ACCEPTABILITY ASSESSMENT PREPARATION FOR ISOMETRIC BACKUP-MODE OF ACTIVE INCEPTORS

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Abstract

The inherent isometric back-up mode of an active side stick which uses the force signal as command signal after a potential stick jam failure is subject of a current DLR study. The failure effects and the handling qualities of the back-up mode were evaluated experimentally in a piloted simulation. Two pilots tested the back-up mode in two different mission-task-elements, slalom and hover, for two different response types, rate command and attitude command. The backup-mode was rated handling quality level II. The effect of a sudden transition from nominal mode to failure mode was rated as minor. It is strongly suggested to train the pilots to be able to deal with the sudden change of control behavior at the transition. Only qualitative evaluations were done so far.

SYMBOLS AND ABBREVIATIONS

AC		Attitude command response type
ACT/FHS		Flying Helicopter Simulator based on EC-135
CHR		Cooper-Harper-Rating
DLR		Deutsches Zentrum für Luft und Raumfahrt e.V. (German Aerospace Center)
FCMC		Flight control mechanical characteristics
FCS		Flight control system
HV		Hover MTE
MTE		Mission task element
NOE		Nap-of-the-earth
OFE		Operational flight envelope
RC		Rate command response type
SFE		Service flight envelope
SL		Slalom MTE
D	$\left[-\right]$	Damping factor
k	$\left[\frac{N}{\%}\right]$	Spring gradient or filter gain
ω_0	$\left[\frac{rad}{s}\right]$	Eigen frequency

1. INTRODUCTION

Active inceptors open new possibilities of pilot assistance. Through actuators in the stick they can be used to generate force cues which help to maintain operational limits, like engine torque[1]. Furthermore they allow the optimization of the handling qualities by adaption of the flight control mechanical characteristics (FCMC) as currently done in a common research cooperation of AMRDEC, NASA and DLR[2].

Currently, the application of active inceptors is still limited to research helicopters like the German ACT/FHS, the American RASCAL or the Canadian ASRA. However some military helicopter projects plan to be equip helicopters like the S-92, the UH-60M and the CH53-K with active sticks. Also the cockpit concept for the new planned civil Bell/Boeing 525 relentless, called ARC, is announced to use tactile cueing in combination with side sticks [*Bell Helicopter Textron Inc. The ARC Horizon Flight Deck. Fact sheet from www.bell525supermedium.net, access on February 10, 2012*].

Active inceptors have several benefits. However, one may ask for the safety aspects of new high fidelity and complex subsystems in the cockpit. Generally, an inceptor has to fulfill a high safety standard since a complete loss of the controller leads inevitably to a dangerous situation, especially in a single piloted helicopter. According to Federal Aviation Regulation (FAR) part 29 this means a level of reliability of less than 10^{-9} failures per flight hour. Compared to a classical mechanical leverage system an active inceptor is a complex electromechanical system consisting of motors, several sensors and a computer (CPU) as illustrated in Figure 1. As more components mean more possibilities to fail, the overall reliability has to be assured through reliable components and/or redundancy. This is connected with higher weight and also higher costs of the overall system. Especially the motors and the gearing are heavy parts which would quickly increase the weight when used in multiplicity. An alternative to redundancy is a back-up through reconfiguration. The idea is to use the remaining subsystems or modes to fulfill the task of the failed subsystem. The main task of an inceptor clearly is to provide a means for the control input of the pilot and to transmit the control signal to the flight control system (FCS). If for example the stick would jam due to a problem with the gearbox, it would not be possible to modify the deflection to get an output signal. In this case it would be possible to use the force signal as primary control signal, known as isomet-

