# Automated Evaluation of Handling Qualities and Performance for Preliminary Aircraft Design Using Flight Simulation Models

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## Abstract

In preliminary aircraft design, primary and secondary control surfaces are sized by estimating their impact on performance, stability and controllability using heuristic, semi-empirical handbook methods (HBM). Those methods deliver results of low precision. More accurate results are achieved later during the detailed aircraft design process. At that stage, it becomes increasingly difficult and expensive to make significant design changes to control surfaces. Therefore improved evaluation methods for preliminary aircraft design become important. Such methods require a flight mechanical model, i.e. a nonlinear aircraft simulation model with flight control laws, to assess the influence of the control surfaces on handling qualities and performance in the preliminary aircraft design with much higher precision than with currently used methods. For the assessment, a set of criteria is defined. The criteria cover stability and controllability of longitudinal and lateral motion, the flight performance in all low speed flight phases and the determination of reference speeds. The criteria values are computed by various numerical methods including flight simulations that mimic certification flight tests defined in FAR-AC 25-7. This paper describes the method and its application to a typical midrange aircraft, for which two alternative high-lift systems are investigated. The software tool Multiobjective Evaluation of Preliminary Aircraft Designs (MITRA) is described. It allows controlling the aircraft simulation in an automated process and applying the evaluation of the criteria to it. Results from a take-off evaluation are presented to discuss the advantages of the proposed method.

## Nomenclature

*Symbols*

| | | |
|---|---|---|
| $BPR$ | Bypass ratio of the engines | [-] |
| $C_D$ | Drag coefficient | [-] |
| $C_{D_0}$ | Drag coefficient at $\alpha = 0$ | [-] |
| $C_L$ | Lift coefficient | [-] |
| $d$ | Ground distance | [m] |
| $D$ | Drag force | [kg·m/s$^2$] |
| $g$ | Gravitational acceleration | [m/s$^2$] |
| $h$ | Height | [m] |
| $m$ | Mass | [kg] |
| $q$ | Pitch rate | [°/s] |
| $S$ | Reference surface wing area | [m$^2$] |
| $t$ | Time | [s] |
| $T$ | Thrust force | [kg·m/s$^2$] |
| $V$ | Velocity | [kts] |
| $\alpha$ | Angle-of-attack | [°] |
| $\gamma$ | Flight path angle | [°] |
| $\Theta$ | Pitch angle | [°] |
| $\mu$ | Ground friction coefficient | [-] |
| $\rho$ | Air density | [kg/m$^3$] |

*Acronyms*

| | |
|---|---|
| AC | Advisory Circular |
| CFD | Computational Fluid Dynamics |
| CS | Certification Specification |
| EASA | European Aviation Safety Agency |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulations |
| FEM | Finite Element Method |
| FM | Flight Mechanics |
| HBM | Handbook Methods |
| MIL | Military |
| MITRA | Multiobjective Evaluation of Preliminary Aircraft Designs |
| P. | Percentage |
| PE | Percentage Error |
| Seg. | Segment |

*Superscripts*

| | |
|---|---|
| $\dot{}$ | Time derivation |
| $\bar{}$ | Mean value |

*Subscripts*

| | |
|---|---|
| CAS | Calibrated Airspeed |
| LOF | Liftoff |
| R | Rotation |
| TO | Take-off |
| MAX | Maximum |
| MCG | Minimum Control Speed on Ground |
| MCL | Minimum Control Speed during Approach and Landing |
| MU | Minimum Unstick |

## 1 INTRODUCTION

With the growth of air traffic in the next decades, the demand for new aircraft increases, [1]. The market expects that new aircraft are more fuel efficient, are operating at lower costs and have less emissions than current ones, [2]. It is also expected that aircraft will have to fly more complex departure and approach flight paths with higher precision, due to stricter noise regulations. For example, the city airport in London, UK requires aircraft to land with an approach glide path angle of $\gamma_{APP}$ = -5.5°, instead of the usual $\gamma_{APP}$ = -3° in order to fulfil the city's noise regulations and to avoid obstacles, [3]. For satisfying such requirements with future aircraft designs, new control surface configurations, e.g. leading and trailing edge flaps, are considered.

Control surfaces are required for controlling aircraft attitude, speed, and flight path. They are distinguished as primary and secondary control surfaces. The conventional primary control surfaces are ailerons (and roll spoilers), elevators and the rudder, while the conventional secondary control surfaces are slats, flaps and spoilers when used as airbrakes (refer to Figure 1).

