LOAD ANALYSIS IN YAW MANEUVER: EVALUATING TECHNIQUES, AIRSPEEDS, AND CON-FIGURATIONS EFFECTS ON ROTORCRAFT STRUCTURAL DESIGN

Emre TAŞ
Turkish Aerospace
Ankara, Türkiye

Yağmur BULUT
Turkish Aerospace
Ankara, Türkiye

Pınar ARSLAN DÜLGAR
Turkish Aerospace
Ankara, Türkiye

Ahmet Alper EZERTAŞ
Turkish Aerospace
Ankara, Türkiye

ABSTRACT

Yaw maneuver is one of the design limit maneuvers, which contributes to structural sizing of tail boom and aft fuselage. This paper presents a comprehensive load analysis methodology for rotorcraft yaw maneuvers. Four different simulation techniques, which are the yaw committee's recommendations, are evaluated using a consistent FLIGHTLAB-based model. Each technique is applied across a range of airspeeds and mass configurations, including full-scale variation in weight and center of gravity (CG) configurations. Results demonstrate that the most severe loading conditions occur when high sideslip angles coincide with high airspeeds, particularly for forward CG locations. Among the techniques, three are shown to produce comparable results and may be used interchangeably in load prediction studies. The analysis provides practical insights for rotorcraft design teams and supports the refinement of regulatory guidance in FAR and CS 27/29.351.

NOTATION

*

Acronyms

EASA European Aviation Safety Agency

FAA Federal Aviation Administration

CS Certification Specifications

FAR Federal Aviation Regulations

AC Advisory Circular

V_{NE} Never Exceed Speed

V_{H} Maximum Level Flight Speed

CG Center of Gravity

SF Shear Force

BM Bending Moment

TOW Takeoff Weight

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INTRODUCTION

In both the preliminary and detailed design phases of the rotorcrafts, the evaluation of structural loads is fundamental to ensure safety compliance. Several maneuvers must be either analyzed or tested or both to satisfy safety and performance compliances. These maneuvers can be classified into two main groups, limit maneuvers and operational maneuvers.

Operational maneuvers are utilized for fatigue analyses. Fatigue analyzes are based on a predefined usage spectrum, which contains empirical mission profiles and maneuvers that the rotorcraft performs during its operational lifetime. Operational maneuvers are essential to calculate cyclic loads and cumulative damage due to repeated loading.

Limit maneuvers are used mainly for static structural sizing of the rotorcraft. Rotorcraft must with-stand the occurring loads during these extreme maneuvers. Neither structural failure nor permanent deformation is allowed to occur. Required maneuvers, flight conditions, control inputs and other targets are specified in detailed in both CS 29 and FAR 29 to ensure that the rotorcraft operates under the most demanding flight scenarios.

The yaw maneuver is one of the limit flight maneuvers, which contributes to structural sizing of the tail boom and the aft fuselage. Both the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) have the same regulations for the maneuver, which are described in FAR 27/29.351 and CS 27/29.351 in Ref.2. A comprehensive study which contributes to current Advisory Circular (AC) for 27/29.351 in Ref.3, proposes four different approaches to calculate loads of yaw maneuver Ref.1. Since the maneuver is based on extreme flight conditions, compliance with flight test is not recommended. Therefore, analysis approaches become more vital for limit maneuvers.

Extensive researches and analyses are contributed for each technique, described in Ref.1. Analyses are assessed with same mathematical model to acquire critical conditions. Loads on the rotorcraft throughout yaw maneuvers depend various parameters: utilized technique, airspeeds and its corresponding sideslips, and weight and CG configurations. In this paper, a modern 6-ton utility helicopter model is used for load calculations and each parameter is evaluated in terms of the effect of load distribution on the rotorcraft. Four different dynamic simulation approaches, detailed in Methodology section, are analyzed. This research investigates how load distribution changes when different techniques described in Ref.1 are applied.

Analyzed airspeeds on the line are: $0.6V_{NE}$, $0.7V_{NE}$, $0.8V_{NE}$, $0.9V_{NE}$ and V_H. To analyze with various airspeed on the line provides a comprehensive understanding of load distribution across various limit scenarios, ensuring the rotorcraft meets performance and safety standards.

Weight and CG configuration is another critical parameter affecting load variation. Since the working rotorcraft under investigation has a wide lateral and longitudinal CG envelope, all possible weight and CG configurations are examined.

In the analyses, 12 different mass states are combined with 5 different airspeeds and their corresponding yaw angles. Since the yaw maneuver is more critical for the aft fuselage and vertical fin, the study focuses on the loads acting on these components. Various airspeeds and several configurations are simulated also for each technique and the results of these simulations are presented in Results section.

Regardless of the technique employed, it is expected that the trends in fuselage and vertical fin load distributions as a function of both airspeed and configuration will remain consistent. The study also evaluates the applicability of ”the line” for a high-speed rotorcraft.

THE YAW MANEUVER AND OTHER LIMIT FLIGHT MANEUVERS

Limit Flight Maneuvers

There are various limit maneuvers such as pull-up, push-over, and rolling pull-out. Among these, the yaw maneuver distinctively generates the highest shear forces (FX, FY) and bending moments (MX, MZ), particularly in the aft fuselage region. This is primarily due to the significant contribution of tail rotor forces during yawing motion, which is more dominant in this maneuver compared to others. As a result, the aft fuselage experiences the highest structural loads.

