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Title: Test Conditions for Evaluation of FCL-Monitor Robustness

Project: EASA.2021.HVP.28 “Horizon Europe Project: Flight Control Laws and Air Data Monitors” Lot 1

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Summary: This Technical Note describes the test conditions for evaluation of FCL Monitor robustness. The test program in the Flight Simulation Environment is summarized, the selection of representative simulation initial conditions (trim points), disturbance 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-4.2 of the “Horizon Europe Project: Flight Control Laws and Air Data Monitors” Lot 1 (EASA.2021.HVP.28)” project.

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Revision History

Version	Date	Author	Description of Changes
01	04.12.2023	D. Chernetsov	Initial version
02	10.09.2024	D. Hübener	• Updated Trim Points (p. 11-12) • Updated terminology of POD and PFA (p. 15) • Added crosswind from right (p. 18-19) • Updated rules of combination and list of test conditions (p.20) • Updated list of test conditions (p. 20)

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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].

Term	Definition/Meaning
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
H_{msl}	Height above mean sea level
N_E	Total number of Effectiveness Simulations
N_{FN}	Number of False Negative Simulations
N_{FP}	Number of False Positive Simulations
N_R	Total number of Robustness Simulations
N_{TN}	Number of True Negative Simulations
N_{TP}	Number of True Positive Simulations
V_{CAS}	Calibrated airspeed
V_D	Dive speed
$V_{FCL,max}$	FCL maximum speed protection boundary
$V_{FCL,min}$	FCL low speed protection boundary
V_{FE}	Maximum flap extended speed
V_{MO}	Maximum operation speed
V_{NE}	Never exceed speed
V_S	Stall speed
V_{TAS}	True Air Speed

Symbol	Meaning
V_w	Wind speed
n_y	Lateral load factor
n_z	Normal load factor
t_f	Point of time when failure occurs
t_g	Time when A/C is recoverable with a significant increase in pilot workload
t_r	Latest monitor reaction time
α_{max}	Maximum angle of attack
η_F	Flap deflection angle
$\dot{\chi}$	turn rate
$\Phi(\Omega)$	spectral density
H	Altitude
L	scale length, characteristic turbulence wavelength
Ma	Mach number
m	Mass
Φ	Roll angle
α	Angle of attack
β	Sideslip angle
θ	Pitch angle
σ	root mean square (RMS) turbulence intensity

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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	`Monospace Consolas` font, underlined	`bus signal`

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-4.2 of the “EASA Horizon Flight Control Law Monitors” project.

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 robustness of the IMFs proposed in [6]. It comprises the investigated trim points, atmospheric disturbances and flight manoeuvres.

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

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 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.

