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Title: Test Conditions for Evaluation of FCL-Monitor Effectiveness

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Summary: This Technical Note describes the test conditions for evaluation of FCL Monitor effectiveness. The test program in the Flight Simulation Environment is summarized, the selection of representative simulation initial conditions (trim points), failure injection and manoeuvre selection are explained. The evaluation criteria for independent monitor effectiveness and robustness as well as the proposed criteria for aircraft recoverability assessment is described.

This Technical Note represents the deliverable D-4.1 of the "Horizon Europe Project: Flight Control Laws and Air Data Monitors" Lot 1 (EASA.2021.HVP.28)" project.

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01	06.11.2023	D. Chernetsov	Initial version
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03	10.09.2024	D. Hübener	• Updated Trim Points (p. 11-12) • Updated hazard assessment (p.15) • Updated terminology of POD and PFA (p. 15-16) • Added asymmetrical failures (p. 19-20) • Updated list of test conditions (p.21)

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Contents

Abbreviations

Acronym	Description
A/C	Aircraft
C	Source Code Manipulation
CAT	Catastrophic Flight Condition
CG	Centre of Gravity
DL	Direct Law
FAR	False Alarm Rate
FCF	Flight Control Function
FCL	Flight Control Laws
FMRA	Fachgebiet Flugmechanik, Flugregelung und Aeroelastizität, TU Berlin
FSEnv	Flight Simulation Environment
HAZ	Hazardous Flight Condition
HIR	Hit Rate
LOG	Flight Control Law Logics
IMF	Independent Monitor Function
NL	Normal Law
PFA	Probability of False Alarms
POD	Probability of Detection
PRT	Protection Function
SG	Signal Generator
SW	Software
THS	Trimmable Horizontal Stabilizer
TP	Trim Point
TS	Test Scenario

Definitions

Term	Definition/Meaning
Failure	A loss of function or a malfunction of a system or a part thereof. (ARP4761).
Active Failure	Failures where FCL function acts erroneously and independent from the input signals and cannot be influenced e.g., by the pilot commands. However, the outcome of the failure may vary in amplitude or its time response depending on the input signals. One typical signature of failures of this class is a runaway, which is an actuator-like failure [1].
Reactive Failure	Failures where FCL function reacts erroneously on inputs and is highly dependent on at least one input signal e.g. a command of the flight crew or from the measured signals of the flight condition itself. This class includes failures that increase the A/C's PIO tendency, reduce the damping of flight dynamic modes or deteriorate the A/C's handling qualities in other ways [1].
Failure Condition	The effect on the aircraft and its occupants both direct and consequential caused or contributed to by one or more failures, considering relevant adverse operational and environmental conditions. A failure condition is classified according to the severity of its effects as defined in advisory material issued by the certification authority (DO-178C Annex B).
Trim Point	An initial aircraft state which contains calculated dynamic aircraft parameters for desired flight envelope point. The trim routine and trim conditions are described in [2]
Test Scenario	Test Scenario comprises test inputs during simulation execution. It includes pilot inputs and initiation of FCL failures. A test scenario is a MATLAB script that specifies required deviations from the default test scenario.
Test Program	Generic term that includes all activities for testing to evaluate the monitor effectiveness and robustness.
False Positive	The FCL-Monitor triggers a false alarm during failure-free operation. This criterion is used for effectiveness tests and robustness tests.
False Negative	The FCL-Monitor does not detect a failure caused by a FCL development error. This criterion is used for effectiveness tests.
True Positive	The FCL-Monitor detects a failure caused by a FCL development error. This criterion is used for effectiveness tests.
True Negative	The FCL-Monitor does not trigger an alarm during failure-free operation. This criterion is used for robustness tests.

Symbols

Symbol	Meaning
α	Angle of attack
α_{max}	Maximum angle of attack
β	Sideslip angle
θ	Pitch angle
Φ	Roll angle
η_F	Flap deflection angle
n_z	Normal load factor
n_y	Lateral load factor
H	Altitude
H_{msl}	Height above mean sea level
m	Mass
N_E	Total number of Effectiveness Simulations
N_R	Total number of Robustness Simulations
N_{TP}	Number of True Positive Simulations
N_{FP}	Number of False Positive Simulations
N_{FN}	Number of False Negative Simulations
N_{TN}	Number of True Negative Simulations
t_f	Point of time when failure occurs
t_r	Latest monitor reaction time
t_g	Time when A/C is recoverable with a significant increase in pilot workload
V_{CAS}	Calibrated airspeed
V_{TAS}	True Air Speed
$V_{FCL,min}$	FCL low speed protection boundary
$V_{FCL,max}$	FCL maximum speed protection boundary
V_{FE}	Maximum flap extended speed
V_w	Wind speed
V_{MO}	Maximum operation speed
V_{NE}	Never exceed speed
V_D	Dive speed
V_S	Stall speed
Ma	Mach number

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[8] EASA, „Certification Specifications and Acceptable Means of Compliance for Large Aircraft CS-25," Köln, 2016.

[9] Heintisch und Holzhausen, „Flight Control Laws for the Primary Flight Module in the PFCU," Bremen, 2000.

[10] Fokker-VFW International, „Flight Handbook," Schiphol-Oost, 1974.

Typographical Conventions

Following typographical conventions are used in this document:

Item	Convention to use	Example
Example Code	`Monospace Consolas` font	`A=5`
Folder name	*Arial* font, italics	*folder*
File name	***Arial*** font, bold, italics	***filename***
New terms	*Arial* font, italics	*Test Case*
variable	`Monospace Consolas` font	`variable`
bus signal	<u>`Monospace Consolas`</u> font, underlined	<u>`bus signal`</u>

1 Introduction

The Horizon Europe Project: “Flight Control Laws and Air Data Monitors” Lot 1 (EASA.2021.HVP.28) investigates the viability of an *Independent Monitor* for Flight Control Law Software (FCL SW) to detect FCL failures [3]. This Technical Note is a part of the delivery D-4.1 of the “EASA Horizon Flight Control Law Monitors”. It defines the test conditions for Independent Monitor Functions (IMFs) effectiveness evaluation as part of D-4.1.

