Technical University of Berlin

Institute of Aeronautics and Astronautics
Department of Flight Mechanics, Flight Control and Aeroelasticity
Prof. Dr.-Ing. Flávio Silvestre


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# Applied Flight Mechanics and Flight Controls

Task Booklet


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| Professor: | Prof. Dr.-Ing. Flávio Silvestre |
| Assistant: | Dr.-Eng. Pedro J. González |
| Assistant: | M.Sc. Christopher Ruwisch |
| Assistant: | M.Sc. Sutej Singh |

# Contents

## Abbreviations

**FPE** Fundamental Performance Equation

**UAV** Unmanned Aerial Vehicle

**GPS** Global Positioning System

**IMU** Inertial Measurement Unit

**LiDAR** Light detection and ranging

**PIO** Pilot Induced Oscillations

**SAS** Stablility Augmentation System

**CAS** Control Augmentation System

# 1 Flight Mechanics I

## 1.1 Maximum and minimum velocity

### Presentation of the topic

Knowledge of the maximum and minimum velocity of an aircraft is essential. These two velocities represent two of the flight range limits of the flight envelope. The left side of the two flight envelope limits is determined by what is called the maximum lift coefficient $C_{L,\text{max}}$ or stall speed $V_{\text{Stall}}$. When this velocity is reached, a complete stall occurs and the lift on the aircraft collapses, making steady-state level flight no longer possible. The right flight range limit is mostly determined by structure or engine power. Knowledge of these limits is necessary for safe operation of the aircraft.

### Description of the task

Determine the maximum velocity $V_{\text{max}}$ and the stall speed $V_{\text{Stall}}$.

### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band
- Wind influences are negligible

### Working points

1. Familiarization with the theoretical principles for determining maximum and minimum velocities.
2. Specify logging parameters to determine velocities.
3. Flight test development, preparation and conduction
4. Identify stall speed from flight logs.
5. Safety factor design for safe operation based on the stall speed.
6. Summarize all working steps in a paper and present results to an expert audience.

### Objective of the task

The objective of this task is to determine the parameters $V_{\text{max}}$, $V_{\text{Stall}}$. A safety factor should be determined in order to create a safety margin to prevent velocities below the stall speed. All working steps shall to be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

A possible method to determine the stall velocity $V_{\text{stall}}$ is to set the trust level to idle and to observe at which velocity the height cannot be maintained. Similarly, the maximum velocity $V_{\text{max}}$ can be determined by setting trust level to its maximum and maintaining the height.

## Recommended literature


[1] James W Gregory and Tianshu Liu. *Introduction to Flight Testing*. eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[2] Ralph D Kimberlin. *Flight testing of fixed-wing aircraft*. eng. Reston, VA, 2003.

[3] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

## 1.2 Turning flight performance

### Presentation of the topic

The turning flight performance provides information on turn rate, turn radius, load-factor and bank angle over the airspeed at a constant and steady height. Those information are necessary for navigation in a dense environment or a limited airspace, especially for autonomous operating Unmanned Aerial Vehicles (UAVs) which operate in an airspace bounded with a geo-fence.

### Description of the task

In this task, the turning performance shall be be analysed. Considering the theoretical basics from flight mechanics, the turn radius shall be determined for different bank angles and velocities. Also the maximum load-factor shall be estimated. The analytical results shall then be compared to the experimental measurements from flight tests.

### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band
- Wind influences are negligible
- The turning flight is steady, slip free and horizontal.
- The maximum load factor $n_{z,\max}$ is dependent on the maximum roll angle $\phi_{\max}$ and therefore, dependent on the maximum lift coefficient $C_{L,\max}$

### Working points

1. Familiarization with theoretical principles of turning flights
2. Specify logging parameters to determine bank angle, turn radius, turn rate and load factor
3. Flight test development, preparation and conduction
4. Compare theoretical and experimental turning flight results.
5. Determine maximum bank angle for flown velocities to remain at constant altitude.
6. Summarize all working steps in a paper and present results to an expert audience.

## Objective of the task

The objective of this task is to determine the curves for bank angle, turn radius, turn rate and load factor over different airspeeds at a constant height. Also the maximum possible values shall be determined for a turn at constant height as well as the speeds and bank angles for two minute circles. The work has to be summarized in a scientific paper and presented to an expert audience

## Recommended procedure

For this task it is suggested that multiple test flights are performed at varying bank angles, velocities and heights.

## Recommended literature


[1] James W Gregory and Tianshu Liu. *Introduction to Flight Testing.* eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[2] Ralph D Kimberlin. *Flight testing of fixed-wing aircraft.* eng. Reston, VA, 2003.

[3] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems.* John Wiley & Sons, 2015.