The Yaw Maneuver and the ‘Line’

The yaw maneuver plays a decisive role in the structural sizing of the tail boom and aft fuselage of rotorcraft. Regulations for this maneuver are specified in FAR 27/29.351 and CS 27/29.351. To investigate yaw maneuver techniques, the EASA and FAA convened a yaw committee. Based on the committee’s recommendations, Advisory Circular (AC) 27/29.351 has been issued, incorporating Figure 1 Ref.3. As yaw maneuver is a limit maneuver, rotorcraft must withstand the loads for specified yaw angles at corresponding airspeeds, as indicated in Figure 1.

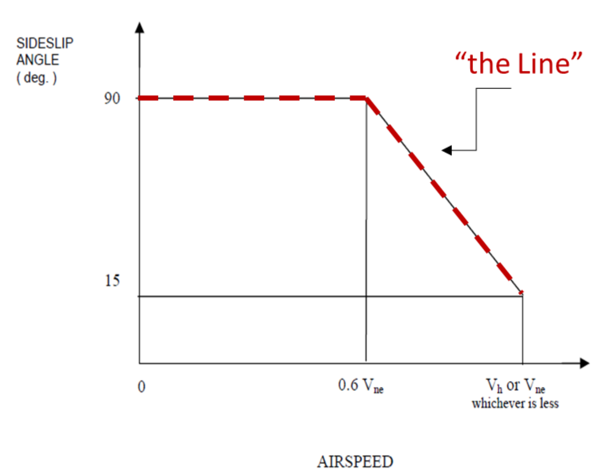

Figure 1. AC 27/29.351

The regulation for the yaw maneuver is described in CS 27/29.351 as:

(b) *To produce the load required in subparagraph (a), in unaccelerated flight with zero yaw, at forward speeds from zero up to 0.6* V_{NE}.

(1) *Displace the cockpit directional control suddenly to the maximum deflection limited by the control stops or by the maximum pilot force specified in CS 29.397(a);*

(2) *Attain a resulting sideslip angle or 90°, whichever is less; and*

(3) *Return the directional control suddenly to neutral.*

(c) *To produce the load required in subparagraph (a), in unaccelerated flight with zero yaw, at forward speeds from 0.6* V_{NE} *up to* V_{NE} *or* V_H*, whichever is less:*

(1) *Displace the cockpit directional control suddenly to the maximum deflection limited by the control stops or by the maximum pilot force specified in CS 29.397(a);*

(2) *Attain a resulting sideslip angle or 15°, whichever is less, at the lesser speed of* V_{NE} *or* V_H*;*

(3) *Vary the sideslip angles of subparagraphs (b)(2) and (c)(2) directly with speed;*

(4) *Return the directional control suddenly to neutral.*

METHODOLOGY

Each yaw maneuver approach mentioned in Ref 1 involves trimming the rotorcraft under specified conditions and performing dynamic simulations. This procedure is applied to all possible mass and C.G configurations at various airspeeds. To ensure quick and robust analyses, a mathematical model based on the FLIGHTLAB program is constructed.

FLIGHTLAB Model

FLIGHTLAB is used to estimate airframe loads through simulation and trim. It is a library-based flight simulation system that employs interchangeable models representing key rotorcraft components, such as the main rotor, tail rotor, fuselage and aerodynamic surfaces. The following key features are utilized in the analyses:

- The Peters–He finite-state and three-state induced velocity models are used for the main rotor.
- Rigid main and tail rotor blades are modeled, allowing for lag and flap motion.
- Analyses are performed under standard sea-level conditions.
- Total weight and C.G remain constant over time due to the short simulation duration.
- A Stability-Augmentation System (SAS) is used to maintain roll and pitch stability during analyses.
- While the interference between the main rotor and fuselage is considered, the interference between the tail rotor and vertical fin is neglected.

Aerodynamic Model

The fuselage aerodynamic characteristics are represented by an aerodynamic database that is a function of both angle of attack and sideslip angle. This database provides aerodynamic force and moment coefficients across a range of flight conditions. The coefficients are derived through a combination of high-fidelity Computational Fluid Dynamics (CFD) analyses and wind tunnel test data. CFD simulations are used to capture detailed flow behavior over the fuselage across a wide range of angles, particularly in regions where experimental data may be sparse or difficult to obtain. Wind tunnel data, on the other hand, provides reliable and validated measurements, especially near nominal flight conditions. The two datasets are merged using interpolation and blending techniques to construct a comprehensive and continuous aerodynamic database. This approach leverages the strengths of both methods - accuracy from physical testing and coverage from numerical simulation - to enhance the fidelity of the fuselage model in dynamic simulations.

Monitor Stations

Monitor stations, are key locations where shear force and bending moments within the fuselage, horizontal tail and vertical tail structures are computed. In Figure 2, monitor stations that belong to fuselage, vertical stabilizer, left and right horizontal stabilizers are represented as scatters.