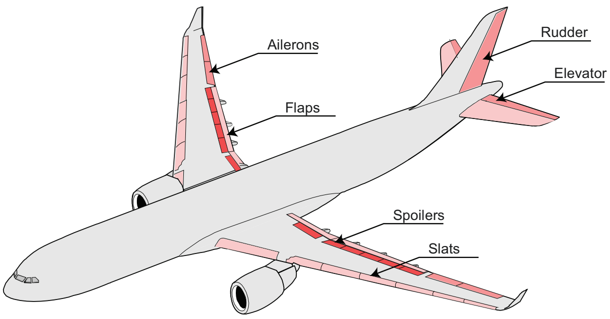


Figure 1: Control surfaces on a typical transport aircraft

The control surfaces are developed during the aircraft design process, which can be separated into three major phases: the conceptual aircraft design phase, the preliminary aircraft design phase and the detailed aircraft design phase. During the conceptual phase the primary requirements, such as payload capabilities, range and cruise speed, are specified. In the preliminary phase, the required aircraft systems are outlined and developed. This includes sizing of the control surfaces by taking into account the flight mechanical requirements regarding stability and controllability, handling qualities as well as take-off, cruise and landing performance of the aircraft. Currently, the flight mechanical properties are estimated by semi-empirical handbook methods in the early design phases, as described in [4] or [5]. Detailed flight mechanical assessments are conducted in the detailed aircraft design phase, when sufficient data are available.

Regarding current and future handling qualities and performance requirements, it is important that the control surfaces ensure the achievement of the desired characteristics. It is also important to investigate the impact of variations of control surface designs as early as possible, because while advancing in the aircraft design process, the freedom to apply design changes decreases and the corresponding costs progressively increase. Therefore, a need to predict the effect of control surface design variations early in the preliminary aircraft design with a high accuracy arises. This in-depth examination is not possible with the currently used handbook methods. Especially the investigation of unconventional designs is not possible, because they rely on semi-empirical factors based on conventional designs. Furthermore, some stability and control requirements as well as new requirements regarding take-off, approach and landing procedures cannot be investigated at all with them. In order to overcome the drawbacks of current methods, more sophisticated flight mechanical analysis methods are needed for the preliminary aircraft design phase.

This paper proposes a method, where predefined simulated flight tests are conducted and evaluated with criteria derived from civil and military regulations in an automated process. The software tool MITRA has been developed for the application of this method (refer to Figure 2). It generates all necessary data for conducting simulated flight tests with a flight simulation model of the investigated aircraft.

With aerodynamic data computed by numerical methods, such as CFD, it is possible to develop an aircraft simulation model in the preliminary aircraft design phase. MITRA analyses steady flight conditions as well as dynamic aircraft responses to determine flight mechanical characteristics, which are then evaluated by the criteria concerning performance and handling qualities defined in a criteria catalogue. MITRA and the criteria catalogue are designed modularly. They can easily be modified and expanded by new criteria for any type of aircraft simulation model. The results of the flight mechanical evaluation are presented in an automatically generated test report.

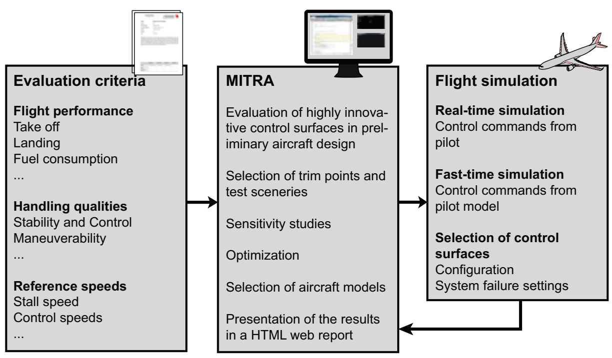


Figure 2: Tool chain for the model based investigation of flight mechanical and performance criteria

A similar evaluation method is investigated by the German Aerospace Research Centre (DLR) that developed the tool MAPET II for this purpose, [6]. It estimates performance parameters for various flight phases: take-off, landing, climb, descent and cruise by using a nonlinear flight simulation. MAPET II automatically generates control commands and simulates flight manoeuvres, that are assessed by criteria from [7]. For the evaluation of handling qualities, the DLR uses the software tool HAREM [8].

This paper introduces first the criteria catalogue and then the software tool MITRA. To demonstrate the benefits of MITRA, the take-off performance for a flight simulation model is investigated. The results are then compared to results from handbook methods and discussed.

## 2 CRITERIA CATALOGUE

The criteria used in MITRA derive from certification specifications, aircraft requirements and from operational requirements, such as those for approaches to London City Airport. Civil certification specifications are issued by the European Aviation Safety Agency (EASA) in the EASA “Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25” specification [7] and by the American Federal Aviation Administration (FAA) in the “Federal Aviation Regulations Airworthiness Standards: Transport Category Airplanes Part 25” specification [9]. Both specifications have only minor differences. At the final stage of the aircraft development process, flight tests are conducted to demonstrate the fulfilment of certification requirements. Those flight tests are defined in the FAA “Advisory Circular (AC) 25-7C” document [10]. This document describes the required conditions of each flight test, including the initial trim states, such as altitude, airspeed, aircraft mass and centre of gravity location.

