DELFT UNIVERSITY OF TECHNOLOGY
FACULTY OF AEROSPACE ENGINEERING

Course	:	Aerospace Human-Machine Systems (AE4316)
Date	:	Jan 25, 2016 from 09:00 until 12:00 hr
Lecturer	:	dr.ir. M.M. van Paassen et al.
Remarks	:	Write your name, initials and student number on your work. Answer all questions in English and mark all pages with your name.

Instructions

This exam consists of 6 questions.

Allowed Items

Formula sheet ae4316
Calculator (programmable calculators are not allowed)
scrap paper, ruler, protractor

Grading information

The exam consists of 6 questions, each correctly answered question is awarded 15 points. The final mark is then:

$$1 \leq 1 + 6/10 * (0 \ldots 15) \leq 10$$

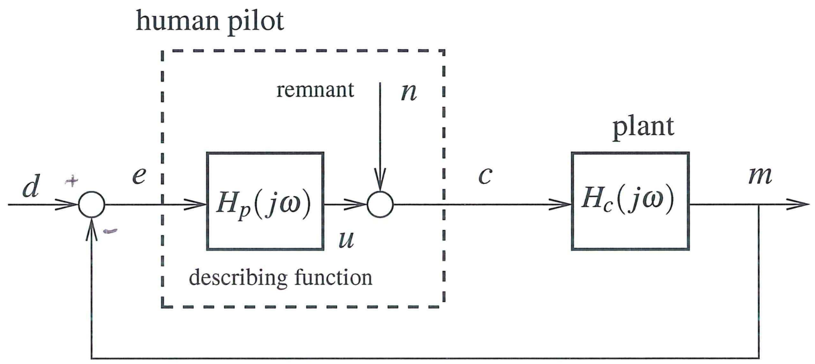

Figure 1: Closed loop manual control task: a following task with a compensatory display.

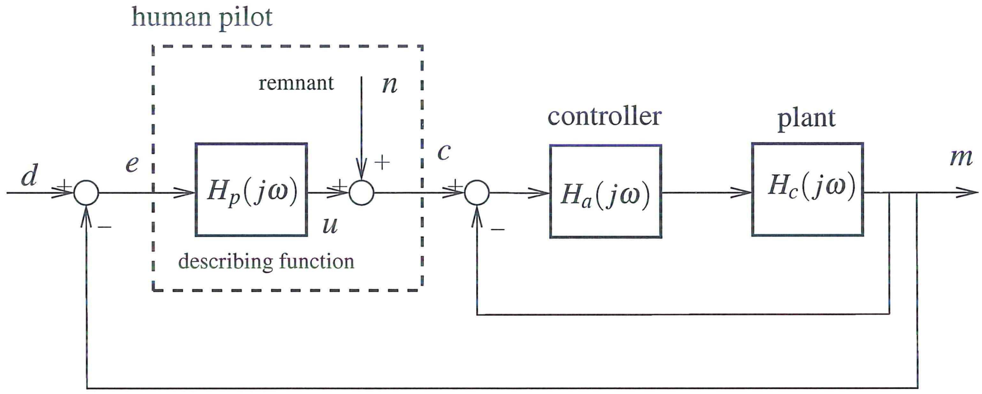

Figure 2: Closed loop manual control task: a following task with a compensatory display, with a control system added.

1. PILOT MODELS

Figure 1 shows a closed loop manual control task. In this figure, $H_c(j\omega)$ depicts the system to be controlled and $H_p(j\omega)$ the pilot frequency response function. The system to be controlled has the following dynamics:

$$H_c(j\omega) = \frac{K_c}{j\omega(1 + j\omega)},$$

with $K_c = 4$. Also in this figure, n represents the pilot remnant signal, and d represents the signal to be followed, which has a bandwidth of 1.1 rad/s.

[a] Draw a Bode plot of the system dynamics $H_c(j\omega)$.

[b] Derive a relationship between the inputs to the closed loop (n and d) and the output m.

[c] Based on McRuer's crossover model, what do you suggest to be the structure of the pilot model $H_p(j\omega)$? Explain your answer.

[d] Using the Verbal Adjustment Rules, compute the parameters of the pilot model, the crossover frequency, and the phase margin.

