System performance specifications

Previously, we have considered how to influence the parameters of a system. We can use it to give aircraft the correct parameters. Now we will take a look at the requirements which an aircraft should have. First, we examine how the requirements are built up. Later on, we'll examine which parameters are subject to these requirements.

1 Requirements on flying and handling qualities

1.1 Flying quality requirements

Most countries have **regulating agencies** (like the **JAR** for Europe and the **FAR** for the US). These agencies specify **flying quality requirements**. These requirements are the minimum acceptable standard of the flying and handling qualities of an aircraft. They define rules subject to which the stability, control and handling of the aircraft must be designed.

The flying quality requirements differ per aircraft class. Small light airplanes are **class I**, medium weight airplanes are **class II**, big heavy airplanes are **class III** and high manoeuvrability airplanes are **class IV**. Next to this, there are also separate criteria per flight phase. **Category A** concerns non-terminal flight phases that require rapid manoeuvring, precision tracking or precise flight path control. (Think of air combat/terrain following.) **Category B** is about non-terminal flight phases that require gradual manoeuvring, less precise tracking and less accurate flight path control. (Think about climb, descent and cruise.) Finally, **category C** relates to terminal flight phases that require gradual manoeuvring and precision flight path control. (This includes take-off and landing.)

Aircraft manufacturers must demonstrate a compliance with the specifications. This is done by using flight tests. In these tests, the flying quality of the aircraft is rated. This is often done based on the **Cooper-Harper scale**. In this scale, a 1 means the aircraft has excellent handling qualities, and the pilot workload is low. On the other hand, a 10 means that there are major deficiencies in the handling quality of the aircraft. A test is never performed for just an aircraft or just a control system. It is always performed for the combination of the aircraft and the control system.

Flight requirements are generally specified for three **levels of flying quality**. **Level 1** means that the flying qualities are clearly adequate for the respective flight phase. **Level 2** means that the flying qualities are still adequate, but there is an increase in pilot workload and/or degradation in mission effectiveness. In **level 3**, the flying qualities are degraded. However, the airplane can still be controlled, albeit with an inadequate mission effectiveness and a high or limiting pilot workload. Airplanes must be designed to satisfy level 1 flying quality requirements with all systems in their normal operating state.

1.2 Flying and handling qualities

Flying quality requirements are present to make sure aircraft have flying and handling qualities. But what do these qualities mean? **Flying qualities** concern how well a (long-term) task can be fulfilled. **Handling qualities**, however, concern how the aircraft responds (short-term) to inputs. Important parameters that influence these qualities include the **stability** of the aircraft and the **flight control system** (FCS) characteristics. Let's take a closer look at these two parameters.

With stability, we mean how easy it is to establish an equilibrium flight condition, without the aircraft having a tendency to diverge. There are two kinds of stabilities. With **static stability**, we mean that every deviation causes an opposing force/moment. However, the deviation does not have to be eliminated. It could simply be the case that a new equilibrium position is created. With **dynamic stability** we also mean that every deviation from the equilibrium position is eliminated. In other words, the system returns to the original equilibrium position. It is usually nice if an aircraft is stable. However, if an aircraft is too stable, then it's not manoeuvrable anymore: it's too hard to get it out of its equilibrium position. So, this isn't a positive thing either.

There are three ways in which the FCS can have a bad effect on the flying qualities. First, something can occur between the cockpit and the actuators. (For example, there may be a lag in the signal that is sent to an actuator.) Second, there can also be a lag in an actuator itself. (For example, when the ailerons takes a long time to deflect.) And finally, the displays in the cockpit can lag. Because this is undesirable, requirements are made concerning these lags. Next to this, also **control system break-out forces** are important. These are the forces which the pilot must apply before his actions have any effect at all.

Giving an airplane the right flying and handling qualities usually isn't easy. It often has a bad effect on the performance and weight of the aircraft. Therefore, trade-offs often need to be made between the flying/handling quality and the performance of the aircraft. That is, if trade-offs can be made. Requirements on the flying and handling qualities are simply present and they have to be followed.

2 Parameters subject to requirements

2.1 Longitudinal flight requirements

Now let's look at some actual requirements for aircraft. First, we'll examine requirements on the longitudinal flight. After that, we'll also consider the lateral flight.

In longitudinal flight, there are requirements on the **control forces** which the pilot needs to exert. These forces are often indicated by the **stick force** F_s. In a manoeuvring flight, the gradient $\partial F_s/\partial n$ with respect to the **load factor** n is important. It should fall within limits. (We're not going to mention any numbers here. There are just too many to mention, and you're not going to remember them anyway.) Also, there should be no significant nonlinearities in it. Next to this, when the airplane configuration changes a bit (e.g. the flaps are deployed), the control forces shouldn't change significantly either.

When the aircraft changes its speed, no strange things may happen either. The **stick-force-speed-gradient** $\partial F_s/\partial V$ must be stable and must meet other specs. Also, the **return-to-trim-speed-behaviour** must meet certain requirements. During take-off and landing (with fixed trim controls) the control force must be within certain limits. Also, during a dive, the control force may not exceed certain values. These values also depend on whether the aircraft is equipped with a stick or a wheel. Also, the allowable values depend on whether it concerns pushing or pulling the wheel/stick.