In Task 4, the test conditions for evaluation of Independent Monitor Functions (IMFs) effectiveness and robustness shall be defined. Additionally, a simplified aircraft recoverability assessment after the failure has been detected is proposed.

TU Berlin uses the FCL SW that was developed in the VFW614-ATD technology project, in which new technologies for an Electronic Flight Control System were developed and demonstrated. The FCL SW and the desktop Flight Simulation Environment (FSEnv) of the VFW614-ATD flight dynamics are representative for a modern Fly-by-Wire (FbW) aircraft (A/C). This desktop flight simulation was prepared in Task 1 of the EASA.2021.HVP.28 project and extended by failure injection means. The documentation comprises a user manual [4], a programmer’s guide [2] and a validation report [5].

This document describes the test conditions defined to evaluate the effectiveness of the IMFs proposed in [6]. It comprises the investigated trim points, FCL failures and flight conditions.

1.1 Motivation

The objective of the Independent Monitor is to increase the safety of the FCS while maintaining highest rates of availability. It needs to be designed with thresholds and confirmation times set not so high as to not trigger when needed (effectiveness), and not so low as to lead to false alarms during failure-free operations (robustness).

The definition of a wide test condition set allows an assessment of IMF effectiveness and robustness. To evaluate the effectiveness, test conditions comprising trim points, catastrophic FCL failures and aircraft manoeuvres are defined. The robustness test conditions are a combination of trim points, flight manoeuvres and external disturbances, e.g. turbulence and gusts.

After the test conditions are defined, simulations executed and evaluated an effective IMF design adaptation and fine-tuning of IMF thresholds and confirmation times can be performed. Subsequently, it can be evaluated which monitor design concepts could prove themselves in practice. For future commercial development and certification purposes, a more extensive analysis over the complete flight envelope (e.g., with help of Monte Carlo simulations) might be required. This is out of scope in in this project.

1.2 Report Structure

The report is structured as follows:

- Section 2 summarizes the approach for effectiveness and robustness evaluation of independent monitors. The test program is described, representative trim points are selected, the approach for effectiveness and robustness test condition definition is described and the IMF evaluation criteria defined.
- Section 3 lists the selected failures and manoeuvres that are used for the definition of effectiveness test conditions. It defines the suitable permutation of trim points, FCL failures and flight manoeuvres.

2 Independent Monitor Evaluation Approach

The desktop Flight Simulation Environment (FSEnv) is used to evaluate the effectiveness and robustness of the Independent Monitor Functions (IMFs). Table 2-1 lists the validity range of the FSEnv. Further technical details about the FSEnv are described in [2].

Table 2-1 Validity Range for Flight Mechanical Model of VFW614-ATD [7].

Parameter	Range
Airspeed	$0 \leq V_{CAS} < 335\ kt$
Mach	$0 \leq Ma < 0.73$
Angle of Attack	$-5° \leq \alpha < 12°$
Sideslip	$-12° \leq \beta < 12°$
Altitude	$0 < H < 30000\ ft$

Effectiveness refers to the ability of the IMF to detect the effects of FCL development errors before they lead to hazardous (HAZ) or catastrophic (CAT) failure conditions. An IMF is considered robust if it does not trigger false alarms under failure-free conditions.

To investigate the effectiveness and robustness of the IMFs test conditions are defined. Effectiveness test conditions comprise:

- initial flight condition (trim point),
- an FCL failure, and
- flight manoeuvres.

Robustness test conditions comprise:

- an initial flight condition (trim point),
- flight manoeuvres, and
- external disturbances (e.g., turbulence, gusts).

Representative trim points, flight manoeuvres, external disturbances and FCL failures are selected to assess the performance, i.e. effectiveness and robustness, of the proposed monitors.

2.1 Test Program for Monitor Evaluation in FSEnv

Figure 2-1 shows a simplified flow chart of the sequential events of the test program for monitor evaluation. The test program is conducted in the FSEnv (VFW614-ATD Flight Simulation Environment) and starts with the generation of the trim data base. The trim data base can be expanded later as needed.

The next step is to define test scenarios for evaluation of monitor effectiveness and robustness. Test scenarios are MATLAB scripts that comprise the inputs that are inserted during the simulation. Each effectiveness test scenario comprises an FCL failure call and flight manoeuvre. The robustness test scenarios include flight manoeuvres and external disturbances. Together with the trim points, the test scenarios form the IMFs test conditions.

Once the trim data base and test scenarios have been defined, the flight simulations can be executed, and the simulation results evaluated. The simulation loop incorporates initialisation of FSEnv, where a selected test condition is loaded, and FSEnv simulation run, where the IMFs, FCL and A/C model are executed, and simulation logs are saved as .mat files.

The evaluation loop consists of three steps. The simulation log evaluation routine reads the simulation logs and evaluates them according to the criteria described in Section 2.4. The TUBPlot routine plots the simulation logs, and an evaluation report is automatically generated. This report incorporates a summary of all simulation results and associated simulation plot and log references.