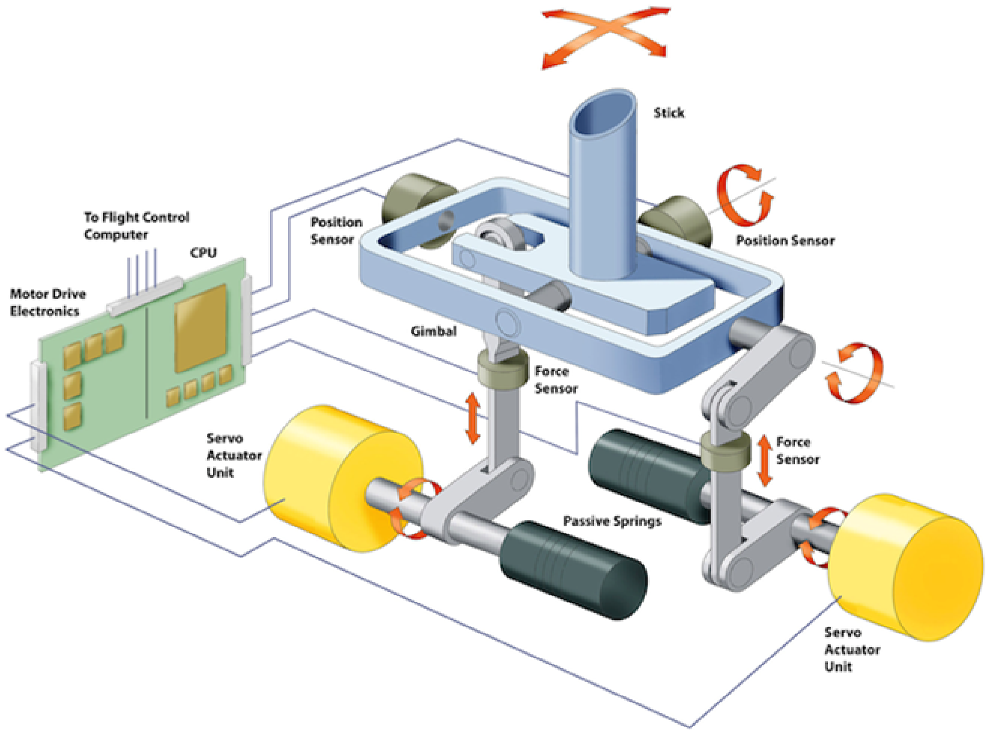

Figure 1: Typical layout with sensors, CPU and the servo actuator unit (from BAE Systems[3])

ric force command. With such a reconfigurability the required reliability could be reached without multiplying subsystems, thus saving cost and weight. Further hypothetic reconfigurations are:

- Jam of servo actuator
  ⇒ Isometric, force steering.
- Loss of motor force
  ⇒ Isotonic (force-free), position steering.
- Loss of sensors
  ⇒ Discrete steering with directional switches.

The above mentioned reconfigurations could be realized with the same components as already used in existent stick designs. Especially in combination with higher response types supported by a FCS, they seem to be successful. The Joint Strike Fighter (JSF) F35 uses isometric and isotonic backup modes with its active sticks as published by and BAE Systems[3] and NAVAIR [*Joseph Krumenacker. Active Sticks / Throttles for JSF from Navair Flight Controls / JSF Vehicle Systems. unpublished presentation, April 26, 2006*]. BAE Systems presents a "*jam failure mode for the remote possibility that the gearbox will jam*" by reverting to the force signal. No detailed information is given about the realization or behavior of those modes yet and the "*need for the development of civil and military standards to cover active inceptor failure modes and handling*" is stated.

A current DLR study deals with the definition of requirements for back-up modes of active inceptors used in future regular helicopter. For this a method is needed to be able to evaluate potential reconfiguration modes.

This paper describes the collection of existing schemes for back-up mode evaluation and the design of an experimental assessment for a later test campaign. It reports a first experimental test with two pilots to explore if the method is applicable to large scale experiments. The above mentioned jammed gearbox failure and its isometric force command reconfiguration were realized in the ACT/FHS fixed base ground simulator. This contained two active side sticks whose force-feel behavior could be configured, so that it was possible to mimic a failure by setting the appropriate parameters. The assessment was done for two different FCS response types.