Now, a bright student decides that in order to help the human pilot, a fly-by-wire system needs to be installed, see Figure 2. Here, $H_a(j\omega)$ represents an automatic controller with *dynamics of your choice.*

[e] What are the 'equivalent dynamics' to be controlled by the human pilot?

[f] What would the dynamics of the automatic controller *ideally* be, from the perspective of the pilot? Derive the controller's frequency response and explain your answer.

2. AUTOMATION

[a] Automation can be defined as "*the full or partial replacement of a function previously carried out by a human*". Current aircraft automation consist of, amongst others, a Traffic Collision Avoidance System (TCAS), fly-by-wire (FBW) control systems, and a Flight Management System (FMS). Given that human behavior can be classified as skill-, rule-, and knowledge-based behavior, what type(s) of human behavior is/are replaced by a TCAS, FBW, and FMS, respectively? Motivate your answers. (3 points)

[b] To what extent a system can be successfully automated depends on the "openness" of a system. What does this mean in the context of aviation automation? (2 points)

[c] Besides several advantages, automation can also have some clear disadvantages. These disadvantages can be expressed as ironies of automation. Describe the five ironies of automation and clearly indicate what exactly the irony is. (5 points)

[d] The ironies of automation can result in several human performance related problems, most notably vigilance and complacency problems. What do vigilance and complacency problems mean in the context of aircraft automation? (2 points)

[e] To improve human-automation interaction, the late Charles Billings introduced the concept of Human-Centered Automation (HCA). In a nutshell, the HCA concept requires that automation must be more 'transparent'. Explain what is meant by 'transparent' in terms of monitoring automated advisory systems. (3 points)

3. VISUAL PERCEPTION AND VISUAL DISPLAYS

Several compatibility principles for displays exist, like the "Principle of pictorial realism" and the "Principle of the moving part".

[a] What is the "principle of pictorial realism"? (2 points)

[b] What is the "principle of the moving part"? (2 points)

[c] Consider the set of classic flight instruments as depicted in Figure 3. For the following instruments, discuss the compatibility issues involved in the two principles listed above:

- A classic speed indicator (2 points)
- A classic climb speed indicator (2 points)

[d] A conventional artificial horizon display, as shown in Figure 3, is based on a representation that is commonly referred to as "inside-out".

- What is the "inside-out" representation? (2 points)
- What is the alternative representation called? (1 points)