The software tool MITRA uses criteria from the specifications to evaluate the flight mechanical impact of control surfaces. The applicable criteria are extracted and compiled in a criteria catalogue. As the civil requirements are relative vague in terms of handling qualities, criteria from the military specifications “Flying Qualities of Piloted Airplanes” (MIL-HDBK-1797) [11] are used in addition.

Beside those certification requirements, performance criteria for conventional take-off, landing and go-around manoeuvers are included. The criteria catalogue is divided into four different sections containing the following criteria:

- Performance:
  - Take-off,
  - Landing, and
  - Landing climb.
- Stability and Control – Longitudinal:
  - Damping and frequency of the short period motion,
  - Control Anticipation Parameter (CAP),
  - Phugoid stability,
  - Longitudinal static stability,
  - Flight path stability,
  - Loss of altitude during go-around,
  - Stall recovery, and
  - Flap position changes without trim changes.
- Stability and Control – Lateral:
  - Damping and frequency of the Dutch roll motion,
  - Spiral stability,
  - Static directional stability,
  - Roll mode time constant,
  - Roll time delay,
  - Coupled roll spiral oscillation,
  - Roll control performance,
  - Turn performance with engine failure,
  - Directional control with engine failure,
  - Full rudder sideslip, and
  - Steady straight sideslip.
- Speed:
  - $V_{SR}$ reference stall speed,
  - Speed range,
  - $V_{MCG}$ minimum control speed on the ground
  - $V_{MCL}$ minimum control speed during approach and landing, and
  - $V_{MU}$ minimum unstick speed.

The first category ‘performance’ evaluates the aircraft performance during take-off, landing and go-around. The performance during those flight phases is usually estimated using simplified physics and semi-empirical methods in the preliminary aircraft design phase, see [12]. The second and third category cover longitudinal and lateral stability properties. The fourth category ‘speed’ contains criteria that address characteristic low speeds, e.g. $V_{MCL}$, of the aircraft. Each criterion definition in the MITRA criteria catalogue consists of the six sections listed in TAB 1.

| |
|---|
| **Section 1: General description**<br>The criterion and the underlying rationale are described. If the original criterion is modified, additional information is provided. |
| **Section 2: Mathematical description**<br>All required equations for computing the criterion are listed in this section. |
| **Section 3: Required software**<br>The software tools that are required for the evaluation of the criterion are listed in this section. Usually MITRA and the nonlinear flight simulation are the only required tools. Some stability and control criteria additionally require certain MATLAB toolboxes. |
| **Section 4: Range of validation**<br>All start trim points for the simulated flight tests are defined in this section. |
| **Section 5: Required data**<br>Each flight mechanical parameter that is required for the evaluation of a criterion is listed in this section. |
| **Section 6: Procedure / flight test**<br>The proposed test procedure necessary for the assessment of the criterion are described. The test procedures derive from [10]. |

TAB 1: Criterion description structure

So far, the catalogue comprises mainly criteria for low speed characteristics. In the future it will be expanded by criteria for high-speed flight including cruise and with criteria concerning more complex landing and take-off procedures, for example to address future noise abatement requirements.

## 3 MITRA

The software tool MITRA defines the necessary data for the simulated flight tests, starts the simulation, evaluates and presents the results in an automated process (refer to Figure 3).

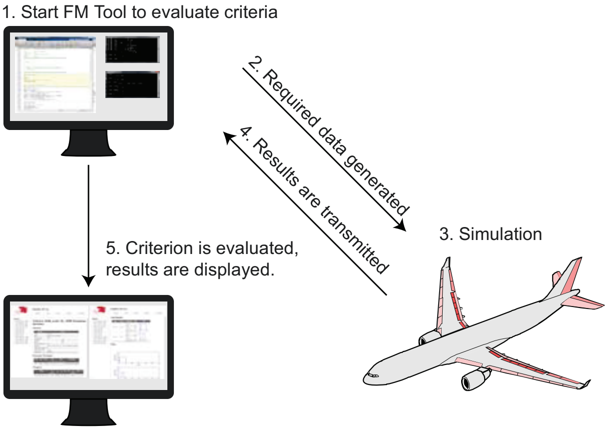


Figure 3: MITRA workflow

Its main function is the automatic evaluation of aircraft simulation models by applying the criteria defined in the catalogue. The only required user inputs are the provision of an aircraft simulation model and the set of criteria, which shall be investigated. With that information, the tool runs autonomously and documents the results in a HTML test report. The tool is programmed in MATLAB under object oriented paradigm to allow easy implementation of new criteria, interfaces to simulation models and of additional features in the future.