2. EVALUATION METHOD

The common severity classification following FAR Part 23[4] distinguishes between five levels of severity of a failure conditions. The severity level defines the acceptable probability of an encounter: The more severe the consequences of a failure are, the more it has to be avoided, as expressed by Table 1 in maximum occurrences by flight hour. To estimate the severity of a failure, several evaluations have to be combined. Qualitative and quantitative evaluations of both, the failure or backup mode itself and the transient from nominal operation to backup mode have to be performed. ADS-33 provides a classification of the probability of failure encounter vs. the resulting handling qualities (Table 2).

Table 1: Severity levels and probability of occurrence[5]

Failure Severity	Maximum Probability of Occurrence
	per flight hour
CATASTROPHIC	$< 10^{-9}$
HAZARDOUS	$< 10^{-7}$
MAJOR	$< 10^{-5}$
MINOR	$< 10^{-3}$
NO EFFECT	$< 10^{0}$

The failure mode can be seen as a regular control mode, which is evaluated by regular handling quality methods, as defined by Cooper-Harper[6] and ADS-33[7]. A failure mode, which provides good handling qualities and does not lead to abandoning the operational flight envelope (OFE) may be permitted more often than a failure which leads to bad handling qualities and a transition into the service flight envelope (SFE).

Table 2: Handling qualities in failure mode and probability of occurrence from ADS-33[7]

	OFE	SFE
Level	per flight hour	per flight hour
II	< 2.5 x 10^{-3}	
III	< 2.5 x 10^{-5}	< 2.5 x 10^{-3}
Loss of control	< 2.5 x 10^{-7}	

A failure may induce a transient or oscillations which the pilot has to recover before a safe continuation of the flight is possible. During that time the helicopter may be uncontrollable and/or performing unintended movements. This could cause a collision with nearby obstacles. This is why the ADS-33 presents quantitative evaluation criteria for the transient effects after a failure. They are expressed in maximum accelerations and attitude changes and the time period for that no recovery action is needed, without leaving the OFE.

The quantitative evaluation of the transient effects can be done according to ADS-33, see Table 3. Even though the quantitative analysis was not yet part of the proof-of-concept-study, which is described in this paper, the table is presented here for the sake of completeness for later use.

For the qualitative evaluation of the transient and ability to recover from a failure a scheme can be used, which is similar to the Cooper-Harper-Rating (CHR) scale and is illustrated in Figure 6 in the appendix. It was originally developed by Hindson et al.[8], was further developed by Weakly et al.[9] for an evaluation of FCS failures of the V-22 and was again redefined by Padfield and colleagues[10].

Table 3: Transients following failures from from ADS-33[7]

	Flight condition *	
Level	Hover and low speed *	Forward up-and-away *
I	3 deg roll, pitch, yaw 0.05 g nx, ny, nz. No recovery action for 3.0 s.	Stay within OFE. No recovery action for 10.0 s.
II	10 deg attitude change or 0.20 g acceleration. No recovery action for 3.0 s.	Stay within OFE. No recovery action for 5.0 s
III	24 deg attitude change or 0.40 g acceleration. No recovery action for 3.0 s.	Stay within OFE. No recovery action for 3.0 s

* For near earth forward flight both "hover and low speed" and "forward up-and-away" requirements apply.

The failure evaluation scheme is divided into two connected parts. One is for rating the short and mid term effects of a failure and leads to a failure rating which is expressed on an alphabetic scale from A to H. The other part is for the long term effects and is taken from the Cooper-Harper-Rating (CHR) scale leading to a handling quality level between I and IV. The interview begins at the bottom of the scheme with a general question about the ability to recover the helicopter after the failure. When answered positively the next question is concerning the safety of the recovery. When the recovery was safe, the scheme enables to categorize the failure as MINOR or MAJOR. If the recovery was not safe, the category is HAZARDOUS. When it is not possible to recover after the failure, the category is CATASTROPHIC. Continuing to the right of the scheme the evaluation of the transient and the recovery leads to the combined failure rating and ultimately to the handling quality rating of the failure or backup mode recovery. To have a benchmark, the handling qualities of the nominal system have to be evaluated before the failure is rated.