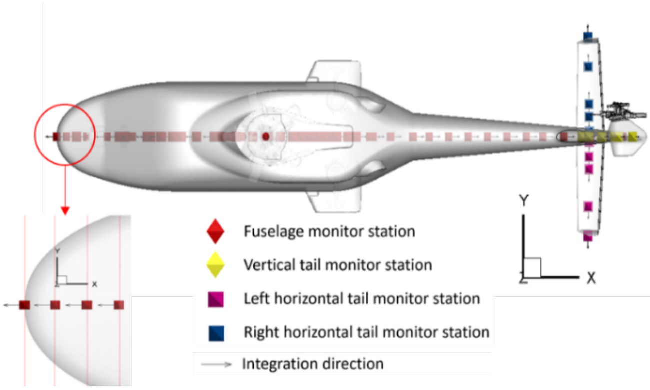

Figure 2. Calculation of Loads at Monitor Stations

Load Model Process

Pre-Process Before proceeding to the analysis, the model must first be set up. Fuselage, main rotor and tail rotor structural and aerodynamic properties are utilized to generate the model. Horizontal tail and vertical tails are modeled as aerodynamic surfaces and relevant aerodynamic coefficients are integrated into the model. To comply with the FLIGHTLAB format, pressure distributions are used to generate aerodynamic coefficient lookup tables as functions of angle of attack and sideslip angle. In addition to that, mass item properties are employed to compute the total mass, center of gravity, and inertia characteristics. Since the analyses are simulated by using varying total mass, center of gravity, and inertias, different models are set up.

Although, attaining detailed mass item information and pressure distribution are available at this stage, these values are stored for post-processing purposes, as FLIGHTLAB requires only the overall mass properties and aerodynamic tables to perform trim and dynamic simulations.

Analysis After the model is properly set up, the rotorcraft is trimmed at predefined flight conditions - for example, forward flight at 0.6 V_{NE} with zero sideslip. Following the trim, a dynamic simulation is performed. At each time step, FLIGHTLAB outputs such as main rotor forces and moments, resultant angle of attack, sideslip angle, angular rates, angular accelerations, and other relevant parameters are used to compute the total loads acting on the rotorcraft in the post-process.

Analysis Results & **Post-Process** Flightlab outputs are utilized to calculate both aerodynamic forces and inertial forces

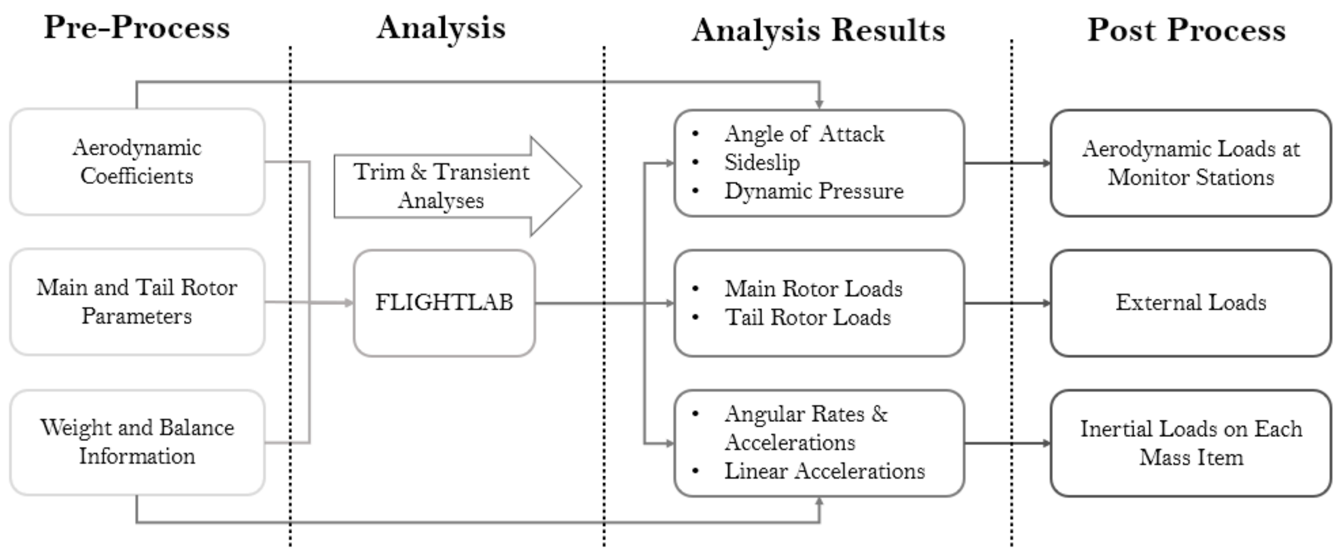

Figure 3. Load Process

at each monitor stations. Analyses are essential to obtain the dynamic pressure, sideslip and angle of attack values of each maneuver. Additionally, angular velocities, angular accelerations, and linear accelerations are attained to compute inertial loads at each item.

Aerodynamic pressure and mesh files are inputs to compute distributed aerodynamic loads at each monitor station. The aerodynamic mesh is divided according to the integration direction of each station, and the resulting pressure forces are transferred to the respective monitor stations to determine local aerodynamic loads. Simultaneously, rotor loads, which are directly provided by the FLIGHTLAB simulation, are treated as external loads. These rotor forces and moments are also transferred to the respective monitor stations for each time step. The final step involves combining the inertial, aerodynamic, and rotor loads at each monitor station to obtain the total load distribution across the airframe.

Yaw Simulation Techniques

In all approaches, rotorcraft is trimmed at any airspeed in level flight condition and full pedal is applied in each direction in a way that rise time does not exceed 0.2 seconds.

Technique 1 Unlike other methods, the first technique employs a full dynamic yaw simulation that completely bypasses the concept of "the line."