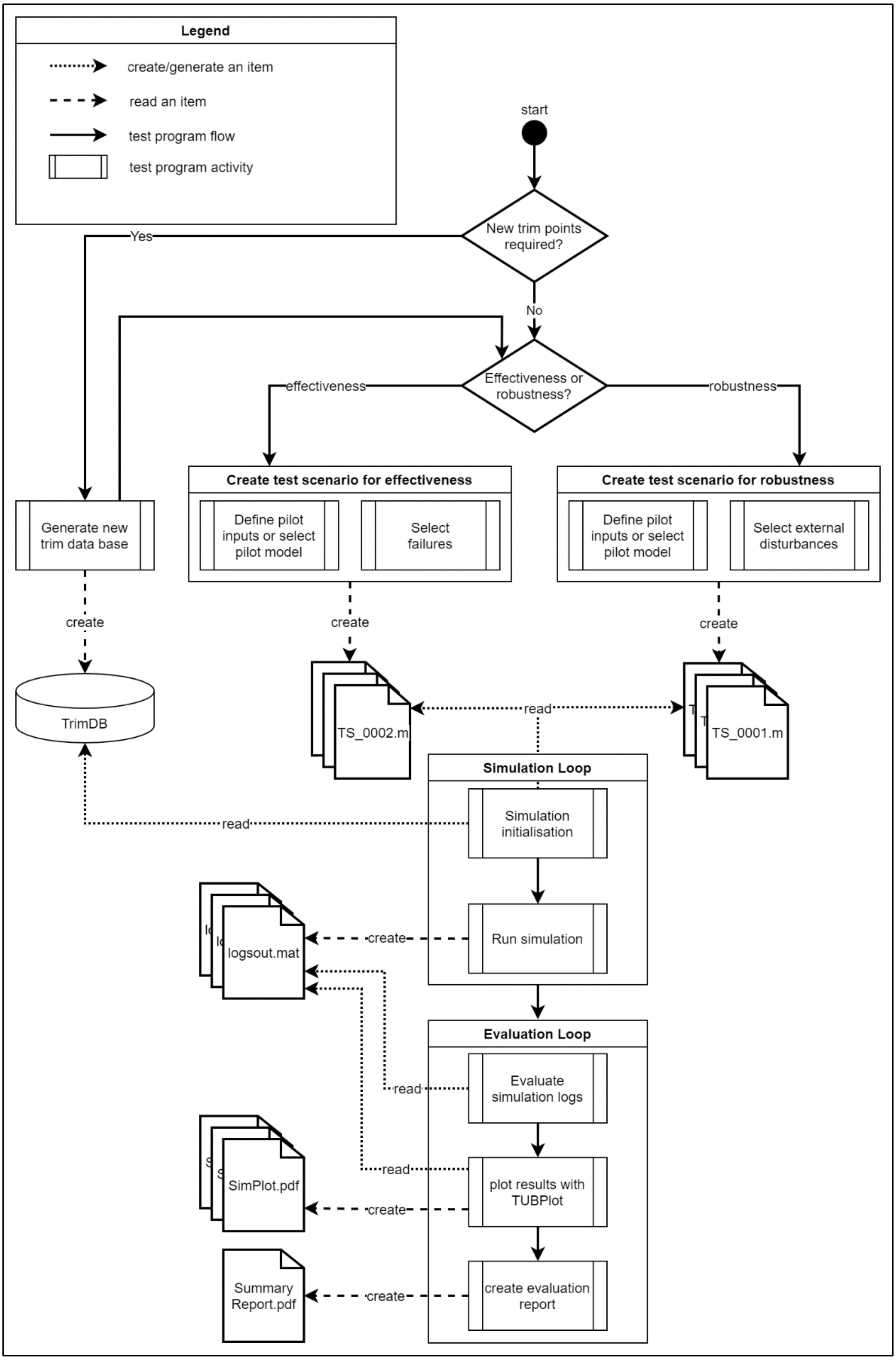

Figure 2-1: Test Program for Monitor Evaluation.

2.2 Selected Trim Points

Representative trim points for the operational flight envelope of the VFW614-ATD aircraft are selected. The focus of the investigation lies on the high and medium altitude trim points, as the aircraft is operated within this area of the flight envelope most of the time. Additionally, some trim points at low altitudes have been selected. The selected trim points are used for both effectiveness and robustness evaluation. The trim points can be categorised by altitude and airspeed:

Altitude:

- TP1XXX: low altitude [0m, 1500m],
- TP2XXX: medium altitude [1500m, 4500m], and
- TP3XXX: high altitude [4500m, 7620m].

Airspeed:

- TPX1XX: low airspeed $[V_{FCL,min}, 1.1\ V_{FCL,min}]$[1],
- TPX2XX: medium airspeed $[1.1\ V_{FCL,min}, 0.9\ V_{FCL,max}]$, and
- TPX3XX: high airspeed $[0.9\ V_{FCL,max}, V_{FCL,max}]$.

Table 2-2 lists the proposed trim points. The aircraft weight m, the centre of gravity CG, the Geo Location and the initial wind[2] conditions are constant for all trim points:

- m=18182.0 kg,
- CG 25 % MAC,
- Lat 52.515326°,
- Lon 13.323655°, and
- $V_w = 0$

Table 2-2: Selected Trim Points for IMF Evaluation.

Trim Point ID	Φ [°]	H [m]	V_K [m/s][3]	γ [°]	Gear: 0 Up 1 Down	Flap configuration
TP3300	0	6000	170	0	0	0
TP3200	0	6000	120	0	0	0
TP3100	0	6000	95	0	0	0
TP2300	0	3000	145	0	0	0
TP2200	0	3000	115	0	0	0
TP2100	0	3000	80	0	0	0
TP1200*	0	1000	80	-3	1	1
TP1201*	0	750	70	-3	1	2
TP1202*	0	500	68	-3	1	4
TP1203	0	250	90	4	1	3
TP3301	25	6000	160	0	0	0
TP3201	25	6000	125	0	0	0
TP3101	25	6000	97	0	0	0

[1] FCL low speed protection boundary $V_{FCL,min}$ for $n_z = 1$ is calculated in ATD FCL Normal Law in dependency of A/C mass, A/C configuration.

[2] External disturbances, such as turbulence or discrete gusts, are defined separately in the robustness test scenarios.

[3] Without wind V_w, V_K is equal to V_{TAS}.