The severity of a failure depends clearly on the situation when it happens, why the selection of the test scenario has an effect on the evaluation result and also on the ability to generalize. This is why one or more appropriate worst case scenarios need to be defined (sect. 4).

3. BACKUP BY ISOMETRIC FORCE COMMAND

It is known that an isometric force control was used as a regular control in the F-16 and also tested as a regular controller for helicopters[11;12]. But it is not known how these modes behave as backup system for a regularly compliant stick. The special problem here is that the flight control system and pilot have to react on an externally triggered sudden failure, which may provoke overreaction and oscillations.

In this study the active stick for cyclic control is configured to mimic a complete jam of both axes after pressing a button. One button is provided on the stick to be used by the experimental pilot for training and one is at the flight test engineer station to be triggered unannounced by a confederate during the test. Based on that trigger the friction is set to 150 N for both axes of the cyclic side stick. This is the maximum force that can be generated by the stick. The pilot could only exceed it through a very high effort and intuitively interprets it as a failure mode.

According to Johnston and Aponso[11] a 2nd order lag pre-filter is useful to *prevent the system from roll ratcheting and other high frequency extraneous effects*. The normal operating stick incorporates the 2nd order dynamic as spring-damper-mass system. The filter has the form of Equation 1. ω_0 is the Eigen frequency, D the damping and k is the filter gain as equivalent to the spring gradient of the mechanical stick.

$$X(s) = \frac{1}{k_{sens}} \frac{{\omega_0}^2}{s^2 + 2D\omega_0 s + {\omega_0}^2} \quad (1)$$

The selection of the filter parameters has do be done with caution, as it works as a lagging element in the control loop. Initially they were set equal to their corresponding parameters of the stick. Later in the experiment they are optimized during system familiarization by the pilots.

It is assumed that a possible implementation of a real backup mode had an automatic failure detection which would send a failure signal to the FCS. This would activate an automatic switching logic which selects the force signals from the stick as new command input for pitch and roll. The switching logic shall avoid a step at switching from nominal to isometric failure mode. Also it provides an ability to trim away the zero force output. For the failure mode simulation the switching is activated directly from the failure trigger button signal. The realized switching logic enables:

- Filter integrator reset: The filter states are reset to the current states of stick-position and stick-speed.
- Current trim value inherited: When releasing the stick-force in failure-mode, the output signal goes back to the last trim value.
- Force trim release and gradual trim (beep-trim).

The FCS of the ACT/FHS ground simulator has a rate command (RC) and an attitude command (AC) response type. Figure 2 shows the signal flow of the pilot input force through the stick, which outputs the position and the measured force. Either the position (nominal mode) or the filtered force (failure mode) are selected as command signal for the FCS, depending on the failure state.

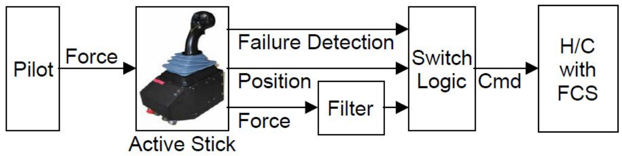

Figure 2: Signal flow for normal and failure mode

4. EXPERIMENT

The evaluation of the failure mode was conducted in DLR's fixed base helicopter flight simulator (see Figure 3) based on appropriate flight tasks. The simulation contains an analytical model of the EC 135 ACT/FHS. It can be controlled by conventional controllers or two active side sticks. Different response types like rate command type (RC) and attitude command type (AC) are available. Two pilots participated in the experiment. Pilot 1 was a DLR research engineer, glider and experienced helicopter simulator pilot. He helped to develop and train the evaluation work-flow in the simulator and made the full assessment as rehearsal before the system was presented to the regular test pilot. Pilot 2 was a licensed helicopter test pilot with a lot of experience on the ACT/FHS and on the simulator. For the evaluation, standardized flight tasks were needed. These should cover different criteria to allow a valid rating of the controllability of the selected failure mode of the cyclic controller. The basic criterion was whether a flight could be terminated safely, also from a dynamic maneuver. These criteria are characterized by high airspeeds and high-frequency inputs with large amplitudes and high demand of precision enforced by proximity to obstacles or ground like in nap-of-the-earth (NOE) flight, to assure the ability to safely land the helicopter.