First, the rotorcraft is trimmed to a zero-sideslip condition. Then, a full pedal input is applied at 0.2 seconds. Once the rotorcraft's yaw angle stabilizes, the pedal input is reversed to return the aircraft to its initial trim condition. Simulation is completed when rotorcraft returned to zero sideslip condition.

Advantages of Technique 1:

- No optimization algorithm is necessary

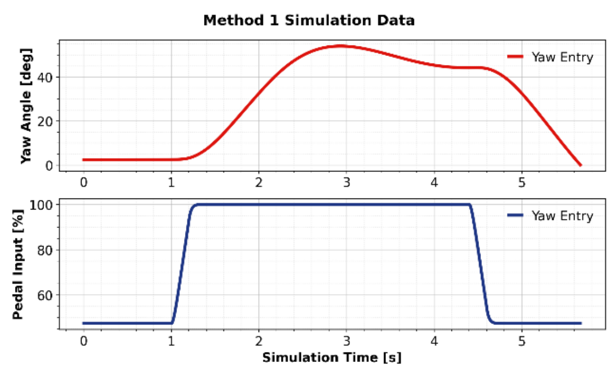

Figure 4. 1^{st} **Technique**

- The analyses are reasonably straightforward to perform and do not pose significant computational or implementation challenges.

Disadvantages of Technique 1:

- As it takes quite long time for some analyses to reach steady sideslip angles, simulation time is longer than other methods.
- A robust controller is required since pedal is pushed for a long time to the limits. Otherwise, pitch and roll angles deviates from trim conditions.
- At lower airspeeds (e.g., $0.6V_{NE}$) the simulation does not converge to steady-state angles, likely due to insufficient aerodynamic damping or prolonged transient behavior. This leads to longer simulation durations and, consequently, increased post-processing time.
- While the rotorcraft is trying to reach stabilized sideslip angle, at higher airspeeds, such as V_{NE}, the maximum achieved sideslip angle following full pedal ap-

plication exceeds the 15-degree limit specified in CS 27/29.351(c)(2), and therefore does not comply with the certification requirements.

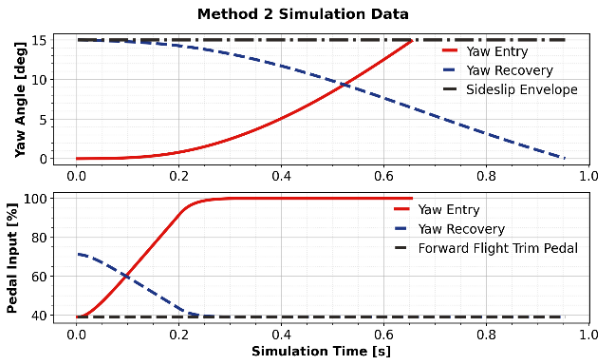

Figure 5. 2^{nd} **Technique**

Technique 2 The second technique consists of two phases: entry and recovery. The entry phase begins with a zero-sideslip trim and follows the same simulation approach, but ending at the point where "the line" is crossed. The second phase, called the recovery phase, starts with the sideslip angle at "the line" at the same entry airspeeds. At this point, a pedal input is applied to return the rotorcraft to a zero-sideslip condition. The maneuver ends once the rotorcraft has returned to zero sideslip.

Advantages of Technique 2:

- No optimization algorithm is necessary.
- Yaw entries are easy to accomplish
- Since analyses are cropped where it reaches zero for recovery and target sideslip for entry, analyses are quite short.
- The analyses are reasonably straightforward to perform and do not pose significant computational or implementation challenges.
- Although the rotorcraft loses airspeed when full pedal input is applied—causing the target sideslip angle to increase—this effect is negligible due to the short duration of the analysis.

Disadvantages of Technique 2:

- Return maneuver completed in 2 steps: Forward flight and Yaw return.
- At certain airspeeds, it is not possible to achieve the desired sideslip angles because the rotorcraft cannot be trimmed; the required main rotor control angles exceed their physical limits.

Technique 3 In the third technique, similar to the first method, the rotorcraft is trimmed at a zero-sideslip condition. A full pedal input is then applied at 0.2 seconds. When "the line" is crossed in the simulation, the pedal input is initiated to return the rotorcraft to the trim position. As the airspeed varies throughout the simulation, the corresponding sideslip angle also changes, as illustrated in Figure 5. During post-processing, all simulation time steps that fall outside the sideslip envelope are excluded.

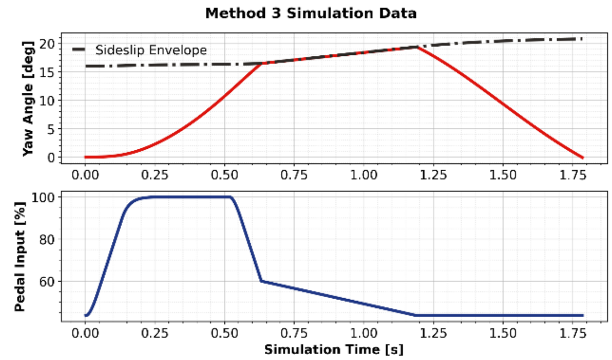

Figure 6. 3^{rd} **Technique**

Advantages of Technique 3:

- No optimization algorithm is necessary.
- Method is relatively easy.

Disadvantages of Technique 3:

- Return maneuver completed in 2 iterations.
- As rotorcraft bleeds airspeed as full pedal applied, target sideslip angle increases.