Trim Point ID	Φ [°]	H [m]	V_K [m/s][3]	γ [°]	Gear: 0 Up 1 Down	Flap configuration
TP2301	25	3000	148	0	0	0
TP2201	25	3000	120	0	0	0
TP2101	25	3000	85	0	0	0
TP1210	25	500	67	0	1	1
TP1211	25	1000	62	0	1	2
TP1212	25	750	58	0	1	4
TP1213	25	750	90	0	1	3

* These trim points can be used together with the available pilot model to simulate dynamic manoeuvres during approach

Figure 2-2 shows the flight envelope limits (V_{TAS} and H_{msl}) of the VFW614-ATD aircraft in clean configuration and the selected trim points of medium and high altitudes. The red line defines the flight envelope limits that shall never be exceeded, see Table 2-3. The green dashed line represents FCL protection limits. Normal Law protection functions are active in the area between the green dashed and the red lines. The selected trim points are shown as blue circles. Filled circles represent steady straight horizontal flights and unfilled circles are steady horizontal turn flights.

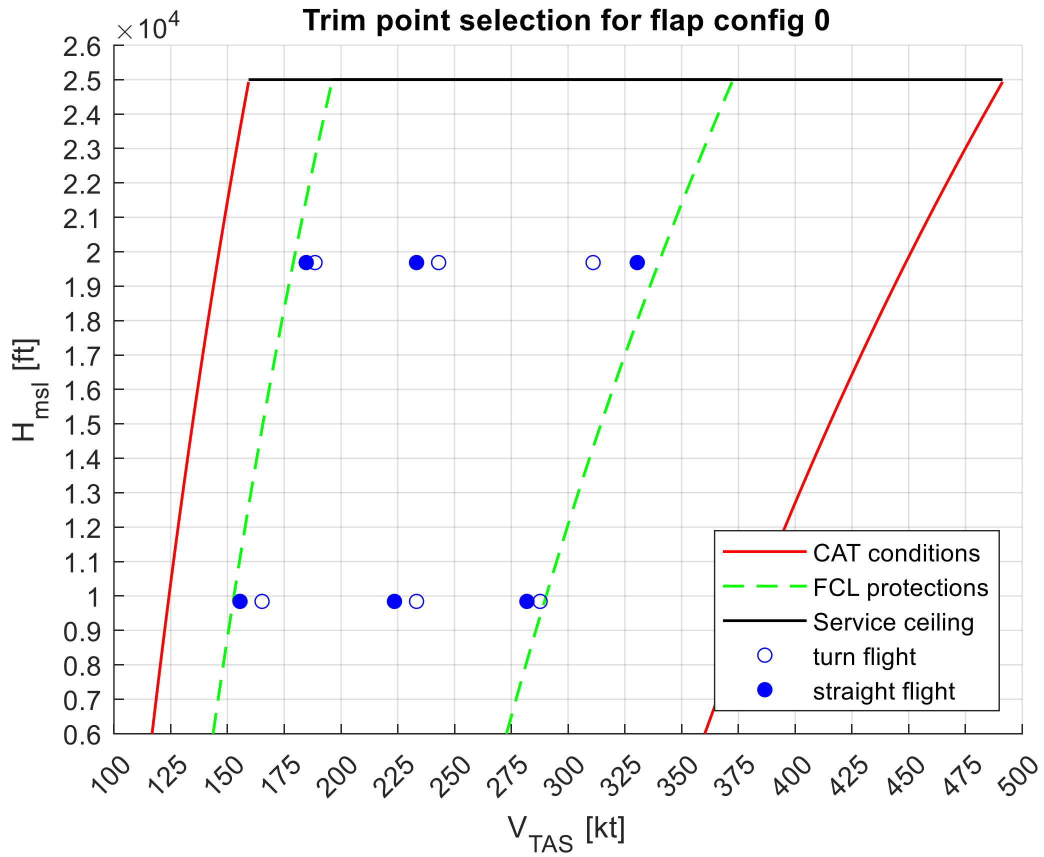

Figure 2-2: VFW614-ATD Flight Envelope Middle and High Altitude, Clean Configuration.

Figure 2-3 shows the flight envelope limits (V_{TAS} and H_{msl}) of the VFW614-ATD aircraft at flaps extended configuration and the selected trim points of low altitudes.

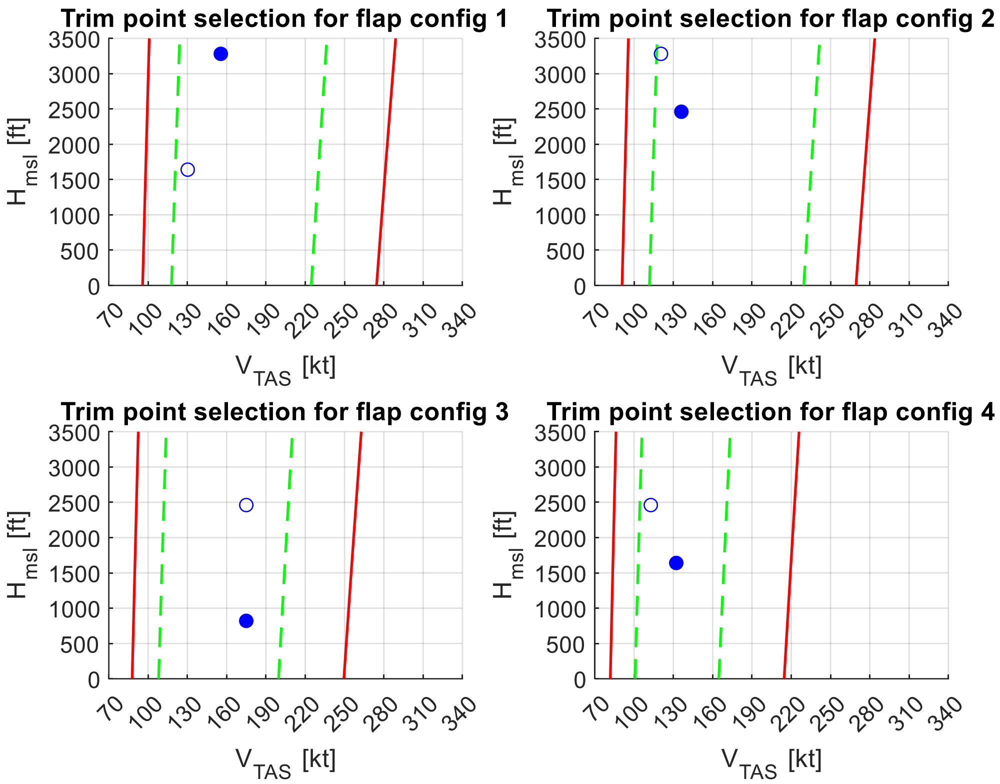

Figure 2-3: VFW614-ATD Flight Envelope Low Altitude, Different Flap Configurations.