Figure 3: DLR fixed base helicopter system simulation with active side sticks used for the study

The flight tasks were selected from the ADS-33[7], which offers a whole catalog of standard mission-task-elements (MTE) for the handling quality assessments of the various helicopter roles. All MTEs are modeled in the simulation environment. Two MTE-tasks were selected, as they meet the demanded criteria:

- Slalom (Criteria NOE, airspeed greater than 40 kts, High amplitude steering)
- Hover (Criteria high frequency, precision and proximity to ground).

Two different response types (RC and AC) combined with two maneuvers (slalom and hover) resulted in four scenarios. Every scenario had to be flown three times. The first flight was for the nominal configuration as a benchmark. After that the task was flown again, while the failure was triggered manually by an assistant in a worst case situation. This was either at full bank angle immediately before passing a gate during the slalom or in the stabilization phase in the hover-task. The pilots had to try to finalize the task even after the failure. The third time the task was flown again, being in the failure mode right from the beginning. The runs of every scenario were flown directly one after the other, only interrupted by the evaluation interviews directly after the runs. Before each scenario the participants could familiarize with the failure mode and train the MTE's as long and often as they needed (1 to 4 runs). The following evaluation interviews were made:

1. Cooper-Harper rating for nominal configuration.
2. Transient and recovery failure rating.
3. Cooper-Harper rating for persistent failure mode.

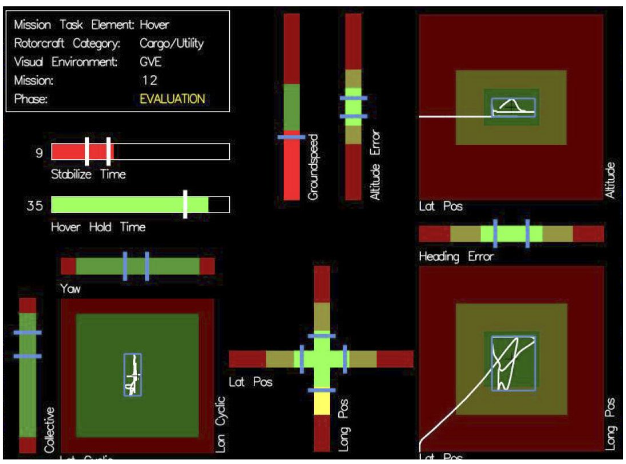

Figure 4: Task performance display[13]

In addition to the qualitative handling evaluation, the MTE-task displays of the ACT/FHS experimental system were observed by the experimenter to get a direct information about the compliance of the adequate and desired limits. Figure 4 shows exemplary the display for the hover MTE. The simulated flight-data were recorded for every run.

The stick dynamics and the filter parameters were initially adapted for the different scenarios with the help of pilot 1 (Table 4). The parameter settings found were used for both pilots. For this study the dynamics of stick and filter were kept purely linear to simplify the realization of a transient free switching from the nominal to the back-up mode. Both were pure linear 2nd order dynamics without breakouts, detents or control death-bands. Other than suggested by Morgan[12] no signal shaping of the force signal was applied in this stage of the study. The unit of the spring gradient or filter gain k is $\frac{N}{\%}$ and the output interval is 0...100% for the stick and the filter.