Technique 4 In the fourth technique, similar to the third method , the rotorcraft is trimmed at a zero-sideslip condition, and a full pedal input is applied at 0.2 seconds.

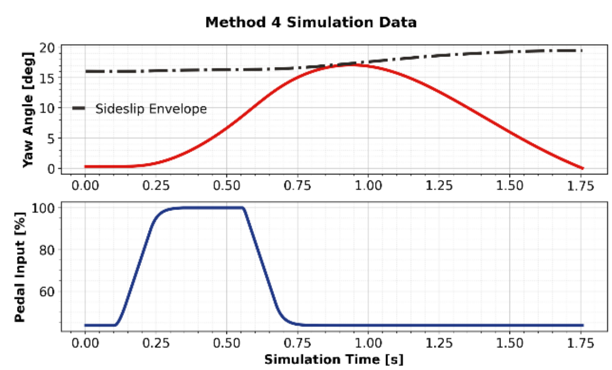

Figure 7. 4^{th} **Technique**

In this method, the total pedal input duration is optimized using the Python library skopt.gp_minimize, which performs Bayesian optimization based on Gaussian Processes. The objective function evaluates the deviation from the desired yaw response, and the optimization minimizes this deviation by adjusting the pedal input duration. Bounds for the duration are typically set between 0.41 and 4.0 seconds, with a cost function guiding the search. As the optimization tool explores different pedal input durations, the resulting airspeed and sideslip trajectories also change, making the target sideslip values dynamic and adding further complexity to the optimization process.

Advantages of Technique 4:

- Although it is classified as a limit maneuver, this method reflects the actual control input a pilot would apply when testing yaw loads, making it representative of real-world conditions.

Disadvantages of Technique 4:

- An optimization algorithm is necessary.
- In some cases, more than 15–20 optimization iterations are required to converge on the optimal pedal input, due to the sensitivity of the response and the nonlinearity of the system dynamics.
- As rotorcraft bleeds airspeed as full pedal applied, target sideslip angle increases.

RESULT AND DISCUSSION

Yaw maneuvers are conducted with 6 tones utility helicopter model. Load distributions of yaw maneuvers are compared as SFBM (Shear Force and Bending Moment) diagrams as explained in methodology section.

Results of this study are concluded under three main sections. In first section, load variation is observed by utilizing four different methods. In the second section load variation is observed for varying different airspeeds. Finally, in the third section load variation is observed for different weight and balance configuration. All techniques are investigated for all airspeeds and for all weight and balance configurations.

Vertical fin and fuselage SF&BM diagrams are investigated, separately. It is observed that the vertical fin and fuselage respond similarly to dominant parameters and their influences on structural loading. Therefore, for a brief evaluation this paper contains only fuselage SF &BM diagrams. Should further detail be required, supplementary figures and analysis results concerning the vertical fin are also available.

Before comparing the effects of different techniques, airspeeds, and mass configurations on loads, it is essential to identify the dominant load contributions on both the upper and lower sides of the SF&BM diagram.

Figures 8 and 9 indicate the dominant loads on the upper and lower sides, respectively. As observed, the loads on the lower side exhibit higher magnitudes compared to those on the upper side. Consequently, the load comparison primarily focuses on the lower side.

Figure 9 reveals that, throughout the yaw maneuver, inertial loads remain relatively minor across all monitoring stations, as expected. This indicates that aerodynamic loads are the primary contributors. Therefore, parameters such as airspeed and aerodynamic coefficients play a more critical role in yaw maneuver load analysis.

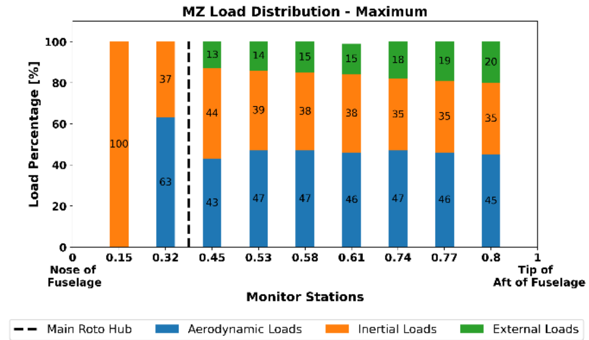

Figure 8. Dominant Loads during Yaw Maneuver (upper-side)

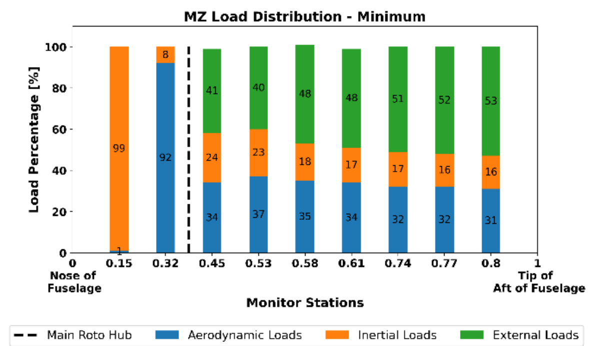

Figure 9. Dominant Loads during Yaw Maneuver (lower-side)