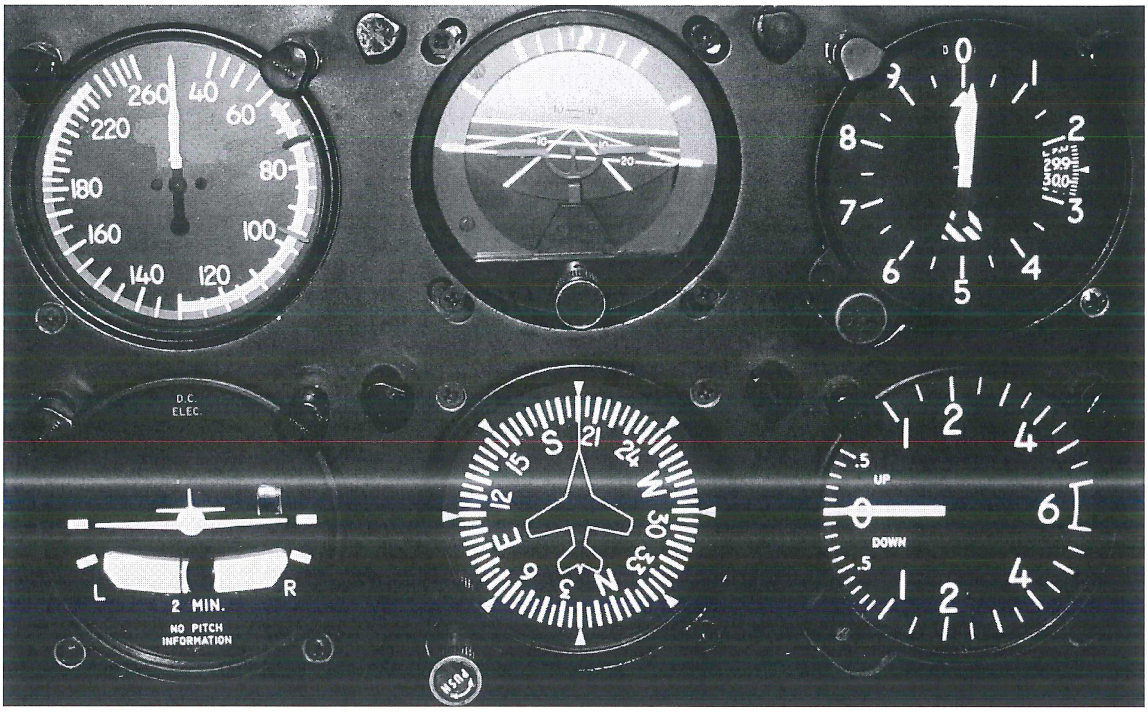

Figure 3: Classic flight instruments in a 'basic T' arrangement.

- In the light of the two display compatibility principles discussed above, what are the main differences between the two alternative representations? (4 points)

4. HUMAN ERROR

The following description is about an incident with a Boeing 737-800

Description

On 31 May 2014, a Gulfstream IV (N121JM) registered to SK Travel and being operated under lease by Arizin Ventures on a private business flight from Bedford MA to Atlantic City NJ initiated a high speed rejected take off in normal ground visibility at night and subsequently overran the end of the 2140 metre-long runway 11 by approximately 570 metres. During the overrun, the aircraft collided with ground obstructions before ending up in a gulley where a post crash fire consumed most of the aircraft wreckage. The three crew and four passengers died and the aircraft was destroyed.

Investigation

An Investigation was carried out by the NTSB. The FDR, CVR and QAR were recovered from the wreckage and data from all three was successfully downloaded. The QAR data covered 303 hours of data on 176 flights. A Preliminary Report on the initial progress of the Investigation was published on 13 June 2014.

The continuing investigation established that the 45 year-old aircraft commander and the 61 year-old Co-pilot were both qualified to act as pilot in command of the accident aircraft and constituted the usual flight crew for the operator's only G-IV. They "customarily changed seats between flights" with the pilot occupying the left seat acting as the commander. The

61-year old Co-pilot was also the Chief Pilot and Director of Maintenance for SK Travel. Both had been flying the accident aircraft type since it had been acquired by the operation seven years previously and both had, earlier in their careers, logged time on business jets other than the accident type. Available evidence indicated that the aircraft commander had been PF.

The accident flight was being made to return the four passengers to Atlantic City from where they had arrived in the same aircraft flown by the same crew several hours earlier. The two pilots and the Cabin Attendant had remained with the aircraft. Once the passengers had boarded, the engines were started and the aircraft taxied to runway 11, reaching it about eleven minutes after the passengers had boarded. During this time, it was noted that the CVR had "recorded minimal verbal communication between the flight crewmembers, and there was no discussion or mention of checklists or takeoff planning" whereas the AFM "includes five checklists to be completed before takeoff: the Before Starting Engines checklist, the Starting Engines checklist, the After Starting Engines checklist, the Taxi/Before Takeoff checklist, and the Lineup checklist."

The 'Starting Engines' Checklist included the requirement to disengage the gust lock, achieved by moving the gust lock handle on the pedestal between the pilots (see picture below) to the OFF (down) position. The 'After Starting Engines' Checklist included a check of the flight controls which is achieved by one of the pilots moving the elevators, ailerons, and rudder from stop to stop to confirm that they move freely and correctly. FDR data showed that "the flight crew did not complete a flight control check after engine start or at any time thereafter".

As the aircraft turned on to the runway, the CVR recorded the pilots discussing the appearance of the RUDDER LIMIT" caution on the EICAS. Such an annunciation would be indicative of the rudder contacting its stops or "being prevented from reaching its commanded position, as would be the case if the rudder was commanded to move with the gust lock engaged". However, the AFM stated that this annunciation is advisory with no crew action required and it was noted that although it appeared because of the interaction of the engaged gust lock with the yaw damper system, it "is not normally used to alert flight crews to the status of the gust lock system" and did not do this.