Next to control forces, also the dynamic behaviour of the aircraft is important. Let's consider the **phugoid requirements** first. The phugoid must have a certain prescribed damping ζ. And if the eigenmotion is allowed to be unstable (for example, during a level 3 flying quality situation), then there will be a requirement on the **time to double amplitude** $T_{2_{ph}}$. This time can be found, by using

$$A_{ph}e^{-\zeta_{ph}\omega_{n_{ph}}\left(t_1+T_{2_{ph}}\right)} = 2A_{ph}e^{-\zeta_{ph}\omega_{n_{ph}}t_1} \qquad \Rightarrow \qquad T_{2_{ph}} = \frac{\ln 2}{-\zeta_{ph}\omega_{n_{ph}}}. \tag{2.1}$$

In the above equation, A_{ph} is the amplitude of the phugoid motion, ζ_{ph} the damping ratio and $\omega_{n_{ph}}$ the natural frequency.

Similar to the phugoid, there are also **short period motion requirements**. These requirements of course concern the damping ratio ζ_{sp}. But for the short period motion also the natural frequency $\omega_{n_{sp}}$ is quite important. However, for (highly) augmented airplanes, these requirements are not used. Instead, the **control anticipation parameter** (CAP) is used, which is defined as

$$\text{CAP} = \frac{\dot{q}(t=0)}{n_z(t=\infty)} = \frac{\omega_{n_{sp}}^2}{n_\alpha}. \tag{2.2}$$

In this equation, $n_\alpha = \partial n / \partial \alpha$ is the gust- or load-factor-sensitivity. By using flight dynamics equations, expressions/approximations can be calculated for $\omega_{n_{sp}}$ and n_α, after which the CAP can be found.

Finally, the aircraft must have **flight path stability**. This means that there are requirements on the derivative $\partial\gamma/\partial V_P$. The term ∂V_P here denotes the changes in velocity that are caused by pitch control only. (So, things like engine throttle effects are not taken into account.)

2.2 Lateral flight requirements

There are several requirements for lateral flight as well. First, we'll look at the **lateral control forces**. These control forces concern both the (sideways) forces on the stick and the forces on the rudder pedals. The force requirements depend on the situation. (For example, there are separate requirements for the situation where one engine isn't functioning anymore.) It also matters whether it concerns a short/temporary force or a prolonged force.

Now let's examine the **Dutch roll**. For this eigenmotion, of course the damping ratio ζ_d is very important, as well as the natural frequency ω_{n_d}. Therefore, there are certain minimum values for these parameters. There are also requirements on the product $\zeta_d \omega_{n_d}$. And, depending on the roll angle ϕ and the sideslip angle β, more complicated requirements can be put on the damping and frequency.

For the **spiral** eigenmotion, divergence is usually allowed. Now the time T_{2_s} until a double amplitude is reached (with cockpit controls free) is an important parameter. For the **roll mode**, the roll mode time constant T_R is important. A maximum value is usually specified.

Stability and manoeuvrability also matter. How quickly can an airplane reach a certain roll angle? Or alternatively, in a given time, what maximum roll angle can be achieved? And is the aircraft **directionally stable**? In other words, it is required that $C_{n_\beta} > 0$. Next to this, it is also desired/required that $C_{Y_\beta} < 0$ and $C_{l_\beta} < 0$.

2.3 The Gibson criterion

The Gibson criterion is a special criterion to prevent certain aircraft behaviour. It is mainly relevant when a pilot is trying to change the pitch rate of the aircraft. The Gibson criterion can be split up into the dropback criterion and the phase rate criterion. We'll examine the dropback criterion first.

Let's suppose that we have a certain pitch angle and we want to reach another pitch angle. We deflect the elevator, until we have reached the desired pitch angle. Then, we let go of the control surfaces. What happens next? If we go back to a situation with a smaller pitch angle, then **dropback** (DB) occurs. However, if the pitch angle continues to increase, then **overshoot** (OS) occurs. (Dropback can thus be seen as negative overshoot and vice versa.)

The **dropback criterion** concerns dropback. Important parameters are the **maximum pitch rate** q_m, the **steady state value** of the pitch rate q_s and the **pitch rate overshoot ratio** q_m/q_s. The dropback criterion now describes a region in which the values of DB/q_s and q_m/q_s should be. Basically, zero dropback is optimal. However, some dropback is preferred to overshoot. Acceptable pitch rate overshoot values are $1 \leq q_m/q_s \leq 3$.

The **phase rate criterion** is present to prevent/reduce **pilot induced oscillations** (PIOs). A PIO can occur when the pilot continuously tries to compensate for something, but by doing so only contributes to oscillations. Important parameters now are the **frequency** at 180° phase lag $\omega_{\phi=-180^\circ}$ and the **phase rate** at 180° phase lag $(\partial\phi/\partial\omega)_{\phi=-180^\circ}$. The phase rate criterion now demands that

$$\omega_{\phi=-180^\circ} \approx 1 \text{ Hz} \qquad \text{and} \qquad \left(\frac{\partial\phi}{\partial\omega}\right)_{\phi=-180^\circ} \leq 100 \text{ deg/Hz}. \tag{2.3}$$

The optimum for the parameters is for $\omega_{\phi=-180^\circ}$ to be somewhere between 1 and 1.4 and for $(\partial\phi/\partial\omega)_{\phi=-180^\circ}$ to be somewhere between 60 Hz and 90 Hz. In this case, then the chance that a PIO occurs is really low.