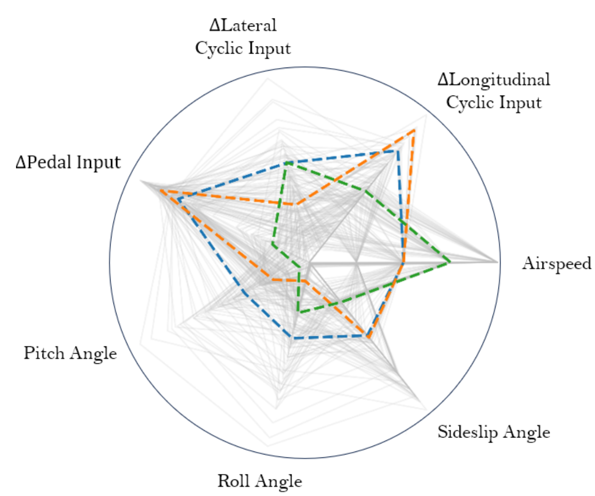

Figure 10. Dominant Parameters - 1

Figure 10 radar chart illustrates the relationship between pilot control inputs and the helicopter's flight state during of simulated yaw maneuvers for all cases for Technique 4, as all techniques showed similar results in terms of critical loading conditions only one technique is used for this evaluation method. The grey lines represent all simulated cases, while the colored dashed lines highlight the most critical scenarios. The overall trend shows a dense clustering of grey lines toward the Pedal axis, confirming that pedal input is the dominant factor in yaw control. The critical cases—represented by the orange, blue, and green lines—share distinct characteristics. All involve very large pedal inputs, indicating that these maneuvers push the yaw control system to its limits. Additionally, they consistently occur at higher airspeeds, where aerodynamic forces are more significant. Notably, the orange and blue cases also show substantial Lateral Cyclic and Longitudinal Cyclic inputs, suggesting that these extreme yaw maneuvers require coordinated cyclic control to counteract induced rolling and pitching moments. Interestingly, the most critical scenarios do not result from the highest sideslip angles alone, but rather from the combination of moderate-to-high sideslip and high airspeed, which together create the most demanding structural and control conditions. In summary, the most critical yaw scenarios are those performed at high airspeeds with maximum pedal input, often accompanied by significant cyclic input to maintain aircraft stability and control.

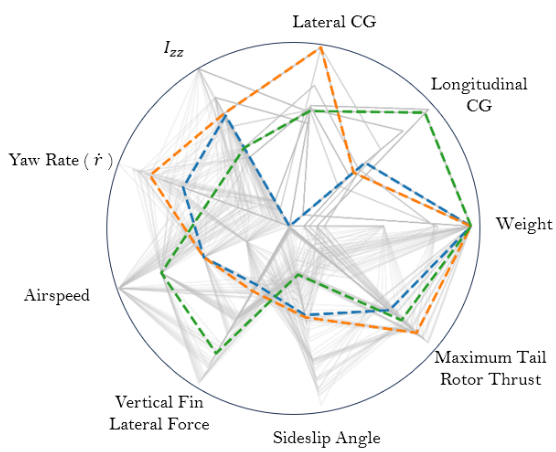

Figure 11. Dominant Parameters - 2

Figure 11 relates the helicopter's design and loading parameters to its weight and balance information, Airspeed, Vertical Fin force, resultant yaw rate and maximum tail rotor thrust. Similarly, critical cases represented by the colored lines. These cases are characterized by high weight, high airspeed, a forward CG, and the tail rotor operating at or near its maximum thrust capacity. Among these factors, the forward CG plays a particularly important role. A forward CG increases the helicopter's directional stability by extending the moment arm between the CG and the vertical fin. During yaw or sideslip maneuvers, the aerodynamic force on the fin produces a stronger restoring moment that resists the yaw motion. While this stabilizing effect is beneficial in steady flight, it presents a challenge during aggressive yaw maneuvers, as the tail rotor must counteract this increased restoring moment. As a result, the pilot's pedal input demands higher tail rotor thrust to achieve the desired yaw rate. Lateral CG position also affects loading, primarily by altering the roll moment arm and requiring small compensatory cyclic inputs, but its impact is much less significant compared to longitudinal CG. In conclusion, the chart shows that the most critical yaw scenarios arise when the helicopter is operating at high speed, high weight, and a forward CG, creating a condition where maximum tail rotor thrust is most critical structural conditions.

Comparison of Different Methods

In this section for each method, all analyses are cumulated to visualize overall critics for each method.