Following brake release for take off, with a likely target EPR of 1.7, FDR data showed that the throttle levers were advanced manually to an EPR of "about 1.42 over a period of about 4 seconds". Then after an interval of about 5 seconds, the A/T was engaged and the EPRs began to increase again to reach their eventual maximum values of about 1.6 as the aircraft reached about 60 knots before beginning to drop to about 1.53 and stabilising as the PF said "couldnt get (it manually any further).

A review of the available QAR data from previous flights over the previous 9 months found that, out of the 176 recorded takeoff events - all made by the accident aircraft flight crew - only 2 had been preceded by a complete flight control check. Data from each take off was examined to note the airspeed at the time that the elevators (and therefore the control columns) had begun to move aft during the takeoff roll and in all cases except for the accident takeoff, this occurred at between 60 and 80 knots. The data for the immediately preceding 20 flights was also examined to see how the accident flight crew had advanced the thrust levers during take off and it was found that in each case, this action had been continuous to the same final position with in each case a corresponding resultant 1.7 EPR (maximum thrust takeoff) set before engaging the A/T.

It was noted that the AFM version of the 'Lineup' Checklist (although not the one recovered from the wreckage) is followed by a note that, at 60 knots during the take off roll, the pilot should confirm that "the elevators are free and the control yoke has moved aft from the full forward to the neutral position". The basis for this is that aft movement of the control yoke (column) should be evident as aerodynamic force on the elevators increases because of their 'at rest' position of about 13 trailing edge down. As the accident aircraft passed 60 knots, FDR data recorded the elevator (and therefore the control columns) as still at about the 'at rest' position.

Calls of 'eighty', 'V1' and 'rotate' followed from the PM. One second after the 'rotate' call, the PF said "...lock is on." and then repeated this six times over the next 13 seconds. Five seconds after the first of these calls, FDR evidence indicated that one of the pilots had moved the Flight Power Shutoff Valve (FPSOV) (see diagram below for its location) to the 'on' position, considered to have probably been an attempt to achieve unlocking of the flight controls whilst the crew were still unaware of the 'on' position of the gust lock lever. It was noted that whilst this action would have removed hydraulic pressure from spoiler and primary flight control actuators, it would not have had the desired effect on locked status of the elevator.

About 11 seconds after the 'rotate' call with the aircraft having reached its maximum ground-speed of about 162 knots and with about 420 metres of the 2140 metre-long runway remaining, the FDR recorded the left and right brake pressures beginning to rise. There was no verbal communication between the pilots about rejecting the takeoff and only four seconds after the brake pressure increase were the thrust levers retarded. Normally this latter action would have led to the ground spoilers being deployed to assist deceleration but the earlier movement of the FPSOV had disabled them due to the consequent loss of actuator hydraulic power. Five seconds after reaching its maximum ground speed and one second after the PF says I cant stop it., the thrust reversers were deployed as the aircraft exited the runway onto the paved RESA at just over 150 knots. One second after reaching the end of the 311 metres of RESA at 105 knots and going onto the grass, CVR data recorded the first impact sound and FDR data ended shortly afterwards with the aircraft still moving at about 90 knots. Having passed through the perimeter fence, the aircraft stopped spanning a small river valley about 570 metres beyond the end of the runway.