2.3 Effectiveness Test Conditions

Effectiveness refers to the ability of the IMF to detect the effects of FCL development errors before they lead to hazardous (HAZ) or catastrophic (CAT) failure conditions. Therefore, CAT failure conditions, that prevent continued safe flight and landing, need to be defined for the VFW614-ATD aircraft.

The FSEnv described in [2] is supplemented with failure injection capabilities. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the FSEnv supplemented by the IMFs and the failure injection. FCL failures can be injected in two ways:

1. signal generator (SG), and
2. source code manipulation (C).

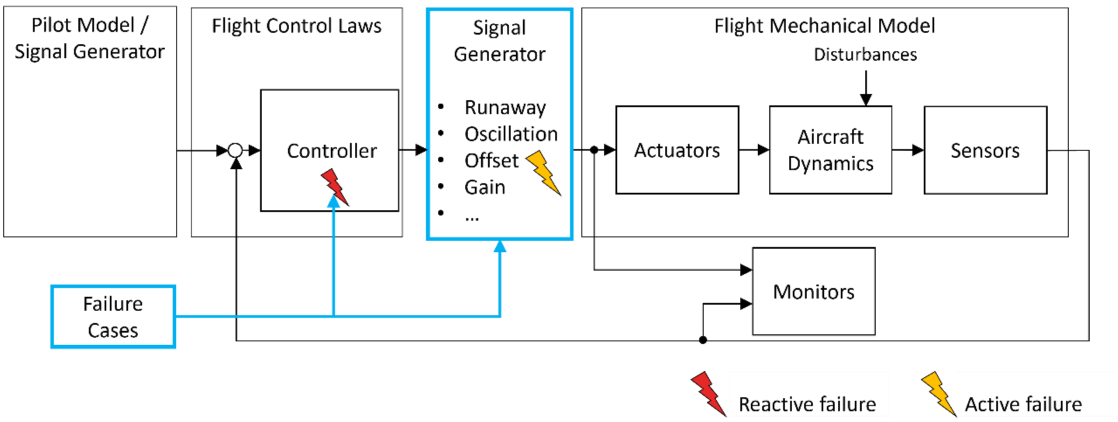

Figure 2-4: FSEnv Failure Injection Mechanism.

The signal generator injects a failure by directly manipulating the FCL output. The signal generator is used to simulate active failures and can be applied for all FCL control surface commands. Source code manipulation is required to simulate reactive failures.

AMC25.671 [8] provides means of compliance to evaluate flight control system failures. Even though, the means of compliance of AMC25.671 are not intended to address development errors, here they are used as guidance. Continued safe flight and landing is generally defined as not exceeding any one of the following criteria (within the transition phase[4]):

- A load sufficient to cause a catastrophic structural failure,
- Exceedance of V_D
- Catastrophic loss of flight path control,
- Bank angle exceeds 90°,
- Catastrophic flutter, or
- Excessive vibration or buffeting conditions.

In summary, a continued safe flight and landing cannot be demonstrated if the failure leads to excessive structural loads, high airspeeds, high bank angles, loss of flight path control (e.g. stalls or loss of manoeuvrability), catastrophic flutter or excessive vibrations. Flutter and vibrations cannot be simulated with the FSEnv and are therefore not considered.

Table 2-3 lists thresholds for CAT failure conditions of the VFW614-ATD aircraft, based on design limits from the aircraft development program [9], VFW614-ATD flight manual [10], and engineering judgement. It is assumed that continued safe flight and landing is not possible if the values of Table 2-3 are exceeded.

Table 2-3 Thresholds for Catastrophic Failure Conditions.

Configuration [1]	**0**	**1**	**2**	**3**	**4**
Flap deflection η_F [°]	-6	1	5	14	35
$V_{CAS,max}$ [kt]	330.0	275.0*	270.0*	250.0*	215.0
$V_{CAS,min}$ [kt]**	$\leq V_S$***				
$n_{z,min}$ [-]	$n_z < -1.5$	$n_z < -0.5$			
$n_{z,max}$ [-]	$n_z \geq 4$	$n_z \geq 3$			
$\lvert\Phi\rvert$ [°]	$\lvert\Phi\rvert > 90°$	$\lvert\Phi\rvert > 80°$			
α_{max}[°]***	12.9	14.4	14.5	13.3	11.2
$n_{y,max}$ [-]	1g				

* Assumption: Exceeding V_{FE} by $50kt$ is assumed to be CAT.

** Stall speeds are listed in Table 2-4

*** Not recoverable stalls are considered CAT. Stalls are assumed to be recoverable for H>1000 m.

Table 2-4 Stall Speeds in [kt] Depending on Flap Setting and A/C Mass.

Configuration / Mass [kg]	**0**	**1**	**2**	**3**	**4**
11818.0	87.0	77.0	73.0	70.0	66.0
14545.0	96.0	86.0	81.0	78.0	73.0
18182.0	107.0	96.0	91.0	88.0	82.0
20909.0	114.0	103.0	97.0	94.0	87.0

It is assumed that exceeding the load factor limits $n_{z,min}$, $n_{z,max}$ and $n_{y,max}$ will lead to structural damage of the aircraft. Also, exceeding the maximum airspeed can cause structural damage and prevent continued safe flight and landing. It is further assumed that stalls cannot be recovered at

[4] The time following an FCS failure up to the disconnection (or switch) of the failed system.

altitudes lower than $1000\ m$ and therefore lead to a catastrophic loss of control. Table 2-4 list the stall speeds of the VFW614-ATD aircraft.