### 1.3 Drag polar

#### Presentation of the topic

The drag polar (*Deutsch - Lilienthalpolare*) is of particular importance for determining the aerodynamic quality of an aircraft which can be modeled under ideal conditions, as a quadratic relationship between the drag coefficient $C_D$ and the lift coefficient $C_L$. The drag polar is a starting point for different flight performance parameters. From an aerodynamic point of view, the largest distance can be covered if the aircraft is flown with the lowest drag to lift ratio. Simultaneously, the glide ratio can also be used to determine the corresponding glide angle of the aircraft.

#### Description of the task

In this task, the drag polar for the UAV Talon Nano Evo shall be determined experimentally. For this purpose, flight tests shall be developed which enable the determination of the drag polar curve. These flight tests have to be prepared, conducted and evaluated.

#### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band
- Wind influences are negligible

#### Working points

1. Familiarization with the theory of drag polars and literature review.
2. Development of appropriate flight tests to determine this polar.
3. Calculation and determination of important parameters ($C_{D_0}$ and $e$).
4. Preparation, execution and follow-up of the flight tests.
5. Evaluation of the flight tests and creation of the drag polars.
6. Documentation of all work steps.

#### Objective of the task

The objective is to determine the drag polar curve for the UAV Talon Nano Evo. The work shall be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

For this task it is suggested that multiple glide flights are performed at various velocities with idle thrust. During each glide flight the velocity should be kept constant. For additional information look up the saw tooth method.

## Recommended literature


[1] James W Gregory and Tianshu Liu. *Introduction to Flight Testing*. eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[2] Ralph D Kimberlin. *Flight testing of fixed-wing aircraft*. eng. Reston, VA, 2003.

[3] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

### 1.4 Specific excess power

#### Presentation of the topic

An aircraft's excess power is of major interest in the performance of an aircraft, since it shows the available power for acceleration and climb which gives information on the operational limits of the aircraft. The specific excess power can be measured in different ways. The climb performance and also the level acceleration can be used to measure the specific excess power of an aircraft at different heights.

#### Description of the task

In this task, the specific excess power shall be determined using the climb performance and the level acceleration.

#### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band
- Wind influences are negligible

#### Working points

1. Familiarization with the theoretical principles of specific excess power.
2. Specify logging parameters to determine the specific excess power
3. Flight test development, preparation and conduction.
4. Determination of the specific excess power.
5. Summarize all working steps in a paper and present results to an expert audience.

#### Objective of the task

The goal of this task is to experimentally determine the specific excess power from two different flight tests - climb performance and level acceleration. The work has to be summarized in a scientific paper and presented to an expert audience

#### Recommended procedure

For this task it is recommended to read up on the theory of the energy angle (*Deutsch Energiewinkel*). To determine the steepest climb, the acceleration $\dot{V}_K$ should be zero. On the other hand for maximum level acceleration the angle of climb $\gamma$ should be zero.

## Recommended literature

[1] Rudolf Brockhaus, Wolfgang Alles and Robert Luckner. *Flugregelung*. ger. Heidelberg u.a., 2011.

[2] James W Gregory and Tianshu Liu. *Introduction to Flight Testing*. eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[3] Ralph D Kimberlin. *Flight testing of fixed-wing aircraft*. eng. Reston, VA, 2003.

[4] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

# 2 Flight Mechanics II

## 2.1 Identification of the Short-Period

### Presentation of the topic

Aircraft are subject to two eigenmodes in the longitudinal motion, the Phugoid (*Deutsch Phygoide*) and the Short-Period (*Deutsch Anstellwinkelschwingung*). The latter is high-frequency relative to the Phugoid, but decays rapidly. The Phugoid, on the other hand, is low-frequency and only slightly damped. The location of the poles of Phugoid and Short-Period can be estimated with the help of the aerodynamic derivatives, but the pole locations have to be confirmed with the help of flight tests.

### Description of the task

In this task, the pole location of the Short-Period shall be investigated experimentally and compared with the poles from the given linear models. For this purpose, preliminary theoretical considerations shall be carried out at first. Before the experimental investigations, relevant aerodynamic derivatives shall be determined from the model. Since the UAV does not have an angle-of-attack sensor, the value must be synthesized.

### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band

### Working points

1. Familiarization with the theoretical principles of short-period mode
2. Specify logging parameters to determine short-period mode
3. Develop suitable manoeuvrer to stimulate short-period mode
4. Flight test development, preparation and conduction
5. Identification of short-period with logged data
6. Comparison of identified poles and poles from linear models
7. Summarize all working steps in a paper and present results to an expert audience

### Objective of the task

The objective of the task is to experimentally identify the pole location of the UAV's Short-Period with suitable stimulations. The work has to be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

A possible method to excite the short period oscillation during a test flight is through a elevator/pitch doublet. Another possibility to excite the short period oscillation is to use a chirp signal.