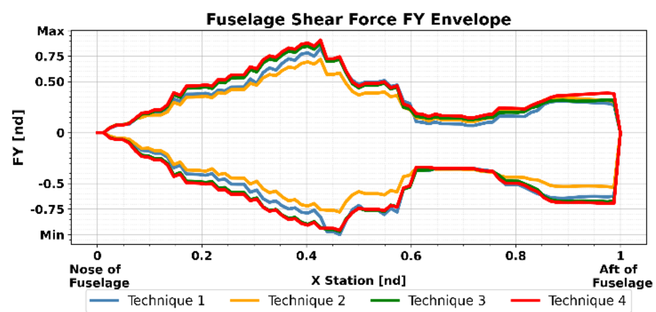

Figure 12. Comparison of Techniques on SF Diagram

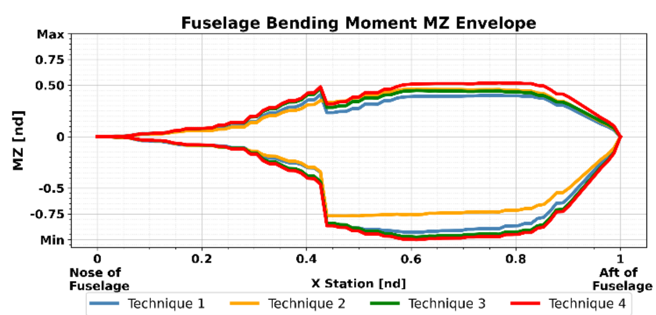

Figure 13. Comparison of Techniques on BM Diagram

Figures 12 and 13 illustrate how the fuselage shear force and bending moment distributions vary along the length of the fuselage for each technique. To allow for a direct comparison, all values in the figures are normalized with respect to the absolute maximum value observed among all techniques. It is clear that Technique 4 produces the highest shear force and bending moment values, both on the upper and lower sides of the diagrams in Figures 12 and 13. This indicates that Technique 4 imposes the most severe loading conditions on the fuselage structure. In contrast, Technique 2 results in the lowest values across the entire fuselage, suggesting a more benign loading profile. These differences high-light how each yaw maneuver technique influences the structural response of the rotorcraft.

As explained in the methodology section, the simulations for Technique 2 are significantly shorter compared to the other techniques. As a result, there is not enough time for angular rates and angular accelerations to fully develop, which leads to lower inertial load contributions. Although there are some minor differences among the remaining three techniques, these variations are not substantial. Therefore, they can be considered interchangeable for most load estimation purposes.

Comparison of Different Airspeeds

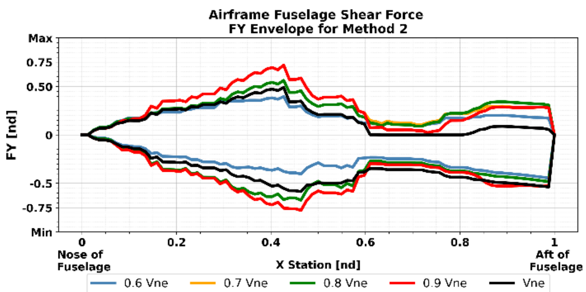

Figure 14. Comparison of Airspeeds on SF Diagram (2^{nd} Technique)

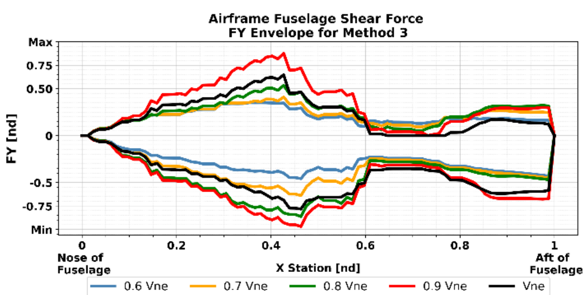

Figure 15. Comparison of Airspeeds on SF Diagram (3^{rd} Technique)

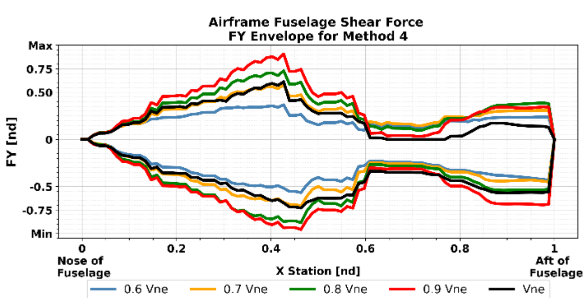

Figure 16. Comparison of Airspeeds on SF Diagram (4^{th} Technique)

Since the aft fuselage is identified as the critical region in terms of structural loading, the focus is placed on the load behavior in this section. For each airspeed and technique combination, the most critical condition corresponds to the one that produces the highest shear force or bending moment in the aft fuselage. These critical cases are summarized below:

For Technique 2:
Upper side on the diagrams: 0.8 V_{NE}
Lower side on the diagrams: 0.9 V_{NE} and V_{NE}

For Technique 3:
Upper side on the diagrams: 0.8 V_{NE}
Lower side on the diagrams: 0.9 V_{NE}

For Technique 4:
Upper side on the diagrams: 0.8 V_{NE}
Lower side on the diagrams: 0.9 V_{NE}

For each methodology, the lower side of the shear force and bending moment diagrams reaches its peak at 0.9 V_{NE} on the upper side, 0.8 V_{NE} results in the maximum values for all methods except the second one. These results indicate that the most critical loading condition occurs when both high sideslip and high airspeed are present simultaneously. This combination leads to the most severe structural response, particularly in the aft fuselage region.

Comparison of Different Weight and Balance Configurations

As mentioned before, aerodynamic loads are the dominant loads for yaw maneuver. It was expected that different weight and CG configurations have not significant effect on loads. However, it is seen that in Figure 17 the loads of analyses by using maximum weight configurations are the highest loads.

CG is the another parameter that is considered as having a minor effect on the loads throughout the yaw maneuver. CG comparison is performed by investigating the maximum loads obtained at each airspeed under the maximum TOW configuration. To ensure that the comparison reflects only the influence of CG, the total mass remains constant while varying only the CG position. The entire range of airspeeds is swept, and for each CG location, the most critical load condition is identified and plotted. When Figure 18 and 19 are evaluated, it is observed that front CG has a major effect on loads however, lateral CG effect remains insignificant.