Note that the limit of the angle of attack exceeds the validity range of the FSEnv, see Table 2-1. The simulated aircraft dynamics and behaviour at high angle of attacks may not correspond to the reality. Also, the values of $n_{z,max}$ and $n_{y,max}$ have been selected based on engineering judgement and may not correspond to critical loads that lead to catastrophic structural failure. A validation of this values might be required in future projects.

In addition to structural damage and stalls (that cannot be recovered), a reduced controllability of the aircraft, that prevents continued safe flight and landing, is assumed to be catastrophic. AMC25.671 [8] defines manoeuvres that need to be performed to demonstrate the capability of continued safe flight and landing following a failure. In this project, a simplified approach is selected to assess the manoeuvrability of the aircraft. The aircraft is considered manoeuvrable if:

- $n_z \leq 0.8\ g$ within 2[5] seconds after a push-over manoeuvre, AND
- $n_z \geq 1.3\ g$ within 2 seconds after a pull-up manoeuvre, AND
- $|\Delta\Phi| \geq 45°$ within 3.8[6] seconds after a full roll input.

Only FCL failures that lead to CAT failure conditions are selected for the effectiveness test conditions. The evaluation of failures is intended to be initiated from 1-g wings level flight condition. A failure is considered catastrophic if at least one of the thresholds defined in Table 2-3 is exceeded or the manoeuvres defined above cannot be performed.

FCL failures that do not lead to CAT conditions are not considered for effectiveness evaluation. Simulating failure conditions classified as major, or minor does not allow any assessment of the effectiveness of a monitoring function. However, a full validation of the IMFs in future projects, may require the investigation of FCL failures that do not lead to HAZ or CAT failure conditions.

The selected FCL failures can be combined with normal flight manoeuvres to create multiple test conditions. The selected FCL failures and manoeuvres are described in section 3.

2.4 Evaluation of Monitor Performance

The evaluation of IMF performance is based on the flight simulation results and IMF outputs for effectiveness and robustness test conditions. These results can be classified as described in Table 2-5.

Table 2-5: Simulation Result Classification

FCL condition / Monitor output	FCL failure	Failure-free
failure detected	True Positive N_{TP}	False Positive N_{FP}
failure not detected	False Negative N_{FN}	True Negative N_{TN}

It is important to note that for the evaluation of the effectiveness of an IMF only simulations with FCL failure injections are evaluated. The total number of effectiveness simulations is given by:

$$N_E = N_{TP} + N_{FN}$$

An indicator of the effectiveness of a given IMF is the percentage of detection (POD). POD equal to 1 represents an effectiveness of 100%.

$$POD = \frac{N_{TP}}{N_E}$$

Robustness test conditions comprise failure-free test conditions. The number of robustness simulations is given by:

[5] Time requirement proposed by EASA test pilot.

[6] Requirement from MIL-F-8785C 3.3.4 Table IXa: Roll performance for Class I and II airplanes [11].

$$N_R = N_{FP} + N_{TN}$$

The false alarm rate (FAR) is an indicator of the robustness of the proposed monitor. Where FAR equal zero represents a very robust monitor, while FAR equal 1 indicates that the independent monitor has no robustness.

$$FAR = \frac{N_{FP}}{N_{TP} + N_{FP}}$$

A further indicator of monitor robustness is the percentage of false alarms (PFA). PFA equal to 0 represents a very robust monitor.

$$PFA = \frac{N_{FP}}{N_R}$$

The performance of an IMF depends on the effectiveness and robustness of the function. The hit rate (HIR) is an indicator of the performance of the FCL monitor. It represents the fraction of times when the independent monitor was correct.

$$HIR = \frac{N_{TP} + N_{TN}}{N_E + N_R}$$

In addition, the recoverability of the aircraft is also an important aspect to determine the effectiveness of the monitor. To assess the recoverability of a failure condition, a failure handling strategy (e.g. switch conditions, command fading) needs to be developed. Additionally, experiments with real pilots are required, i.e. further investigations are necessary. Such an investigation and development of failure handling strategies is out of scope.

In this project, a simplified approach is selected to assess the recoverability of the aircraft. It is assumed that the FCS switches to an alternative FCL, e.g. Direct Mode after a failure has been detected. It is further assumed that the aircraft can be recovered, if the IMF detects the failure a period Δt before a CAT failure condition occurs.

AMC25.671 [8] defines acceptable values for the time delay between a failure condition and the start of recovery actions taken by the pilot. The time delay comprises:

- the recognition,
- the reaction, and
- the operation of disconnection.

The recognition is defined as the time from the failure condition to the point at which a pilot in service operation may be expected to recognise the need to act. Recognition of the malfunction may be through the behaviour of the aeroplane or a reliable failure warning system and should normally not be less than 1 second [8].

The reaction is defined as the time the pilot needs to react and take action. The reaction time is 1 second for manual flight and 3 seconds for automatic flight [8]. The time required to operate any disconnection system should be considered. However, it is assumed that the FCS automatically switches to an error-free alternative after a failure has been detected. Therefore, no extra time delay is considered.

Considering the recognition time and reaction time, a failure condition is assumed to be recoverable, if the IMF detects the failure at least 2 seconds before the values of Table 2-3 are exceeded (CAT failure condition). It is assumed that the pilot flies manually (hands-on). However, for automatic flight a reaction time of 3 seconds is required. Therefore, the recovery window is divided into two sections, green and yellow.

