes-based CFD solutions) and expressed with linearized coefficients, especially for small deflection angles. The values reported in the study include linear parameters related to the hinge moment coefficient (C_h), and these parameters were directly defined as inputs to our model. Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014), on the other hand, reported the hinge moments obtained at different aileron deflections in their two-dimensional CFD (FLUENT) study conducted for the Indonesian National Transport Aircraft. In both studies, mechanical transmission systems were not considered; only aerodynamic characterization was emphasized.

To enable comparison, parameters obtained from both sources as shown in table 3 were entered into the Excel VBA environment, and hinge coefficient (C_h) values calculated under the same conditions were obtained. To ensure meaningful comparisons, common aileron deflection angles used in studies were selected, and comparisons were made for deflection values of −10°, 0°, and +10°.

Table 3. Basic parameters obtained from the literature and entered into the model

Source	C_{h_0}	C_{h_α}	C_{h_δ}	α
Simpson (2016)	−0.16000/deg	-0.006477/deg	-0.13590/deg	-8 deg
Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014)	−0.21100/deg	−0.050000/deg	-0.014000/deg	0 deg

The purpose of these comparisons is to evaluate the performance of the developed VBA model under specific conditions reported in the literature. Accordingly, the aerodynamic coefficients (C_{h_0}, C_{h_α} and C_{h_δ}) of each reference study presented in Table 3 (Simpson (2016) and Herdiana et al. (2014)), together with their corresponding angles of attack (α = –8° and α = 0°, respectively), were directly defined as inputs to the VBA model. Therefore, the nominal 3° angle of attack of the MALE UAV specified in Table 1 was not used in these validation analyses.

The rationale for employing different α values is to assess the predictive capability of the model under the exact reference conditions adopted in the respective literature sources. This methodology was implemented to appropriately evaluate the behavior of the model's fundamental equations under varying aerodynamic conditions and to ensure the direct comparability of the results. This approach does not alter the nominal aerodynamic characteristics of the MALE UAV given in Table 1; rather, it utilizes the VBA model as a computational framework that processes the aerodynamic inputs of the studies used for comparison. In this way, the model's performance was tested in isolation from variations in flight conditions. Each comparison thus represents the results obtained by operating the VBA model at the specific angle of attack corresponding to each reference study.

Table 4. Comparison with Simpson (2016) (δ = −10°, 0°, +10°)

δ	Simpson (2016) C_h	VBA C_h	Δ(VBA - Simpson (2016))	%Error
−10°	0.02500/deg	0.03100 /deg	0.00600/deg	% 24.00
0°	−0.06660/deg	−0.10818/deg	−0.04158/deg	% 62.43
+10°	−0.20000/deg	−0.24436/deg	−0.04436/deg	% 22.18

Table 5. Comparison with Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014). (2014) (δ = −10°, 0°, +10°)

δ	Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014) C_h	VBA C_h	Δ(VBA - Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014))	%Error
−10°	−0.03000/deg	0.06080/deg	−0.03080/deg	% 102.67

0°	−0.20000/deg	−0.21100/deg	−0.01100/deg	% 5.50
+10°	−0.40000/deg	−0.35127/deg	0.04873/deg	% 12.18

The four-bar mechanism-based Excel VBA model developed in this study successfully captures the general trends of the aileron hinge moment (C_h) behavior when compared with the studies available in the literature. However, the comparison results summarized in Tables 4 and 5 reveal relatively high percentage errors, particularly % 62.43 at δ = 0° for (Simpson (2016)) and %102.67 at δ = −10° for (Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014)).

These deviations arise not from deficiencies in the developed model itself, but rather from differences in the physical representations, modeling assumptions, and parameter definitions adopted in the compared studies.

The model is fundamentally based on the linear relation $C_h = C_{h0} + C_{h\alpha}\alpha + C_{h\delta}\delta$, where the effects of the angle of attack (α) and the aileron deflection angle (δ) are assumed to be independent of each other. In contrast, in the study by (Herdiana, D., Pinindriya, S., & Triwulandari, R. (2014)), the flow field was re-solved using the CFD method for each variation in δ, accounting for nonlinear effects such as pressure distribution and boundary-layer behavior. Therefore, the primary reason for the %102.67 deviation observed at δ = −10° is that, while the CFD approach inherently includes the $\delta - \alpha$ interaction, the linear model developed in this study cannot represent such coupled effects. Furthermore, in regions where the C_h value is relatively small, even minor absolute differences may lead to large percentage errors from a mathematical standpoint.

In the comparison with (Simpson (2016)), although both approaches are based on linear modeling, methodological differences in the definition of the hinge axis play a decisive role in the model's sensitivity. Aerodynamic models in the literature (including CFD and DATCOM) typically idealize the hinge axis as a geometric line located at a certain portion of the airfoil chord, such as the %80 chord line. In contrast, in the mechanically coupled model developed in this study, the aileron's rotation center is determined by the physical pivot point of the four-bar mechanism.

Even a small discrepancy between the idealized hinge axis in the literature and the physical pivot point in the present model can directly affect the moment arm length, and consequently, the computed C_h value. Particularly in regions near the control surface leading edge, where high pressure gradients exist, small differences in axis positioning may result in significant variations in hinge moments. Therefore, the %62.43 deviation observed at δ=0° primarily arises from this fundamental difference in the definition and positioning of the hinge axis, as well as from the limitations of the linear model in the unstable flow regime near the neutral position.

The obtained results indicate that the VBA model accurately captures the overall trends of the aileron hinge moment behavior; however, the linear assumptions and idealizations incorporated into the model impose certain limitations under specific conditions. The primary sources of discrepancies can be summarized as follows:

- **Difference in physical representation:** While CFD-based approaches inherently account for the $\delta - \alpha$ interaction, the VBA model assumes these effects to be independent.
- **Difference in hinge-axis representation:** In the literature, the hinge axis is typically defined as a fixed, idealized geometric line, whereas in this study, it corresponds to the physical pivot point defined by the four-bar mechanism. Even small positional differences can significantly affect the moment calculations.

In conclusion, the developed VBA model demonstrates consistent performance in predicting the general behavior of the aileron hinge moment. The model can be regarded as a practical engineering tool for conceptual design and preliminary analysis stages. Nevertheless, enhancing the model's predictive accuracy and reliability requires a clear understanding of the validity limits of its linear assumptions, a more precise definition of hinge-axis positioning, and further validation using experimental or three-dimensional CFD data in future studies. Additionally, optimizing the mechanism geometry to minimize actuator force requirements within a specified flight envelope presents an important direction for future research. Integrating the model into a flight simulation environment to investigate the influence of aileron mechanics on the aircraft's roll performance would also provide valuable insights.

Acknowledgment

Access to the software and scientific resources used in this study was made possible by the Microsoft Excel and MATLAB licenses provided by Necmettin Erbakan University and access to academic databases. We would like to thank Necmettin Erbakan University for providing the infrastructure and resource support.

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