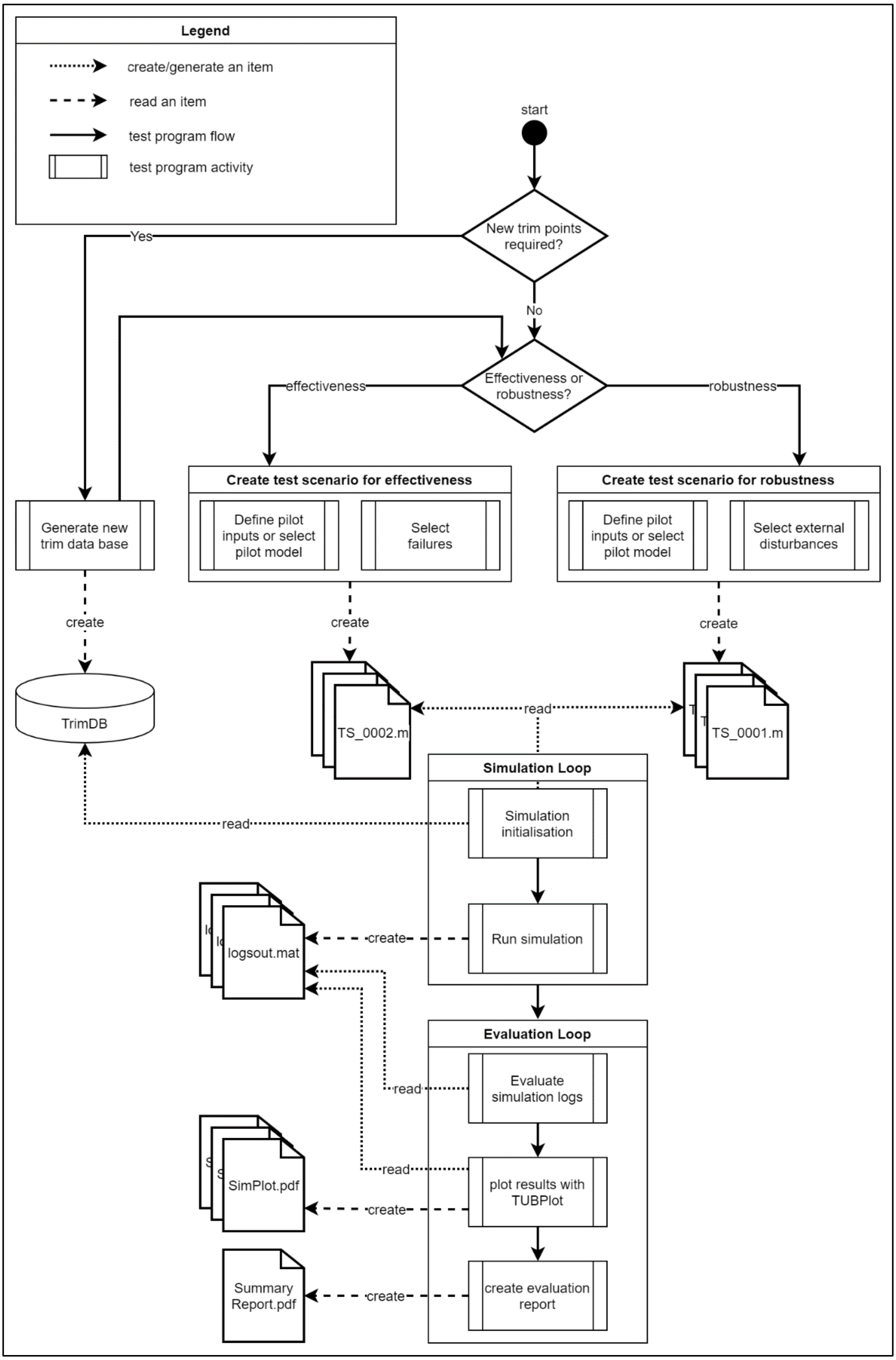

Figure 2-1: Test Program for Monitor Evaluation.

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

[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
TP3301	25	6000	160	0	0	0
TP3201	25	6000	125	0	0	0
TP3101	25	6000	97	0	0	0
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. 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.