Figure 2-5 shows the time range of an FCL failure that leads to a CAT failure condition. The failure is injected at t_f and can be recovered if the IMF detects the failure before $t_r = -2.0\ s$ (green and yellow section). The green section indicates the time range for which the A/C is always recoverable (IMF detection before $t_g = -4.0\ s$). Detections within the yellow section can be recovered if the pilot is flying manually. The red section indicates the time range where the A/C can't be recovered, and a CAT condition is unavoidable.

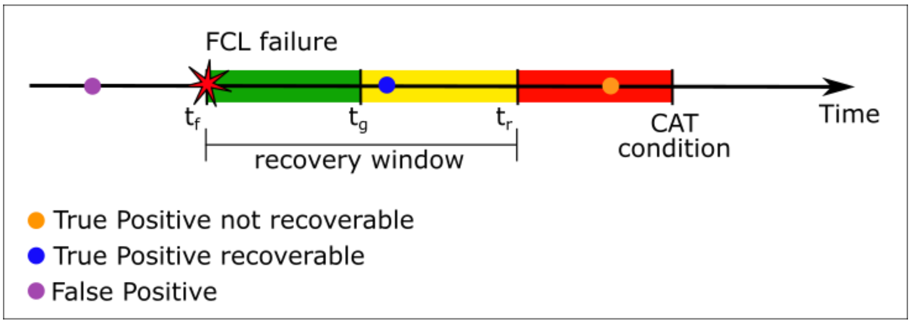

Figure 2-5: Metric for Recoverability after Failure Detection.

If a failure is detected before an FCL failure is injected (t_f), this is not considered to be a True Positive, in this case, the result is a False Positive. Also, failures that cannot be recovered should not be considered to be True Positives. When calculating the statistical measures presented above, the recoverability needs to be considered.

3 Effectiveness Test Conditions

The total set of effectiveness test conditions is the combination of the selected trim points, flight manoeuvres, and selected FCL failures. The following subsections list all FCL failures and flight manoeuvres that are considered for effectiveness evaluation.

3.1 FCL Failures

Potential FCL failures are described and classified in [1]. Two methods for failure classification were proposed:

- Classification method based on the type of a function (mode logic, normal flight control function, envelope protection function),
- Classification method that considers the dependency of a failure on the input signals of the FCL SW
    - Input-independent failures: failures in the FCL functions that affect the output independently from input signals (active class),
    - Input-dependent failures: failures in the FCL functions that affect the output in dependence of input signal (reactive class).

Active failures can be simulated with the signal generator (SG), by directly manipulating the FCL output. Source code manipulation (C) is required to simulate reactive failures. The functional failure classes are considered subclasses of the active and the reactive failure classes. Table 3-1 lists potential FCL failure classes and how they can be injected.

Table 3-1: Combination of Failure Classes and Failure Injection.

ATD FCL Normal Law Functions	Active/Reactive Failure	Failure Injection
Normal Law Mode Logic Functions (**LOG**)		
Normal Law Modes (Ground Mode, Flight Mode)	R	C
Protection Activation	A/R	SG/C
Control & Stability / Flight Control Functions (**FCF**)		
Pitch Normal Law	A/R	SG/C
Roll Normal Law	A/R	SG/C
Yaw Normal Law	A/R	SG/C
Protection Functions (**PRT**)		
Load Factor Protection	R	C
High-Speed Protection	R	C
Pitch Attitude Protection	R	C
High AoA Protection	R	C
Bank Angle Protection	R	C

For effectiveness evaluation of the IMFs, failures shall be investigated in different flight envelope domains depending on its class, as proposed in Figure 3-1. The FCF failures are only originated from the normal flight envelope. Also, the LOG failures are only originated from the normal flight envelope to investigate failure conditions that are caused by erroneous activation of the protections or erroneous mode activation. Failures that are caused by non-activation of protections in the yellow domain are not considered. In these cases, the pilot is responsible for preventing the A/C from reaching the limits of the peripheral flight envelope and returning the A/C to the normal flight envelope. Therefore, the non-activation of a protection function in itself is not hazardous or catastrophic.

The PRT failures are considered from the yellow domain only where the protection functions are correctly activated but are erroneous. A manoeuvre that leads the aircraft into the yellow domain is required, before the PRT failure is injected, as all trim points are within the normal flight envelope (see Figure 2-2 and Figure 2-3).

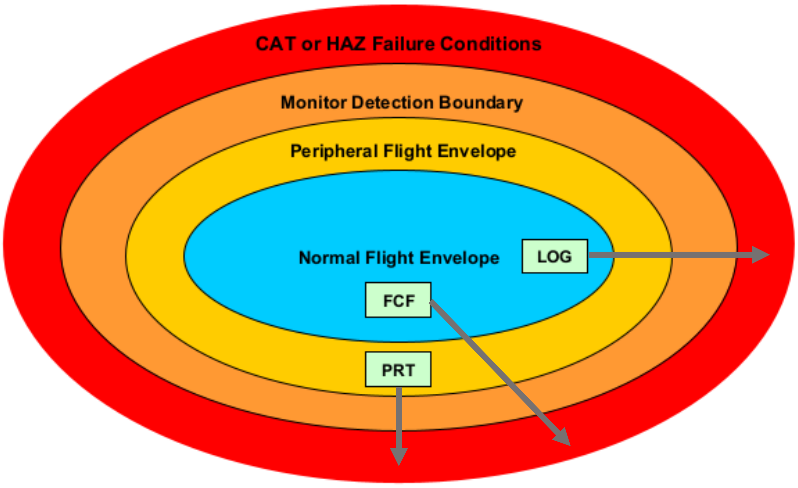

Figure 3-1: Distribution of Functional Failure Classes over the Flight Envelope.