MITRA requires a nonlinear flight simulation for each aircraft model that shall be investigated. For that, at least aircraft geometries, mass data and aerodynamic coefficients of the aircraft as well as system parameters, e.g. control surface deflection rate, have to be available. As almost all modern commercial transport aircraft have an electronic flight control system, flight control laws are needed as well. The validity of the criterion results depends on the fidelity of the provided aircraft data. To automatically conduct flight simulations, an interface between the MITRA tool and the investigated flight simulation model is required. It shall accept control commands from either predefined stimuli from a control command generator (such as impulse, step, sweep etc.), or accept pilot models to control the simulation dynamically. An additional interface is required to export simulation results, such as time traces of pitch, bank and yaw angle. All required time traces for each criterion are defined in the criterion catalogue.

Figure 3 clarifies the interaction between the tool and the simulation program. When a user selects the desired aircraft simulation model and criteria, initial data and input signals for the simulation are generated and simulations are performed. After each simulation run, recorded flight mechanical data are transmitted to MITRA, which evaluates the data and starts the next simulation run, until all test cases are investigated. The results are presented in a HTML test report. MITRA is capable of comparing different aircraft models or aircraft variants (e.g. the same basic aircraft, equipped with different control surface types).

Figure 4 shows the software structure of MITRA. It consists of six different modules, with each being exchangeable. All modules except for the simulation interface are completely independent of the investigated flight simulation model. Therefore, only the simulation module has to be adapted, when a new aircraft model shall be investigated. Each module is described below.

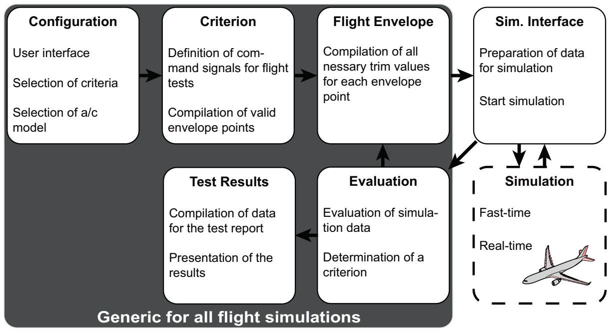


Figure 4: Different modules of MITRA

### Configuration

This module is initialized when starting MITRA. It is the main user interface of the program. The user can interact with it by defining aircraft simulation models and criteria in a MATLAB script file. In the default configuration, all valid envelope points of a criterion will be investigated. It is possible to evaluate a subset of the valid envelope points as well.

### Criterion

This module generates the initial parameters and control commands for the aircraft simulation. Pilot models are defined in SIMULINK block diagrams. For the usage with simulation environment other than MATLAB, an interface for the automatic export to C-code is available.

### Flight Envelope

Depending on the selected set of criteria, a list of the start flight envelope points is generated in this module.

### Simulation Interface

The interface converts the output data of MITRA into the data format of the simulation. For example, initial parameters can be exported as text files. Then, the simulation is started. After a simulation, this interface converts the output data of the simulation into a data structure of MITRA. If a simulation was not completed successfully, the simulation interface skips that test point and continues with the next one, while notifying the user with a warning message.

### Evaluation

The simulation interface passes the required data for the evaluation of the criterion to this module. Here, the algorithm described in the criteria catalogue for the specific criterion is applied. The results are saved in a predefined data structure. After the evaluation, the flight envelope module is called to proceed with the next test point until all test points are investigated. After that, the program proceeds with the execution of the Test Results module.

### Test Results

This module saves all, i.e. input and output data of the simulation and all computed criteria values. The data can be viewed in the automatically generated HTML test report (refer to Figure 5).

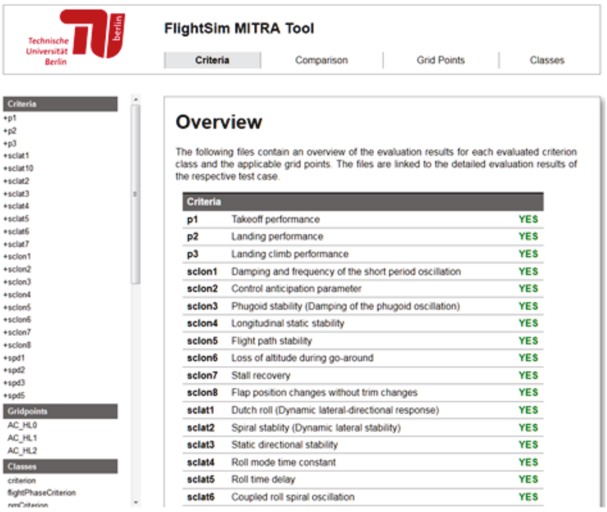


Figure 5: Start page of the test report

The report consists of four parts, which can be selected in the top menu and on the left side drop down menu and are defined as:

- Criteria – informs which criterion has been evaluated and contains the result pages for each investigated criterion,
- Comparison – shows plots of the computed parameter values of all envelope points and aircraft models for a specific criterion,
- Grid Points – shows all valid start grid points for each investigated aircraft type and
- Classes – contains the software documentation of MITRA.