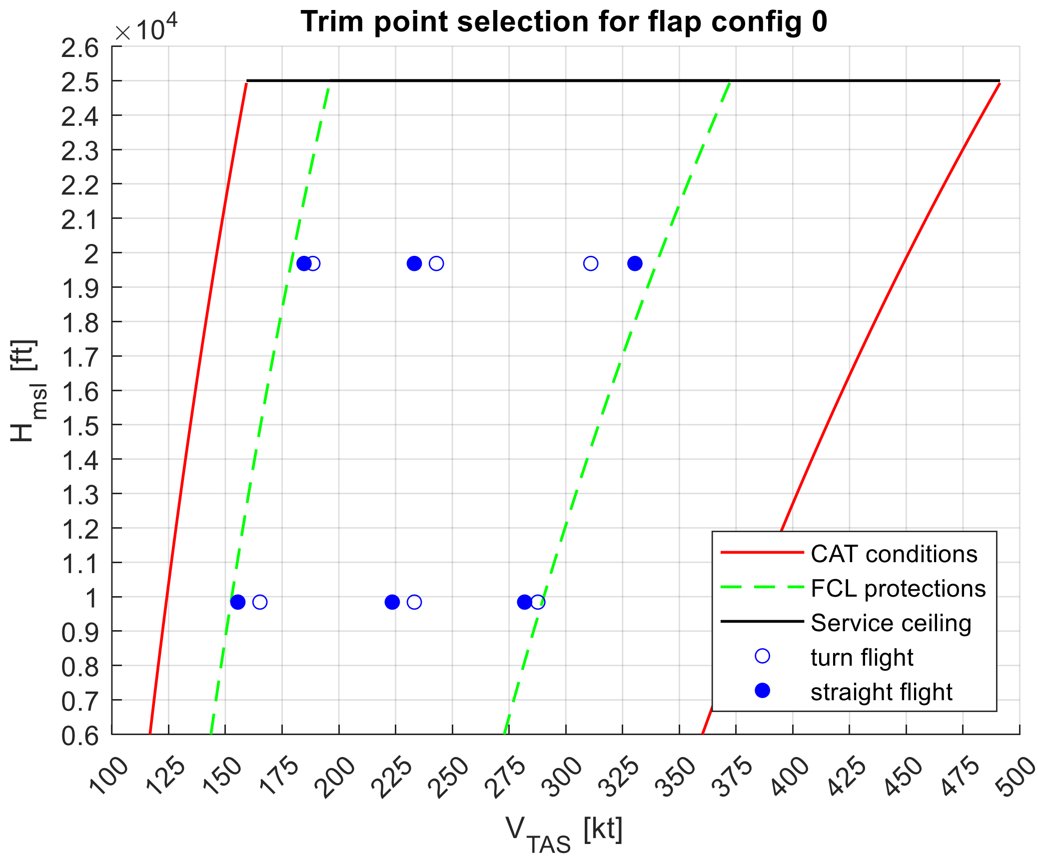

Figure 2-2: VFW614-ATD Flight Envelope Middle and High Altitude, Clean Configuration.

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.

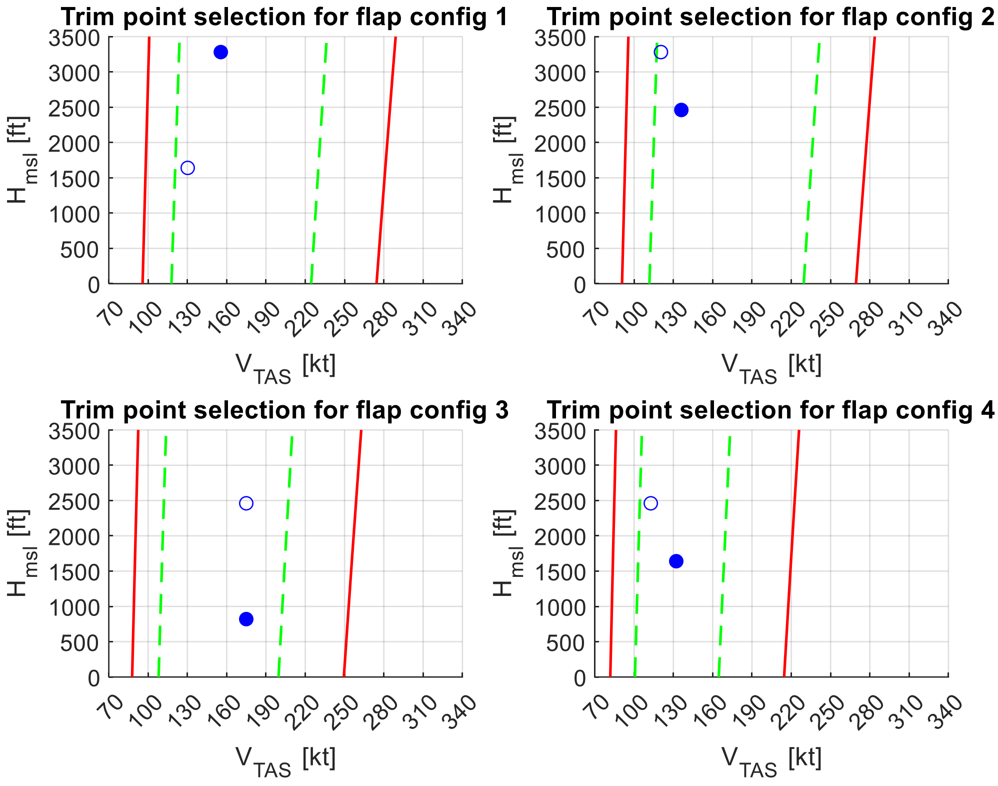

Figure 2-3: VFW614-ATD Flight Envelope Low Altitude, Different Flap Configurations.

2.3 Robustness Test Conditions

Robustness test conditions comprise foreseeable flight conditions during failure-free operations. An IMF is considered robust if it does not trigger false alarms under these conditions. In addition to normal operation manoeuvres (e.g. turn flight, climb, descent, etc.) considered in the effectiveness test conditions, high-gain manoeuvres (e.g. emergency decent, fast turn, etc.), and external disturbances (e.g. discrete gusts and turbulence) are investigated.