## Recommended literature

[1] Randal W Beard and Timothy W McLain. *Small unmanned aircraft : theory and practice*. eng. Princeton u.a., 2012.

[2] Vladislav Klein and Eugene A Morelli. *Aircraft system identification : theory and practice*. eng. Reston, Va., 2006.

[3] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

[4] W. Youn et al. "Model-Aided State Estimation of HALE UAV With Synthetic AOA/SSA for Analytical Redundancy". In: *IEEE Sensors Journal* 20.14 (2020), pp. 7929–7940. DOI: 10.1109/JSEN.2020.2981042.

### 2.2 Identification of the Dutch-Roll

#### Presentation of the topic

Aircraft are subject to three eigenforms in the lateral motion, the spiral (*Deutsch Spirale*), the roll (*Deutsch Rolle*) and the Dutch-Roll (*Deutsch Taumelschwingung*). The Dutch-Roll eigenmode is an oscillation which inherits rolling and yawing motion and depends on the roll and yaw damping characteristics as well as on side-slip derivatives. The Dutch-Roll is controlled to improve the flight characteristics. The roll mode is an aperiodic motion and the spiral can be stable, indifferent or unstable. Since the spiral mode is very slow, an unstable spiral can be handled well from a pilot or an autopilot. For this purpose, a precise knowledge of it is necessary.

#### Description of the task

In this task, the pole location of the Dutch-Roll shall be investigated experimentally and compared with the linear models. For this purpose, preliminary theoretical considerations shall be carried out at first. Before the experimental investigations, relevant aerodynamic derivatives shall be determined from the model. Since the UAV does not have a side-slip angle sensor, the value must be synthesized.

#### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band

#### Working points

1. Familiarization with the theoretical principles of Dutch-roll mode.
2. Specify logging parameters to determine Dutch-roll mode
3. Develop suitable manoeuvrer to stimulate Dutch-roll mode
4. Flight test development, preparation and conduction
5. Identification of Dutch-roll with logged data
6. Comparison of identified poles and poles from linear models
7. Summarize all working steps in a paper and present results to an expert audience

#### Objective of the task

The objective of the task is to experimentally identify the pole location of the UAV's Dutch-Roll with suitable stimulations. The work has to be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

A possible method to excite the Dutch-roll oscillation during a test flight is through a rudder/yaw doublet.

## Recommended literature


[1] Randal W Beard and Timothy W McLain. *Small unmanned aircraft : theory and practice*. eng. Princeton u.a., 2012.

[2] Vladislav Klein and Eugene A Morelli. *Aircraft system identification : theory and practice*. eng. Reston, Va., 2006.

[3] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

[4] W. Youn et al. “Model-Aided State Estimation of HALE UAV With Synthetic AOA/SSA for Analytical Redundancy”. In: *IEEE Sensors Journal* 20.14 (2020), pp. 7929–7940. DOI: 10.1109/JSEN.2020.2981042.

# 3 Flight Controls

## 3.1 Control systems for the longitudinal motion

### Presentation of the topic

Achieving a stable flight condition in longitudinal motion is always desirable in civil aviation. This provides comfortable travel for the passenger. Controllers are used to achieve this condition without having to constantly re-trim an aircraft. Manually flown UAVs are supported with a Stablility Augmentation System (SAS)/ Control Augmentation System (CAS) which shall simplify the conduction of a flight task. Another very important task of a controller is to ensure a stable flight condition even in different flight phases and even during unforeseen manoeuvrers that require large control deflections.

### Description of the task

The dynamics of the UAV in longitudinal motion must be modified in such a way that the damping of the system meets the requirements of the Handling Qualities (MIL-F-8785C). Following this basis, damping controllers shall be designed. The Short-Period shall be modified to provide adequate damping. It can be assumed that the UAV serves reconnaissance purposes, e.g. mapping. Following this, consideration should be given to the entire state space for longitudinal motion, as well as the approximation for the Short-Period. The stationary horizontal flight and the corresponding state space around the selected trim points are considered as a reference point for the states of the UAV.

### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant
- The ambient pressure and temperature are constant within the height band

### Working points

1. Familiarization with the theoretical basics of a SAS.
2. Determination of desired flight characteristics from MIL-F-8785C.
3. Evaluate state space at given trim points concerning eigenmodes.
4. Design longitudinal SAS based on state space models.
5. Design a pitch attitude controller based on state space models.
6. Design an altitude tracker based on state space model.
7. Specify logging parameters to check controller performance.
8. Flight test development, preparation and conduction.