## 4 EXAMPLE: TAKE-OFF CRITERION

As stated, the flight mechanical assessment of control surface design variations early in the preliminary aircraft design needs to be more accurate. By using more sophisticated models and data than handbook methods, MITRAs assessment methods fulfil the needs. For a demonstration of MITRA's capabilities, the take-off run performance of three variants of a typical 150 mid-range aircraft with two engines is investigated and results are compared to handbook methods.

Each aircraft variant is equipped with one of the following high-lift systems (HL):

- HL0 – the reference high-lift system similar to the configuration shown in Figure 1,
- HL1 – first alternative high-lift system, which produces more lift and less drag than HL0 in all deflection settings and
- HL2 – second alternative high-lift system, which can produce more or less lift than HL0 depending on the flaps deflection.

All three high-lift systems have the same two take-off deflection settings.

The take-off run (see Figure 6), as defined in CS 25.113 [7], begins from a standing start on the runway. At that point and with released brakes, the throttle levers are moved from the idle position to the maximum take-off thrust $T_{TO}$ position. After setting the thrust, the aircraft begins to accelerate. First, the aircraft reaches the minimum unstick speed $V_{MU}$, the lowest speed at which the aircraft can safely lift off with the highest thrust setting and the maximum possible pitch angle on ground. While still accelerating, the aircraft reaches the rotation speed $V_R$, at which the pilot begins to rotate the aircraft for acquiring the lift-off pitch angle $\Theta_{LOF}$. The aircraft lifts off when it achieves the lift-off speed $V_{LOF}$. Then the aircraft begins to climb. The take-off run ends when the aircraft achieves a radio height of 35 ft and the minimal take-off climb speed $V_2$. The travelled ground distance is $d_1$.

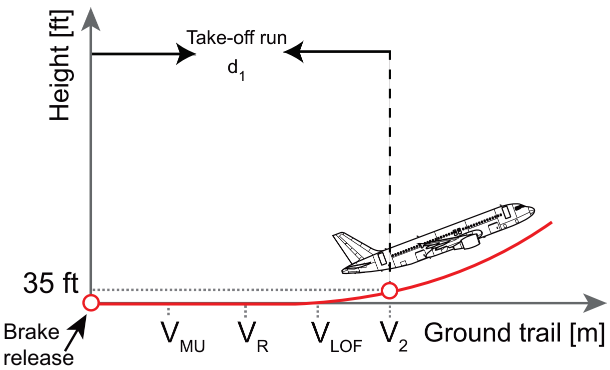


Figure 6: Take-off run

For the take-off run performance assessment, twelve test cases are investigated with following varying parameters (see TAB 2):

- Three mass settings $m_{1\text{-}3}$, with the relationship : $m_3 > m_2 > m_1$,
- Two HL take-off settings $TO_{1\text{-}2}$ (in $TO_2$ the flaps and slats are more deflected than in $TO_1$) and
- Two centre of gravity locations: most forward and most aft, which both depend on the mass setting.

| Test case # | Mass Setting | High-lift Setting | centre of gravity position |
|---|---|---|---|
| **1** | $m_1$ | $TO_1$ | most forwards |
| **2** | $m_1$ | $TO_2$ | most forwards |
| **3** | $m_1$ | $TO_1$ | most aft |
| **4** | $m_1$ | $TO_2$ | most aft |
| **5** | $m_2$ | $TO_1$ | most forwards |
| **6** | $m_2$ | $TO_2$ | most forwards |
| **7** | $m_2$ | $TO_1$ | most aft |
| **8** | $m_2$ | $TO_2$ | most aft |
| **9** | $m_3$ | $TO_1$ | most forwards |
| **10** | $m_3$ | $TO_2$ | most forwards |
| **11** | $m_3$ | $TO_1$ | most aft |
| **12** | $m_3$ | $TO_2$ | most aft |

TAB 2: Test case definitions

In this example, following three performance parameters are investigated:

- The minimum unstick speed $V_{MU}$,
- The lift-off speed $V_{LOF}$ and
- The take-off run distance $d_1$.

MITRA performs two different simulation runs for the assessment. For both simulation runs, the same initial conditions are used. The only difference is the configuration of the pilot model, which commands different control signals in both simulation runs. It shall be noted that the control gains for both control strategies are constant. They are not adapted to the different test cases (1-12).