The external disturbances are inserted with a turbulence model that was developed at the department Flight Mechanics, Flight Control and Aeroelasticity (FMRA). The turbulence model is part of FSEnv and described in detail in [8]. The FSEnv contains the EASA CS-AWO [9] wind model 1, as the DRYDEN spectrum is suitable for simulations in the time domain. It has the same form for the longitudinal, lateral, and vertical component.

$$\Phi_{CS-AWO}(\Omega) = \frac{2\sigma^2}{\pi} \frac{L}{1 + \Omega^2 L^2}$$

with:

$\Phi(\Omega)$	spectral density [(m/s)² / (rad/m)],
σ	root mean square (RMS) turbulence intensity [m/s],
L	scale length, characteristic turbulence wavelength [m],
$\Omega = \omega/V$	spatial frequency [rad/m],
ω	temporal frequency [rad/s],
V	aircraft speed [m/s]

The turbulence model is quantitatively described via the root mean square (RMS) turbulence intensities σ_u, σ_v, σ_w, the characteristic turbulence wavelengths L_u, L_v, L_w, and the airspeed V. The turbulence intensities are given as

$$\sigma_u = \sigma_v = 0.15 \cdot V_{10}$$

$$\sigma_w = 2.8 \frac{km}{h} = 0.77\overline{7} \frac{m}{s},$$

The parameter V_{10} corresponds to the average wind speed at an altitude of 10 m above ground. The characteristic turbulence wavelengths are given as

$$L_u = 183\ m\ (600\ ft)$$

$$L_v = L_u$$

$$L_w = 9.2\ m$$

Alternatively, an altitude dependent vertical root mean square density and vertical turbulence wavelength is defined for altitudes bellow 1000 m

$$\sigma_w = 0.09 \cdot V_{10}$$

where:

V_{10} mean wind, selected according to [9]

$L_w = 4.6\ m, \quad H \leq 9.2\ m,$

$L_w = 0.5 \cdot H, \quad 9.2\ m < H \leq 305\ m$

$L_w = 152.5\ m, \quad H > 305\ m$

Additionally, discrete gusts of 1-cos shape are defined for robustness evaluation. The gust intensities are based on the CS-25 [10] and SAE AS94900 [11] standards. The CS-25 discrete gust has a probability of occurrence of 1 in 70,000 flight hours. This gust is used to estimate the maximum A/C gust loads. In the context of IMF robustness evaluation, this gust represents the most critical gust encounter during which IMFs shall not trigger false alarms.

Gust intensities based on the SAE AS 94900 are selected, to investigate gusts with lower intensities and higher probabilities of occurrence. Table 2-3 lists RMS gust intensities for selected Probabilities of Exceedance (PoE). Values for $PoE = 10^{-3}$ are selected for the robustness test cases.

Table 2-3: RMS Gust Intensities for Selected Cumulative Exceedance Probabilities (ft/s, TAS) SAE AS94900 [11]

Flight Segment	Altitude (ft)	Probability of Exceedance (PoE)						
		$2 \cdot 10^{-1}$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Terrain Following	Up to 1000 (Lateral)	4.0	5.1	8.0	10.2	12.1	14.0	23.1
	Up to 1000 (Vertical)	3.5	4.4	7.0	8.9	10.5	12.1	17.5
Normal Flight Climb Cruise and Descent	500	3.2	4.2	6.6	8.6	11.8	15.6	18.7
	1750	2.2	3.6	6.9	9.6	13.0	17.6	21.5
	3750	1.5	3.3	7.4	10.6	16.0	23.0	28.4
	7500	0	1.6	6.7	10.1	15.1	23.6	30.2
	15000	0	0	4.6	8.0	11.6	22.1	30.7
	25000	0	0	2.7	6.6	9.7	20.0	31.0
	35000	0	0	0.4	5.0	8.1	16.0	25.2
	45000	0	0	0	4.2	8.2	15.1	23.1
	55000	0	0	0	2.7	7.9	12.1	17.5
	65000	0	0	0	0	4.9	7.9	10.7
	75000	0	0	0	0	3.2	6.2	8.4
	Over 85000	0	0	0	0	2.1	5.1	7.2

The described disturbances are introduced in combination with the flight manoeuvres. The effectiveness flight manoeuvres are reused for robustness simulations. Additionally, high-gain manoeuvres are defined to push the A/C into operational limits and activation of FCL protection functions.