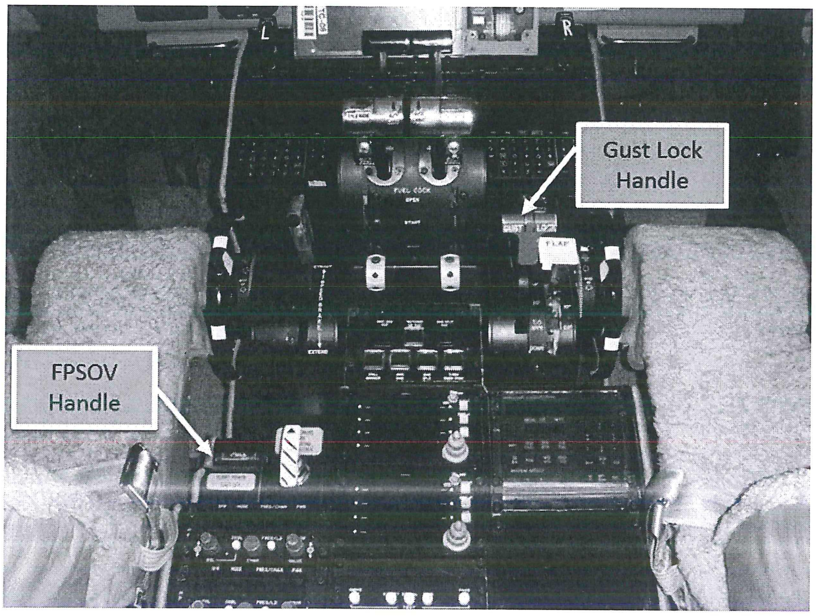

Figure 4: The position of the gust lock and FPSOV levers.

Abbreviations

FDR	Flight Data Recorder	CVR	Cockpit Voice Recorder
QAR	Quick Access Recorder	PF	Pilot Flying
AFM	Airplane Flight Manual	EICAS	Engine Indication & Crew Alerting System
EPR	Engine Pressure Ratio	A/T	Autothottle
RESA	Runway End Safety Area		

In trying to understand the reason for the use of the FPSOV handle, the investigators asked a pilot familiar with the type, who stated that *"When the gust lock was not disengaged before starting the engines, some pilots occasionally used the FPSOV handle to momentarily remove hydraulic pressure from the flight controls, which allowed the gust lock to be disengaged without shutting down the engines"*

Note that the gust lock is there to prevent damage to the aircraft's control surfaces due to wind gusts while the aircraft is parked on the ground. Removing the gust lock requires that there is no force exerted on the control surfaces or the controls, otherwise the gust lock mechanism (essentially a set of pins) stays jammed in. This gust lock lever also limits throttle travel.

[a] The pilots in the scenario given above failed to use the checklist and proper flight deck procedures. Determine whether that is a rule-based, knowledge-based or skill-based error, and argue why that is so. (3 points)

[b] From the abstract above, identify at least four other errors. Indicate whether the error was skill-based, rule-based or knowledge-based, and motivate that. For two of these, indicate the possible error shaping factor. (4*2 points)

[c] Explain what the "bad apple theory" is, and discuss whether or not it is applicable here. (4 points)

5. NEUROMUSCULAR SYSTEM

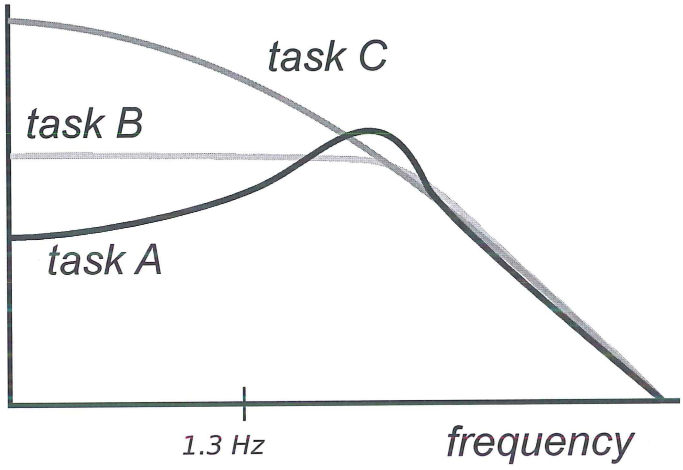

Figure 5: Results from admittance measurements in the three standard tasks.

The human neuromuscular system is highly adaptive. When measuring the frequency-dependent properties of the neuromuscular system, these are normally identified as admittance. Figure 5 shows multiple hypothetical admittance graphs.

[a] Assume the limb movements are expressed as rotations, and forces as moments, what is then the (SI) unit of admittance? (2 points)

[b] The force task, position task and relax task are standard tasks to determine neuromuscular system properties. Lines A, B, and C in the admittance graph represent the force task, position task and relax task. Which line belongs to which task? (2x2 points)

[c] Name the two main proprioceptive sensors in the neuromuscular system, and name their location. (2 points)

[d] How are these sensors used in a position task? (3 points)

Consider a pilot flying in moderate turbulence (which to inexperienced passengers will feel like severe turbulence!). Suppose he performs two actions (not simultaneously), he drinks some water from a cup, and he reaches for the heading select button on the glareshield panel. For holding the cup and drinking, the acceleration of the cup should be minimized, and for reaching for a button, the relative motion with respect to the aircraft should be minimized.