The first simulation run determines (only) the speed $V_{MU}$. The pilot model increases the aircraft's attitude in the acceleration process on the runway to the maximum possible pitch angle. The target is to have ground contact with the aircraft's tail until the aircraft lifts off. The speed at that point is $V_{MU}$. As required in CS 25.107 [7], only the test cases with most forward centre of gravities (test case 1, 2, 5, 6, 9 and 10) are investigated. The determined speed $V_{MU}$ is used to calculate the rotation speed $V_R$ (see Equation 3 in Section 4.2) for the second simulation run.

In the second simulation run the conventional take-off procedure according to CS 25.113 is performed for calculating $V_{LOF}$ and $d_1$. The lift-off speed $V_{LOF}$ is determined when the main gear loses ground contact. For the "most aft centre of gravity" test cases, the calculated $V_R$ speeds from the corresponding "most forward centre of gravity" are used. Here $V_R$ is assumed to be independent from the centre of gravity location.

In the next subsection, the results of MITRA's calculation and the results of the handbook methods are investigated and compared.

## 4.1 MITRA results

Figure 7 shows the results of the performed (six for the determination of $V_{MU}$ and twelve for $V_{LOF}$ and $d_1$) simulations. In the left column, the results for each aircraft variant is shown. In the right column, the percentage change of the results from HL1 and HL2 in comparison to the results from HL0 are shown. The baseline reference is marked as a red line.

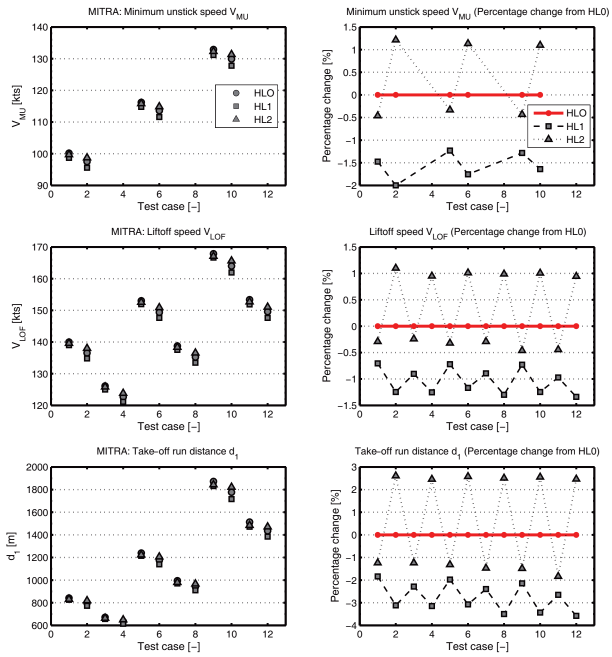


Figure 7: Take-off performance calculated with MITRA

First, the left column is inspected. After every fourth test case, the take-off weight is increased. As expected this causes higher take-off speeds and take-off run distances. For each weight setting, the initial high-lift and centre of gravity are varied. With the higher high-lift setting $TO_2$, the aircraft takes off at a lower speed and it has a lower take-off run distance. With aft centre of gravities, the aircraft takes off at a lower speed and has lower take-off run distance. The aircraft is able to rotate much faster in those test cases.

The right column shows that in comparison to the aircraft HL0, the variant HL1 has lower take-off speeds (~ 0.6 – 2 % less) and less take-of run distances (~ 1.9 – 3.8 % less). HL1 can take off on shorter runways, use less take-off thrust or may carry more payload in comparison to HL0.

The variant HL2 with high-lift setting $TO_1$ has lower take-off speeds (~ 0.3 – 0.5 % less) and achieves lower take-off distances (~1 – 1.3 % less). With high-lift setting $TO_2$ on the other hand, the calculated performance values are higher than to the results for HL0. HL2's take-off performance is better in $TO_1$ and worse in $TO_2$ than the one of HL0.

## 4.2 Handbook methods

The handbook methods, described in [4] and [5], depend either on heuristic semi-empirical equations or on simple flight mechanical equations. First the minimum unstick speed $V_{MU}$ is determined. For this, following assumptions are made:

$$(1) \qquad \gamma = \Theta - \alpha = 0 \quad \text{and} \quad \alpha_{MU} = \Theta_{MU} \quad ,$$

where $\gamma$ is the flight path angle, $\Theta$ the pitch angle and $\alpha$ the angle-of-attack.

With the assumption that the aircraft is geometrically limited (the maximum "pitch angle on ground" limitation relates to the length of the fuselage), $\Theta_{MU}$ can be derived from the aircraft geometry. The lift coefficient $C_{L_{MU}}$ is a function of $\alpha_{MU}$. With this information, $V_{MU}$ can be computed by:

$$(2) \qquad V_{MU} = \sqrt{\frac{2\, m_{TO}\, g}{\rho\, S\, C_{L_{MU}}}} \quad ,$$

where $g$ is the gravity constant, $\rho$ is the air density and $S$ is the wing reference area.