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 2-4.

Table 2-4: 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:

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

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 [10] 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 [10].

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 [10]. 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 CAT failure condition are exceeded. 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 2-4 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. 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.

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.

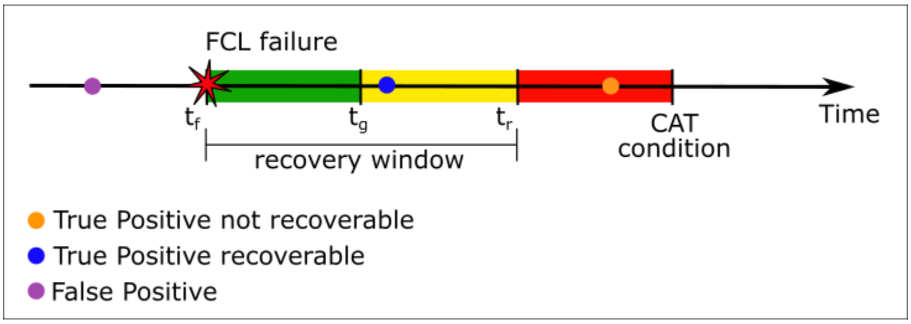

Figure 2-4: Metric for Recoverability after Failure Detection.

3 Robustness Test Conditions

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

3.1 Atmospheric Disturbances

The atmospheric disturbances are introduced either with a CS-AWO turbulence model [9] or by script. Figure 3-1 shows the cumulative probabilities of reported mean wind speeds V_{10} and the three selected values for turbulence test cases. For trim points with altitudes below 1000 m the altitude dependent CS-AWO turbulence model is selected. For all trim points with altitudes over 1000m the altitude independent turbulence model is used.

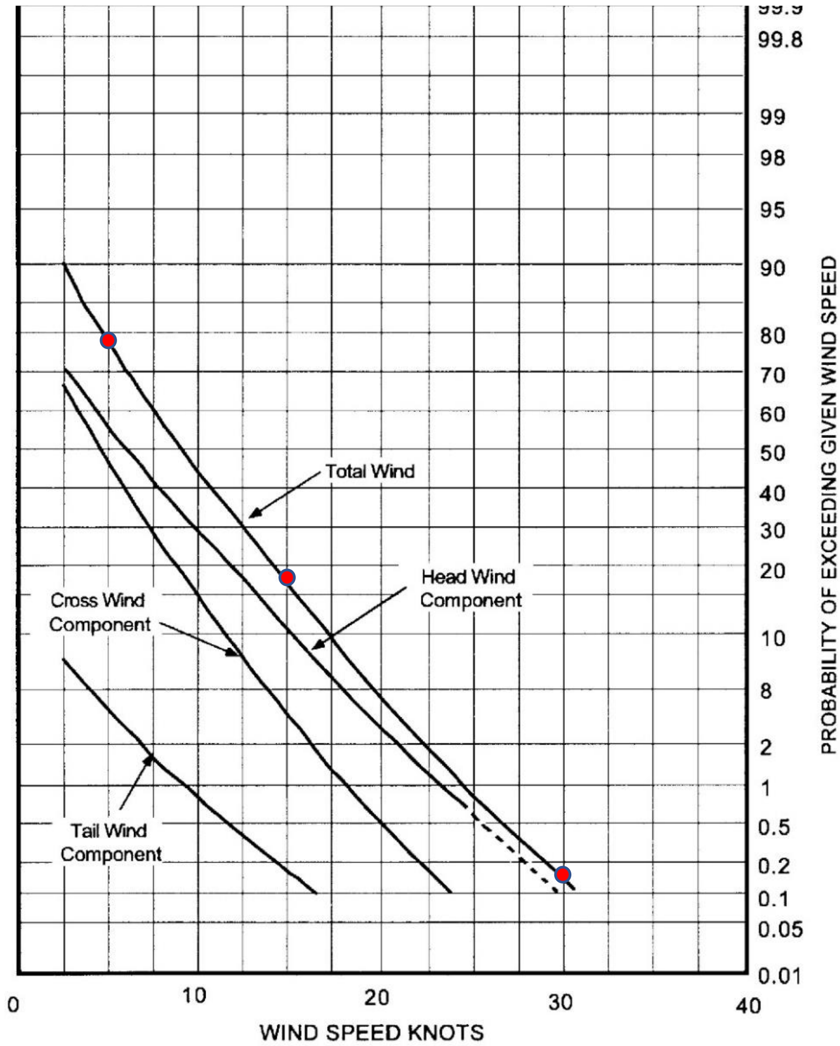

Figure 3-1: Cumulative probability of reported Mean Wind V10 and Headwind, Tailwind and Crosswind Components when landing [9].