To evaluate the effectiveness of the IMFs, active failures of the flight control functions are simulated. Active failures lead to actuator-like failures, i.e., runaways [1]. Therefore, runaway-like failures on all control surface commands are selected. The runaway may be positive or negative, and slow or fast. However, active failures affecting the lateral motion are only investigated for one direction, i.e. right wing down, if the flight condition is symmetrical. It is expected that runaways in the opposite direction will have the same effects, as the aircraft is symmetrical. Additionally, command freeze of the elevator and aileron commands, that reduce the controllability of the aircraft, are selected.

At last, reactive failures of all functional failure classes are selected. I.e., erroneous ground mode and protection activations, high gains in the FCF that lead to unstable aircraft dynamics and sign failures in the PRT functions. Table 3-2 lists the selected FCL failures.

Table 3-2: List of Selected FCL Failures.

Failure ID	Injection	Class	Failure Description
IHCRNWSP	SG	A-FCF	THS runaway slow positive*
IHCRNWSN	SG	A-FCF	THS runaway slow negative*
IHCRNWFP	SG	A-FCF	THS runaway fast positive*
IHCRNWFN	SG	A-FCF	THS runaway fast negative*
ETCRNWFP	SG	A-FCF	elevator runaway fast positive
ETCRNWFN	SG	A-FCF	elevator runaway fast negative
ETCRNWSP	SG	A-FCF	elevator runaway slow positive
ETCRNWSN	SG	A-FCF	elevator runaway slow negative
ETCOHLD	SG	A-FCF	elevator command freeze
XICRNWUP	SG	A-FCF	aileron symmetric runaway up fast
XICRNWDW	SG	A-FCF	aileron symmetric runaway down fast
XICRNWASS	SG	A-FCF	aileron asymmetric runaway (right wing down) slow
XICRNWASF	SG	A-FCF	aileron asymmetric runaway (right wing down) fast
XICRNWASS2	SG	A-FCF	aileron asymmetric runaway (left wing down) slow
XICRNWASF2	SG	A-FCF	aileron asymmetric runaway (left wing down) fast

Failure ID	Injection	Class	Failure Description
XICHLD	SG	A-FCF	aileron command freeze
ZECRNWFP	SG	A-FCF	rudder runaway fast positive
ZECRNWSP	SG	A-FCF	rudder runaway slow positive
ZECRNWFN	SG	A-FCF	rudder runaway fast negative
ZECRNWSN	SG	A-FCF	rudder runaway slow negative
SP34CRRNWF	SG	A-FCF	right spoilers 3 and 4 fast runaway* (right wing down)
SP34CRRNWF2	SG	A-FCF	left spoilers 3 and 4 fast runaway* (left wing down)
GNMD	C	R-LOG	erroneous activation of ground mode*
AAOA	C	R-LOG	erroneous activation of angle of attack protection*
AHISPD	C	R-LOG	erroneous activation of high speed protection*
ATHPRT	C	R-LOG	erroneous activation pitch attitude protection*
APHIPRT	C	R-LOG	erroneous activation roll attitude protection*
PNL	C	R-FCF	high gain in pitch normal law*
RNL	C	R-FCF	high gain in roll normal law*
YNL	C	R-FCF	high gain in yaw normal law*
FAOA	C	R-PRT	erroneous sign angle of attack protection
FHISPD	C	R-PRT	erroneous sign high speed protection
FPHIPRT	C	R-PRT	erroneous sign roll attitude protection

* Note that some of the selected FCL failures might not lead to catastrophic failure conditions as described in section 2.3 at every trim point. In this case, the FCL failure will not be combined with the specific trim point to generate effectiveness test conditions.

3.2 Aircraft Manoeuvres

Representative flight manoeuvres are selected for the effectiveness test conditions. Typical flight manoeuvres of cruise flight phase and a landing approach are selected. In cruise flight the following manoeuvres are defined:

- hands-free (i.e., no pilot input),
- climb,
- descent,
- turn,
- turn and climb, and
- turn and descent.

Hands-free flight conditions represent steady state conditions without any pilot inputs. Climb and descent manoeuvres are required to achieve an altitude difference of 1000 ft in 30 s. Turn manoeuvres are limited to a 90-degree change of direction at a turn rate of $r = 3\ °/s$. This allows short simulation times (about 60 seconds) and reduces the computational overhead. Climb and descent manoeuvres are also performed during a turn.

The landing ILS-approach uses a pilot model to simulate the pilot inputs during this flight phase. This manoeuvre is combined with low altitude trim points and reactive failures. Table 3-3 lists the flight manoeuvres that are used for effectiveness test conditions.

Table 3-3: Selected Manoeuvres for Effectiveness Test Conditions.

ID	Description
HF	Hands-free
CLB	1000ft climb manoeuvre, 2000ft/min rate of climb
DSNT	1000ft descent manoeuvre, -2000ft/min rate of descent
TURN	Initiate a 90-degree turn, with turn rate of $r = 3\,°/s$
TCLB	Stationary turn, 1000ft climb manoeuvre
TDSNT	Stationary turn, 1000ft descent manoeuvre
LND	Landing approach with lateral offset to localiser with pilot model

The selected flight manoeuvres can be combined with the trim points described in section 2.2 and the selected FCL failures, see section 3.1. However, some combinations are not plausible and will not be considered for effectiveness evaluation, e.g. landing manoeuvre at high and medium altitude trim points. Combinations of trim points and flight manoeuvres that are not considered:

- LND at medium and high altitudes.
- DSNT, TDSNT at medium and high altitudes and high-speed range (would lead to overspeed).
- CLB and TCLB at medium and high altitudes and low-speed range (would lead to stall).
- DSNT, TDSNT at low altitudes and middle speed range H<500 m (is covered with LND).

Also, FCL failures that do not lead to an aircraft reaction without pilot inputs will not be combined with HF manoeuvre, e.g. elevator command freeze.

The full combinations of trim points, flight manoeuvres and failures is given in the effectiveness test condition list which is attached at the following Link:

/test_conditions/effectiveness_test_conditions_v02.pdf

This list is used to generate automatically the test sequences where the manoeuvre initiation and failure injections calls are implemented.