This equation can be used to determine the minimum unstick speed for all high-lift configurations. The results are comparable with the ones from MITRA. With $V_{MU}$ the rotation speed $V_R$ can be calculated using an approximation from [13] (page 44-47).

$$(3) \qquad V_R = 1.08\, V_{MU} \quad .$$

The thrust during the ground run is required for calculating the take-off run distance $d_1$. Because the thrust decreases during the acceleration, a constant median thrust force $\bar{T}$ is used (see [4] part VII page 119) in the calculation. It is defined as:

$$(4) \qquad \bar{T} = \text{Thrust at } V = \frac{V_{LOF}}{\sqrt{2}} \quad .$$

If $V_{LOF}$ is not known beforehand, following approximation for a two engine aircraft ($n$ = 2) can be used (see [4] part VII page 119):

$$(5) \qquad \bar{T} = 0.75\, n\, \frac{5 + BPR}{4 + BPR}\, T_{TO} \quad ,$$

where the bypass ratio $BPR$ is the ratio between the mass flow rate that bypasses the engine core through the fan and the mass flow rate passing through the engine core.

The simplification of Equation 5 directly influences all following equations. Each variation here has an impact on the resulting parameters.

With the median thrust force, the acceleration $\dot{V}_{d1}$ during the ground run (the segment between the starting point and becoming airborne) (see [5], page 580) can be calculated. It is assumed that the acceleration between $V_R$ and $V_{LOF}$ is constant.

$$(6) \qquad \dot{V}_{d1} = \frac{\bar{T}}{m_{TO}} - \mu g - (C_{D_{TO}} - \mu C_{L_{TO}}) \frac{\rho\, V_R^2\, S}{2 m_{TO}} \quad ,$$

where the friction coefficient $\mu$ = 0.02 for concrete dry runway is used. The acceleration during the ground run is directly influenced by the high-lift system through $C_{D_{TO}}$ and $C_{L_{TO}}$, but it is difficult to estimate the correct aerodynamic coefficients at take-off.

With the take-off pitch angle $\Theta_{LOF}$ and the pitch rate $q_{LOF}$ following equation can be applied for the calculation of $V_{LOF}$:

$$(7) \qquad V_{LOF} = V_R + \dot{V}_{d1} \left( \frac{\Theta_{LOF}}{q_{LOF}} \right) \quad .$$

Then the horizontal distance $s_1$ between the starting point and the point of becoming airborne can be calculated with following equation (see [4], pt. VII, page 122):

$$(8) \qquad s_1 = \frac{V_{LOF}^2}{2\, g} \frac{1}{\frac{\bar{T}}{m_{TO} g} - \bar{\mu}} \text{ , with } \bar{\mu} = \mu + 0.72\, (C_{D_0}/C_{L_{Max}}) \; .$$

The horizontal distance between the point of becoming airborne and achieving 35 ft radio height $s_2$ can be calculated with following trigonometrical relationship (35 ft are 10.67 m):

$$(9) \qquad s_2 = \frac{10.67}{\sin \gamma} \quad .$$

The climb angle $\gamma$ can be approximated by (see [5], page 168):

$$(10) \qquad \gamma = \frac{0.9\, \bar{T}}{m_{TO}\, g} - \frac{0.3}{\sqrt{AR}} \quad .$$

This approximation computes the same solution for different high-lift configurations, because only the aspect ratio of the wing $AR$ is used as an aerodynamic input parameter. The total take-off run is simply the sum of both horizontal distances:

$$(11) \qquad d_1 = s_1 + s_2 \quad .$$

Figure 8 shows the results for each test case and aircraft variant in the left column and the percentage change of HL1 and HL2 (referenced to HL0) in the second column in the same way as Figure 7 for the MITRA results.

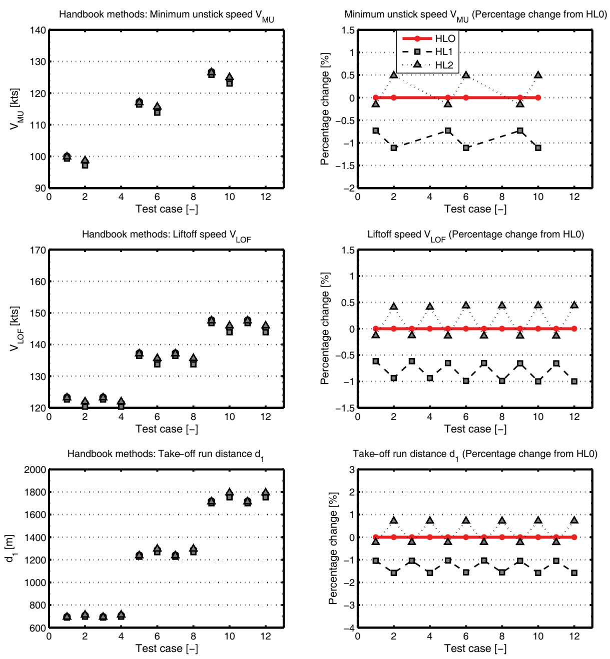


Figure 8: Take-off performance calculated with handbook methods

The effects of the take-off weight changes can be seen here as well (with increasing weights, the low speeds and take-off run distances increase). Since the centre of gravity is not considered in any equation, it does not influence the results.