Table 4: Parameter settings for the active stick and filter

	k_{pitch}	k_{roll}	D	ω_0
	$\frac{N}{\%}$	$\frac{N}{\%}$	$[-]$	$\left[\frac{rad}{s}\right]$
RC SL Stick	0.8	0.8	1.2	20.1
RC SL Filter	2.0	1.0	1.2	24.0
RC HV Stick	2.0	2.0	1.2	20.1
RC HV Filter	2.0	2.0	1.2	24.0
AC SL Stick	0.8	0.5	1.0	20.1
AC SL Filter	2.0	1.0	1.2	24.0
AC HV Stick	2.0	2.0	1.2	20.1
AC HV Filter	2.0	2.0	1.2	24.0

The complete session of 24 individual simulator flights with CHR and failure rating interviews directly after each run took about two hours for every pilot with a net flight time of one hour for each pilot.

5. RESULTS AND DISCUSSION

During the training it became evident that both pilots initially had problems to deal with the failure and in the very first trials even crashed. After some flight trials in the failure mode pilots were generally able to control the helicopter in the failure mode also when it happened unannounced.

The qualitative evaluation results are displayed separately for both pilots in Figure 5 according to the combined failure evaluation scheme of CHR and transient/recovery (Figure 6 in the appendix). The ratings are presented in rating-triples for every tested scenario. The triple representation was selected to see the failure effect at a glance. It consists of a CHR-pair, indicating a change of the CHR from nominal (unfailed) mode to failure mode and the failure rating.

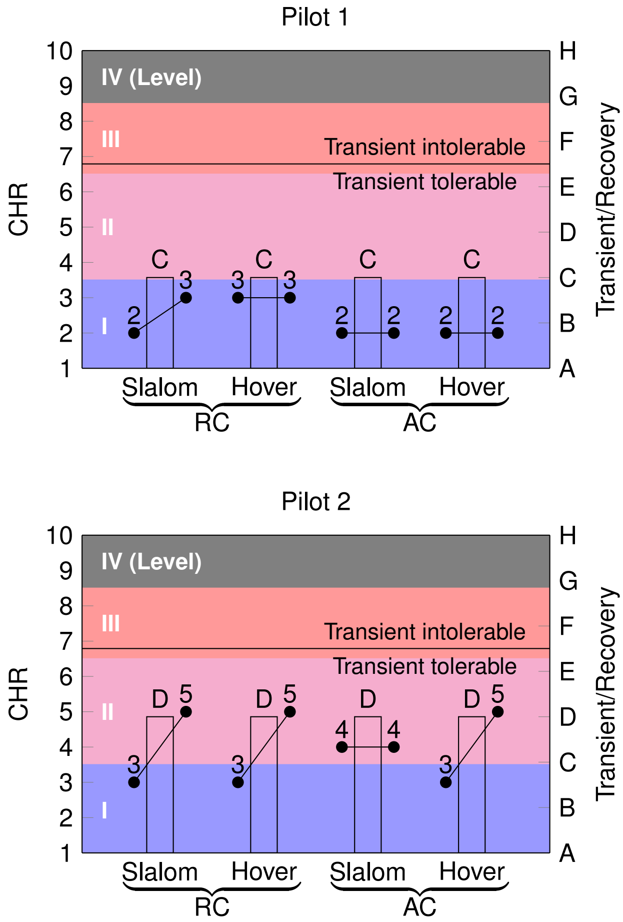

Figure 5: Qualitative failure ratings

The failure transient and recovery were rated separately and the worst of both was selected as final failure rating. The CHR number pairs are related to the right-hand axis, the transient/recovery rating letter is related to the right-hand axis. The figure's background is colored to indicate the regions for the different handling quality levels from I to IV. A horizontal line between E and F indicates the tolerable and intolerable intervals for the transient/recovery rating.

Comparing both figures it is obvious that the regular test pilot evaluated the system more critical than the engineer. The test pilot rated the failure mode for three of four scenarios worse than the nominal mode, the engineer did this only once. But both pilots rated the failure mode with handling quality level II. Pilot 1 rated all failures C, pilot 2 rated all failures D. Both ratings are in the tolerable region.