Discrete gusts are defined according to [10] and [11]. The CS-25.341 gusts are defined for characteristic gust length of $H = 107\,m$. The SAE AS94900 gusts are defined for probabilities of exceedance of 10^{-3}. The gust magnitude is calculated according to [12][4] (see Figure 3-2) from

[4] Note that SAE AS94900 [11] references MIL-STD-1797 [12] for the calculation of discrete gust magnitudes.

the RMS gust intensities defined in Table 2-3. Figure 3-2 shows the ratio between gust length and gust magnitude and the selected gust lengths.

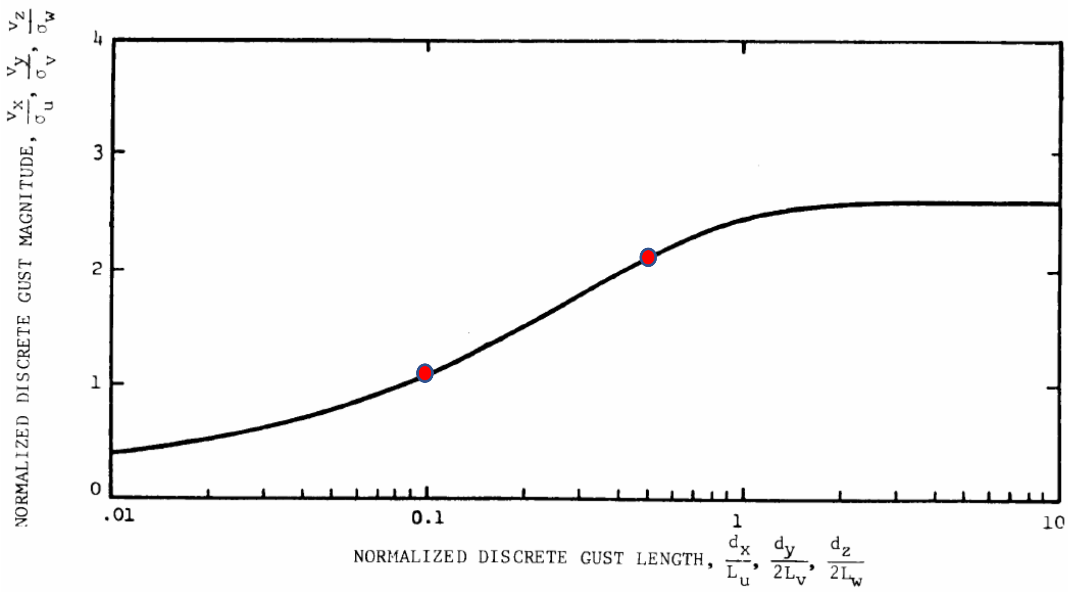

Figure 3-2: Magnitude of Discrete Gust [12]

All selected discrete gusts are introduced as crosswind gust, downwind gust, upwind gust, and headwind gust. Tailwind gusts are excluded from robustness evaluations due to their negligible impact on IMFs, as demonstrated in reference [13]. Table 3-1 lists all selected atmospheric disturbances.

Table 3-1: List of Atmospheric Disturbances

Disturbance ID	Description
GCS25CRL	Discrete crosswind gust from left according to CS 25.341 with $H = 107\ m$
GCS25CRR	Discrete crosswind gust from right according to CS 25.341 with $H = 107\ m$
GCS25DW	Discrete downwind gust according to CS 25.341 with $H = 107\ m$
GCS25UP	Discrete upwind gust according to CS 25.341 with $H = 107\ m$
GCS25HW	Discrete headwind gust according to CS 25.341 with $H = 107\ m$
GMIL1CRL	Discrete crosswind gust from left according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.1$
GMIL1CRR	Discrete crosswind gust from right according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.1$
GMIL1DW	Discrete downwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.1$
GMIL1UP	Discrete upwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.1$
GMIL1HW	Discrete headwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.1$
GMIL2CRL	Discrete crosswind gust from left according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.5$