The second column of Figure 8 shows similar trends as the ones in Figure 7. However, the percentage change is less in all cases than in the test cases computed with MITRA. For example, the travelled ground distances with HL1 are only ~ 1 – 1.6 % lower than with HL0 instead of ~ 2 – 3.8 % as computed with MITRA.

### 4.3 Comparison of MITRA and HBM results

Because MITRA uses detailed flight mechanical models and more realistic data, it can be assumed that it is more accurate.

Figure 9 shows the percentage error (PE) of the percentage change (PC) between handbook methods results and the reference MITRA results (the relative difference of the values from the right column of Figure 7 and 8). The percentage error can be calculated with following equation:

$$PE = \frac{PC_{HB}+PC_{MITRA}}{PC_{MITRA}} \cdot 100\ \% \quad . \tag{12}$$

A negative PE means that that the handbook methods predict lower values than MITRA for the take-off performance. The PE varies in Figure 9 between -10 and -90 %, depending on the test case and is mainly caused by the stated simplification, the lack of considering nonlinear effects and the use of empirical terms regarding aerodynamic forces (see Equations (4), (5), (6) and (8)).

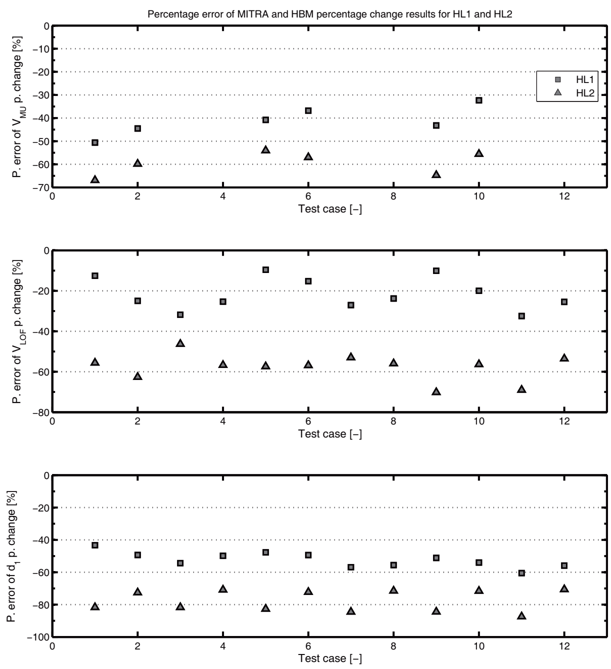


Figure 9: Error percentage of handbook methods results

In all test cases, the handbook methods predict smaller performance changes for HL1/HL2 than MITRA. For example, the percentage change between HL2 and HL0 of the travelled ground distance is much lower (~80 %) with handbook methods than with MITRA. It can be concluded that MITRA predicts a higher potential of HL1 and HL2 than handbook methods.

In the classic preliminary aircraft design process the aerodynamic properties of the high-lift control surfaces are roughly estimated. In this assessment, the aerodynamic data have higher accuracy as they are generated by CFD methods. Both methods, the handbook methods and MITRA, use this data. That means, the difference between both methods would be even larger if estimated data are used in the handbook methods.

The assessment of unconventional high-lift designs, e.g. wings with active flow control, with handbook methods becomes even less accurate or impossible as handbook methods, which are derived from conventional designs, do not have the capability to model such aspects.

Another feature of MITRA, which has been not covered in this example, is that it uses dynamic flight simulations for the assessments. Operational influences, i.e. retracting the slats/flaps during the ground run, can be easily investigated. With handbook methods, this is not possible.

## 5 CONCLUSION

Thanks to the available computational power it has become possible today to compute aircraft properties with a higher fidelity using numerical methods, such as CFD and FEM even in early aircraft design. Those data can be used to develop flight simulation models earlier in the aircraft design process. The proposed method MITRA that is based on flight simulation models makes use of this progress. The methods can be automated and can contribute to reduce development costs and risks of future aircraft designs.

The benefits of applying such more sophisticated aircraft design methods instead of traditional handbook methods has been demonstrated for the assessment of different high lift configurations and their impact on take-off performance compared to a reference configuration. Although both methods predict the same trends, the predicted performance improvements differ. Here the handbook methods predicts less. This may lead to wrong conclusions and wrong decisions if only handbook methods are used. For example, a project management may decide not to pursue a proposed high lift system modification when a handbook method underestimates its benefits.

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