For the quantitative evaluation the proof of maintaining the defined MTE limits for desired and adequate handling quality rating was conducted. No severe transients in attitude, speed and deviation from course were observed. One gate was closely failed during the slalom maneuver in persistent failure mode from Pilot 1 in RC and Pilot 2 in AC. The hover maneuver could be flown well but at the occurrence of the failure, pilot 2 was outside the 6 ft hover square for adequate performance for a short period. The error was lower than 3 ft. In addition to the ratings, both pilots commented different issues, as are:

- Learning effect: Pilot 2 said, he could handle the failure mode better with increasing experience.
- Oscillation: Pilot 2 remarked a too high sensitivity in RC and an oscillation in AC hover. Problems occurred especially with the pitch axis. The observed oscillations were not classified as PIO.
- Nominal configuration: Pilot 2 wished a breakout to give a clearer cue for side stick center position.
- Short term effects: Pilot 2 claimed a tendency to over control initially (AC Slalom), although he had trained before and knew, that the failure would happen during the task. He forced himself to reduce control activity and "let it go". He discovered light oscillations but no PIO. Especially the short term period in RC hover was found very demanding.
- Long term use: Pilot 2 remarked, that the failure mode would not be flyable longer than 0.5 h. He found it demanding to hit the gates in the slalom maneuver.
- System aspects: Pilot 1 commented, that a use of force trim release (FTR) directly after the transition to failure mode would be difficult to handle. It should be blocked for a short period directly after the transient.

6. CONCLUSION AND OUTLOOK

The paper reported an assessment program which was prepared to evaluate the severity of potential failures of active inceptors using a general failure evaluation scheme for aircraft. It was applied on a simulated isometric failure mode. It was shown that the test method is applicable for the evaluation of back-up modes. Furthermore first test results were collected, which showed a first trend for the acceptability of an isometric failure mode for an active cyclic side stick in combination with higher response types.

If these first results can be generalized in further studies, the isometric failure mode would have to be classified as MINOR, according to Figure 6. These failures would be acceptable at a probability of encounter 2.5 per 1000 flight hours according Table 2.

For future studies more test pilots need to be involved in the evaluations in the simulator and ultimately also in real flight experiments with the ACT/FHS. The selected standard mission task elements hover and slalom from ADS-33 suited best to cover the most important flight situations regarding a sudden isometric-failure mode of the cyclic controller. The maneuverability and precision could be well evaluated. Being able to handle the hover task well, the ability of a safe landing is probable.

To gain a better understanding of the maneuver accuracy the development of a flight task incorporating a dense obstacle or nap-of-the earth scenery is useful for further evaluations in the simulation. This would provide a higher level of urgency to maintain a high level of precision in order to avoid collisions. No analysis of the recorded flight data was done so far.

In order to complete the evaluation a check for the satisfaction of the transient criteria from ADS-33 (Table 3) should be done. This comprises of an analysis of the changes in attitude and accelerations and the ability to stay within the operational flight envelope after a failure.

It is strongly suggested to train flying in the isometric back-up mode well. In this study the training session took place only minutes before the evaluation and the pilots knew that a failure would happen sometime during the flight. In reality the training experience may lay back several month and a failure would happen suddenly. To gain knowledge about the permanency of the training the experiment can be repeated with the same pilots after a period of some weeks or months or even a year, of course without additional training and without a proper announcement.

From the technical point of view, the realized backup-mode which consists of a simple 2nd order prefilter and a switching logic worked out well. No stepwise control inputs from signal switching were noticed. To get rid of the light oscillations noticed in the pitch axis a deeper analysis could help to optimize the filter characteristics. A signal shaping could help to reduce oscillations around the neutral position. Attitude Command systems or higher modes may not need a force signal filter anyway, as the filter was suggested from Morgan[12] especially for rate command response types. Instead an indication of the commanded input value in the primary flight display could help the enhance situation awareness and relieve over control. The applied method can also be used to assess further hypothetic failure modes, like the force less stick or the discrete control through directional switching.