[e] For each of these two tasks, discuss how the setting of the neuromuscular system might be adapted to improve performance on the task. and indicate which of the standard tasks is closest to the expected setting. (4 points)

VESTIBULAR SYSTEM

The Subjective Vertical (SV) is the direction perpendicular to the earth's surface, as perceived by a human observer. Thereby, the SV tells us how we think we are *oriented* with respect to the direction of gravity. The DESDEMONA simulator, see Fig. 6, is used for training pilots for critical flight scenarios in which the SV is a factor. For example, DESDEMONA is sometimes used as a *centrifuge*, to perform "high-G training" under increased gravitational accelerations. Such increased gravity levels can achieved with *constant rotations* of DESDEMONA's main axis (Axis 1), while the cabin is at a *fixed offset* from this rotation axis, as shown in Fig. 6.

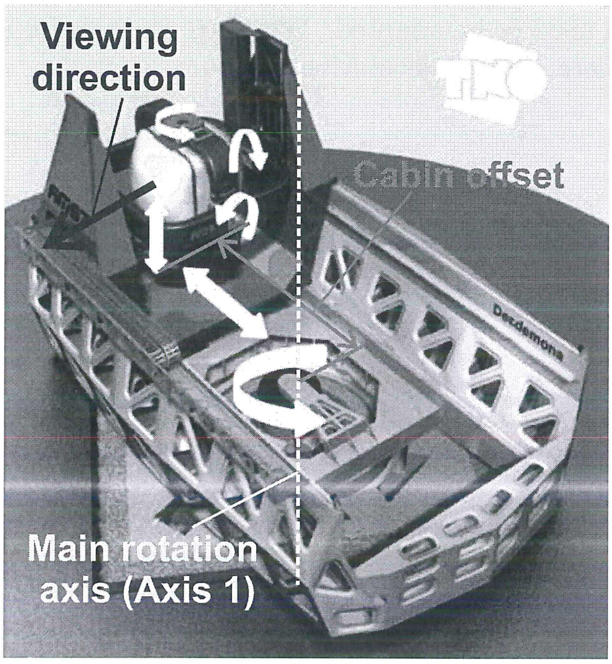

Figure 6: The DESDEMONA simulator.

6. [a] What is the definition of “specific force”? Why can the otoliths’ measurement of specific forces lead to problems with self-motion perception? (2 points)

[b] Explain the contribution of specific forces perceived by the otoliths to the formation of the subjective vertical. Does the otolith signal contribute to quick changes in SV or to slow adaptation? (2 points)

You are asked to investigate the following centrifuge scenario that is to be performed in DESDEMONA:

- A gravity level of 3g, so three times normal earth gravity.
- Fixed cabin offset of 4 m.
- No visual cues, so pilots can only rely on inputs from their vestibular system.
- Pilots are facing the direction of forward cabin velocity, as indicated in Fig. 6.

[c] Calculate the constant rotational velocity of Axis 1 that is required to achieve a 3g centrifugal force at the cabin position. How many seconds does it take for DESDEMONA to complete one full revolution? (2 points)

[d] For the scenario defined above and further assuming an upright cabin orientation, with pilots’ vertical body axis aligned with the axis of centrifuge rotation, describe what will happen to pilots’ subjective vertical after prolonged exposure to this 3g centrifugal force. What orientation of their bodies will pilots perceive as a result? (4 points)

[e] The undesired perception of body orientation from the SV with an upright cabin orientation can be overcome by *tilting the cabin*. In which direction and by how many degrees should the cabin be rotated to ensure the desired perception of a constant 3g gravitational acceleration? Note that to achieve 3g with a tilted cabin, the rotational velocity

of Axis 1 will also need to be adapted. What are the required Axis 1 rotational velocity and time to complete one full revolution? (5 points)