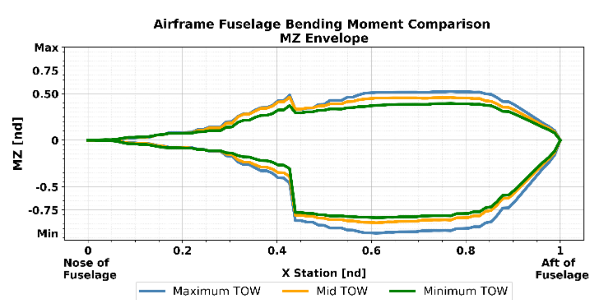

Figure 17. Comparison of Loads in Terms of Total Mass

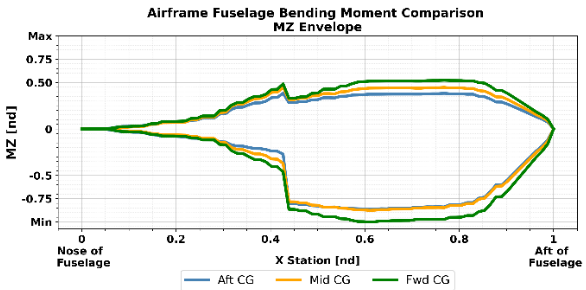

Figure 18. Comparison of Loads in Terms of Longitudinal CG

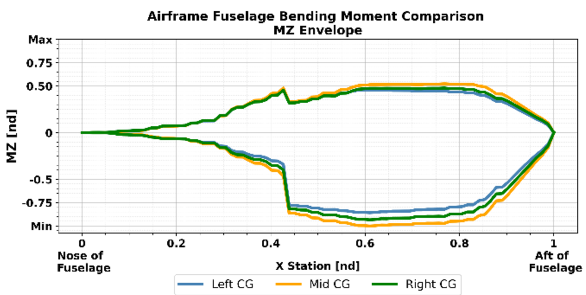

Figure 19. Comparison of Loads in Terms of Lateral CG

For each method and weight configuration, the critical condition corresponds to the case that generates the highest loads in the aft fuselage. For all methods, these conditions have the same trend for both upper and lower sides of the SF & BM diagrams:

$$MaximumWeight > MidWeight > MinimumWeight \quad (1)$$

This load trend clearly shows that increased weight significantly affects inertial loads. Heavier configurations require greater main and tail rotor forces to maintain trimmed flight, leading to higher force and moment inputs to the fuselage. Although the larger mass results in smaller angular and linear accelerations during maneuvers, these configurations generally have high moments of inertia, which still lead to notable inertial effects.

Applicability of "the line"

Throughout the analyses and across all methods, the rotorcraft was simulated at various airspeeds, each corresponding to a different sideslip angle as defined by "the line." Regardless of the technique used, at low airspeeds—such as 0.6 V_{NE}—this sideslip boundary is almost never reached. It becomes reachable only in certain cases where full pedal input causes the helicopter to bleed off enough airspeed. Additionally, since the final value of "the line" (15 degrees) is defined relative to either V_{NE} or V_H, whichever is lower, the definition of the line varies between configurations. However, intermediate points—such as 0.8 V_{NE}—do not simply become 0.8 V_H when V_H is significantly different from V_{NE}. In such cases, the slope of the line changes, which can lead to an lower resultant loads when compared to using a line based on V_{NE}.

CONCLUDING REMARKS

1. Technique 4 yields the highest structural loads on the fuselage. Techniques 1 and 3 show similar results to Technique 4 but slightly lower values, while Technique 2 produces the lowest loads due to its shorter simulation time and limited development of inertial effects. Although Techniques 1, 3, and 4 are largely interchangeable for load estimation, Technique 1 does not comply with CS 29.351, as noted in the Methodology section.

2. The most critical structural loads in the aft fuselage occur when high sideslip and high airspeed coincide typically at $0.9V_{NE}$ for the lower side and $0.8V_{NE}$ for the upper side of the shear force and bending moment diagrams. An exception is observed for Technique 2, where the peak load on the upper side occurs at a highest airspeed due to differences in trim and simulations.

3. Heavier weight and forward CG configurations consistently produce the highest aft fuselage loads across all methods, due to increased rotor forces and higher moments of inertia, while the effect of lateral CG remains insignificant by comparison.

4. Across all methods, the rotorcraft was tested at various airspeeds linked to sideslip limits defined by "the line," but at low speeds (e.g., 0.6 V_{NE}) this boundary is rarely reached, and when V_H differs significantly from V_{NE}, the change in the line's slope can lead to lower loads compared to using a V_{NE}-based definition.

Author contact:

Emre TAŞ emre.tas@tai.com.tr
Yağmur Bulut yagmur.bulut@tai.com.tr

REFERENCES

1. Avampato, D., and Kelly, S., "The Yaw Return Maneuver – The Regulatory History, Future, and Impact on Structural Design Loads," in *Proceedings of the 65th American Helicopter Society International Annual Forum*, Structures & Materials Session, May 2009.

2. European Union Aviation Safety Agency, " Easy Access Rules for Large Rotorcraft (CS29)," Amendment 11, 7 December 2023. [Online]. Available: [EASA Easy Access Rules for Large Rotorcraft (CS29)][Accessed: 27 July 2025].

3. United States Department of Transportation, Federal Aviation Administration, "AC29 2C –Certification of Transport Category Rotorcraft (Changes 1–9 incorporated)," Advisory Circular, Washington, DC, 30 September 1999. DOI:10.21949/1514566 [Online]. Available: FAA Advisory Circular [Accessed: 27 July 2025].

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