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7. APPENDIX

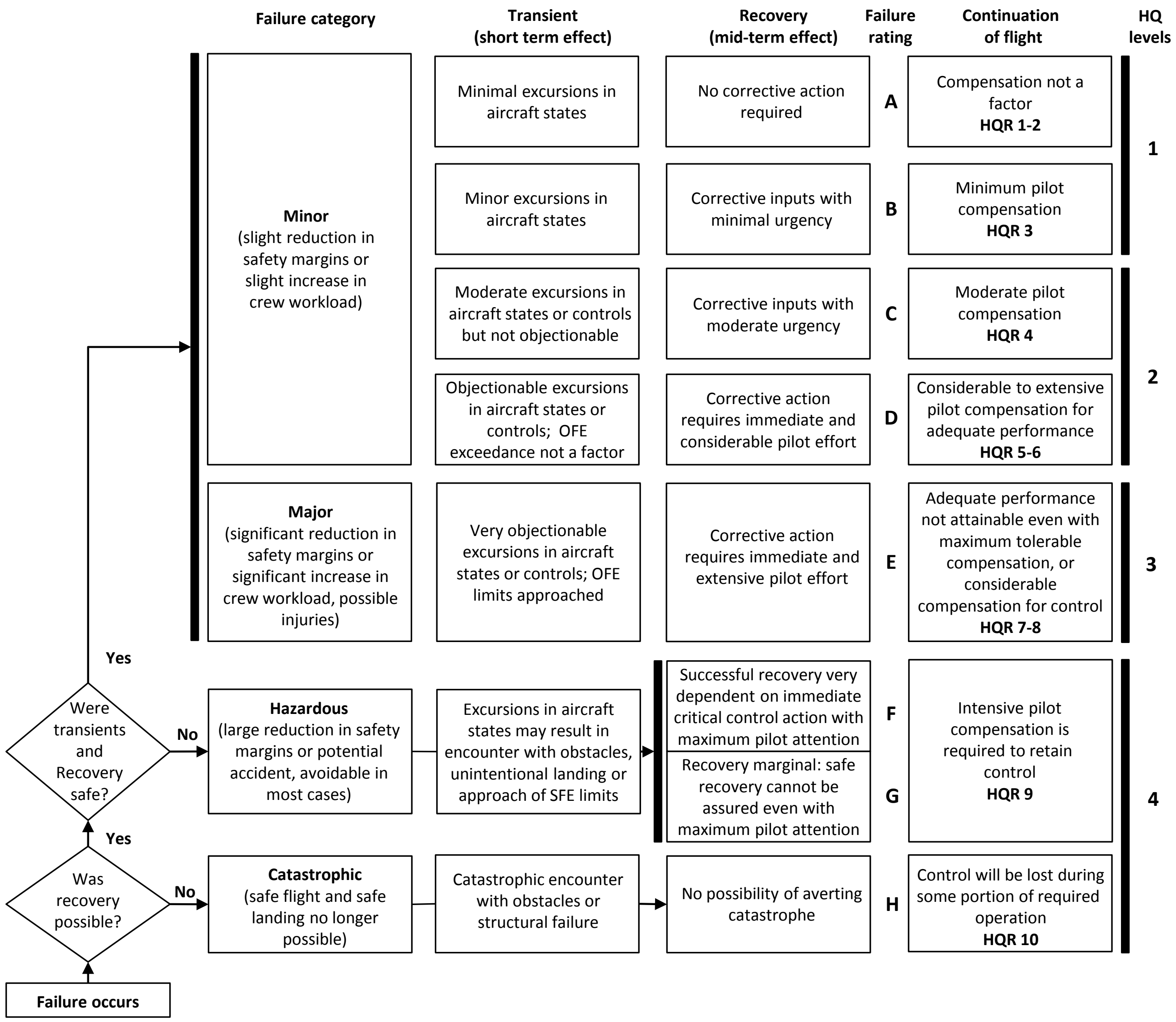

Figure 6: Integrated failure evaluation scheme (redrawn from Padfield [10])