9. Evaluate the SAS / CAS.
10. Summarize all working steps in a paper and present results to an expert audience.

## Objective of the task

The objective of this task is to improve the flight characteristics of the UAV. Adequate damping shall be ensured for the short-period eigenmode. The effect of the designed controllers shall be analysed, tested and compared in detail to the simulation and flight tests. The work has to be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

It is recommended that a PI-controller be used for the pitch attitude controller.

## Recommended literature

[1] Rudolf Brockhaus, Wolfgang Alles and Robert Luckner. *Flugregelung.* ger. Heidelberg u.a., 2011.

[2] James W Gregory and Tianshu Liu. *Introduction to Flight Testing.* eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[3] David J Moorhouse and Robert J Woodcock. *Background information and user guide for MIL-F-8785C, military specification-flying qualities of piloted airplanes.* Tech. rep. Air Force Wright Aeronautical Labs Wright-Patterson AFB OH, 1982.

[4] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems.* John Wiley & Sons, 2015.

### 3.2 Control systems for the lateral motion

#### Presentation of the topic

Achieving a stable flight condition in lateral motion is always desirable in civil aviation. This provides comfortable travel for the passenger. Controllers are used to achieve this condition without having to constantly re-trim an aircraft. Manually flown UAVs are supported with a SAS/ CAS which shall simplify the conduction of a flight task. Another very important task of a controller is to ensure a stable flight condition even in different flight phases and even during unforeseen manoeuvrers that require large control deflections. Undesirable lateral movements can lead to a deviation from the optimum point for cruise flight. As a result undesirable consequences, such as increased fuel or energy consumption may occur. Furthermore, 3 eigenmodes are involved in lateral motion. The roll and the spiral are non-oscillating motion forms for which there are certain requirements regarding handling qualities. The Dutch Roll (*Deutsch Taumelschwingung*) is an oscillating motion form, with side-slip, yawing and rolling involved in the motion. Sufficient characteristic parameters must also be met for this motion, otherwise an undesired, undamped oscillation with high frequency could impair the safety of the flight. This is to be avoided by the implementation of a suitable controller design.

#### Description of the task

The UAV's lateral motion dynamics shall be modified in an appropriate manner using the design of dampers to improve flight characteristics. The Handling Qualities literature (MIL-F-8785C) will be used as a benchmark for establishing requirements. The damping of the Dutch Roll shall be modified to a suitable level. If required, the roll time constant shall be modified as well to an appropriate time constant. For the UAV it can also be assumed, in this task, that it serves exploration purposes, e.g. cartography. Additionally, the entire state space for the lateral motion, as well as the approximation for the Dutch Roll shall be considered. The stationary horizontal flight and the corresponding state space around the selected trim points are considered as reference points for the states of the UAV.

#### Assumptions

- The mass of the aircraft is constant.
- The Oswald's factor, the aspect ratio and additional geometrical parameters are fixed constants.
- The zero-lift drag coefficient $C_{W0}$ is assumed to be constant.
- The ambient pressure and temperature are constant within the height band.

#### Working points

1. Familiarization with theoretical principles of SAS and CAS.
2. Determination of desired flight characteristics from MIL-F-8785C.
3. Evaluate state space at given trim points concerning eigenbehaviour.
4. Design lateral SAS based on state space models.

5. Design a roll attitude controller based on state space models.
6. Design a heading autopilot based on state space models.
7. Specify logging parameters to check controller performance.
8. Flight test development, preparation and conduction.
9. Evaluate the SAS / CAS.
10. Summarize all working steps in a paper and present results to an expert audience.

## Objective of the task

The objective of this task is the improvement of the UAV's lateral flight characteristics. With respect to this, adequate damping of the Dutch Roll must be ensured. If necessary, the roll eigenmode shall adapted as well. The effect of the designed controllers shall be analysed, tested and compared in detail with the simulation and flight tests. The work has to be summarized in a scientific paper and presented to an expert audience.

## Recommended procedure

It is recommended that a PI-controller be used for the roll attitude controller.

## Recommended literature


[1] Rudolf Brockhaus, Wolfgang Alles and Robert Luckner. *Flugregelung*. ger. Heidelberg u.a., 2011.

[2] James W Gregory and Tianshu Liu. *Introduction to Flight Testing*. eng. Aerospace Series. Newark: John Wiley & Sons, Incorporated, 2021. ISBN: 111894982X.

[3] David J Moorhouse and Robert J Woodcock. *Background information and user guide for MIL-F-8785C, military specification-flying qualities of piloted airplanes*. Tech. rep. Air Force Wright Aeronautical Labs Wright-Patterson AFB OH, 1982.

[4] Brian L Stevens, Frank L Lewis and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.