Disturbance ID	Description
GMIL2CRR	Discrete crosswind gust from right according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.5$
GMIL2DW	Discrete downwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.5$
GMIL2UP	Discrete upwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.5$
GMIL2HW	Discrete headwind gust according to SAE AS94900 with normalized discrete gust length $\frac{d}{L} = 0.5$
TAWO5LA	Turbulence according to CS AWO with $V_{10} = 5\ kt$, at altitude under 1000 m, vertical turbulence components depend on altitude.
TAWO15LA	Turbulence according to CS AWO with $V_{10} = 15\ kt$, at altitude under 1000 m, vertical turbulence components depend on altitude.
TAWO30LA	Turbulence according to CS AWO with $V_{10} = 30\ kt$, at altitude under 1000 m, vertical turbulence components depend on altitude.
TAWO5HA	Turbulence according to CS AWO with $V_{10} = 5\ kt$, at altitude over 1000 m, vertical turbulence components are altitude independent.
TAWO15HA	Turbulence according to CS AWO with $V_{10} = 15\ kt$, at altitude over 1000 m, vertical turbulence components are altitude independent.
TAWO30HA	Turbulence according to CS AWO with $V_{10} = 30\ kt$, at altitude over 1000 m, vertical turbulence components are altitude independent.

3.2 Aircraft Manoeuvres

The manoeuvres from the effectiveness tests are reused for the robustness tests. The full list of normal operation manoeuvres is given in [14]. Additionally, high-gain manoeuvres are defined to bring the aircraft and the FCL close to the operational limits.

Climb and descent manoeuvres are required to achieve an altitude difference of 3000 ft with climb/descent rate over 4000ft/min[5]. Turn manoeuvres are limited to a 180-degree change of direction at a turn rate of $\dot{\chi} > 5\ °/s$ [5]. Fast climb and descent manoeuvres are also performed during a fast turn. without exceeding the operational limits of the FCL.

The emergency descent is simulated for trim points with high altitude by setting the speed brakes (spoilers), achieving 6000 ft/min descent rate until altitude of 3000 m is achieved.

The landing ILS-approach uses a pilot model to simulate the pilot inputs during this flight phase. The pilot model gains for the turn and pitch commands are increased. Table 3-2 lists the flight manoeuvres that are used for robustness test conditions.

Table 3-2: Selected Manoeuvres for Robustness Test Conditions.

ID	Description
FCLBPS	3000ft fast climb manoeuvre, $\dot{H} > 5000 ft/min$ rate of climb, if target altitude is reached high push command.
FDSNTPL	3000ft fast descent manoeuvre, $\dot{H} < -5000 ft/min$ rate of descent, if target altitude is reached high pull command.

[5] The specified rates of change may not be achieved for all trim points due to activation of FCL protections.

ID	Description
EDSNT	Emergency descent, full spoiler, thrust 0, $\dot{H} = -6000 ft/min$ rate of descent.
FTURN	Initiate a 180-degree turn, with turn rate of $\dot{\chi} > 5\,°/s$, high pull-up command allowed, constant altitude +-500ft.
TFCLB	fast 3000ft climb manoeuvre and turn with turn rate of $\dot{\chi} > 5\,°/s,$ then level flight.
TFDSNT	fast 3000ft descent manoeuvre and turn with turn rate of $\dot{\chi} > 5\,°/s$, then level flight.
LNDHG	Landing approach with high lateral offset to localiser with pilot model, high gain pilot.

The selected flight manoeuvres can be combined with the trim points described in section 2.2 and the selected atmospheric disturbances, see section 3.1. However, some rules for combinations of trim points and manoeuvres are defined:

- Only LND and climb maneuvers at low altitudes and middle speed range,
- No EDSNT at low altitudes,
- No LND, LNDHG at medium and high altitudes,
- All descent maneuvers only at medium and high altitudes,
- All climb maneuvers only at medium and high-speed range,
- Crosswind gusts from the right are only combined with trim points where $\Phi \neq 0°$, or turn maneuvers.
- CS-25 gusts are only combined with nominal maneuvers from effectiveness tests.

The full combinations of trim points, flight manoeuvres and disturbances are given in the robustness test conditions list which is attached at the following Link:

test_conditions/robustness_test_conditions_v02.pdf

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