Evaluation of glider handling qualities

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Abstract
This thesis was performed with the purpose of investigate what influence different control system characteristics have on pilots’ perception of handling qualities. Two gliders were investigated and compared, the JS1 [1] and the ASH26 [2]. Both are high performance gliders with similar type of configuration and aerodynamic performance, but with slightly different handling qualities.

The stick force transfer functions in roll axis were calculated, the rate of angular change for a certain control input was measured and the subjective experience of the pilots were acquired through a pilot survey from flight tests. The pilots' experiences were then linked to how the gliders reacted on control input and control system design.

It was found that the most important feature of the control system was control harmony, meaning that the responses in each control axis of the glider are in correspondence with each other. Also, the relationship between the stick force and response was much more important than the actual force itself.

Introduction
For all aircrafts, good handling quality is a property designers and engineers strive to accomplish. Especially for gliders, whose purposes are limited to only competition and leisure, easy handling qualities are of great importance. Easy handling qualities allow the pilot to focus more on planning his flight and/or enjoy the time spent.

The problem with the "easy handling qualities" is that these are subjective feelings and can vary from pilot to pilot. It is thus more difficult to quantify handling qualities compared to other properties of an aircraft. Also, gliders that have very similar flight performance in terms of glide ratio, roll rate, minimum sink speed etc. can feel very different to fly according to the pilots. Because of these reasons, there is a need for studies that defines "good handling qualities" and relates this to design features.

This thesis aims to identify the difficulties of quantifying pilot experience and defining what pilots refer to as "easy handling", and also to investigate how the design of the control system affects these. The questions to be answered is what characteristics do the pilot associate with easy handling, and how do these depend on the control system. In order to determine the correlation between control system design and pilot experience, it is beneficial to study more than one glider and compare the result between the different gliders.

It is assumed that the matter of most importance regarding pilots' impressions of handling qualities is how the glider responds to control input in roll, and how much pilot effort this requires. For this reason the investigation of the control system is limited to analyze only the stick forces for roll, although the pilot evaluation contains more elements.

A rating scale is needed to quantify how easy a glider is to handle. There are many rating scales in use, and airplane manufacturers often have their own systems of rating. However, one problem with many of these is that they in most cases focuses on whether the airplane is controllable and safe, and does not treat how nice or easy the airplane is to fly. A well used rating scale is the Cooper-Harper rating [3], which was developed for the US Air Force and focuses on the safe handling and controllability of an aircraft.

In this study it is the easy handling and maneuverability that needs to be quantified and a rating scale with focus on this needs to be used.

How to evaluate pilot experience from flight tests can be difficult since it is subjective feelings that need to be quantified. Every pilot has his own personal opinion about the same glider, and in order to link these subjective feelings to actual handling properties, the way people interpret and share information has to be analyzed.

Control transfer functions
How much force the pilot has to apply to the stick of the glider in order to achieve a certain control surface deflection can be described by a control transfer function. The control transfer function gives the relation between the aerodynamic forces acting on the control surface and the feedback forces the pilot feels in the stick.

As mentioned in the introduction, the most important part of pilots' perception of handling qualities was assumed to be the inputs required for roll action. Thus, only the stick transfer function for this action was determined. This was constructed by first establishing a spreadsheet for each glider that described the control surface deflection as a function of stick position, and this information was used with an aerodynamic model to obtain the feedback forces in the stick.

Spread sheet
For the JS1 glider the spreadsheet was constructed by studying the drawings of the control system. The JS1 has flaperons along the whole trailing edge of the main wing and depending on the flap setting, the flaperon reference angle to the wing is changed. From the drawings five spread sheet models could be constructed, one for every flap setting [1].

For the ASH26 there were no drawings for the control system available and the spreadsheet had to be constructed by measuring the relation between stick input and control surface output. The ASH26 has two flaperons on each wing that are moving independently of each other. This implies that separate spreadsheets for both flaperons had to be constructed.

For the measurements the ASH26 was placed with the wings parallel to the horizon i.e. zero bank angle. Wooden plates were fixed on the flaperons and the control stick, and an inclinometer was attached to the plates. The inclinometer was used to measure the relative angle towards the horizontal reference plane. The stick position was varied from the far left to the far right, and deflection angles of the stick and corresponding flaperon deflection angles were documented. The angle of zero stick input for the known flap settings [2] was measured and compared to the relative angle measured for the flaperons, and thereby the actual flaperon deflection angle could be determined.

The measurements were performed for each flap setting, and these were done on three
separate days to collect a satisfactory number of data points. The measured results were used to generate least square-fitted third order polynomials for all flap settings describing the corresponding spreadsheet model.

**Aerodynamic forces**

Deflection of a control surface gives rise to a change in aerodynamic force acting on this, and from that, a change in the hinge moment of the control surface. To keep the control surface in the new state, the pilot has to counteract this change in hinge moment, and the magnitude of this hinge moment determines how much force the pilot has to apply to the stick. To determine the hinge moment from a control surface deflection an aerodynamic model from XFOIL was used.

XFOIL is a software released under GPL*, and is a tool to perform 2D-analyze of airfoils in subsonic speeds. XFOIL uses the geometrical properties of each wing and computes the hinge moment as a function of control surface deflection and angle of attack [4].

In order to obtain the stick transfer functions for the gliders, the spreadsheets describing deflections as functions of stick position were used together with the results from the model in XFOIL, which gave the hinge moment as a function of stick position. To relate the hinge moment to pilot effort, the hinge moment was multiplied with the ratio between the deflection of the control surface and the deflection of the stick. This gives the corresponding moment in the stick attachment joint, and thus a measurement of the effort required by the pilot. The stick in the JS1 and the ASH26 has the same length and thus the moment in the stick joint will have the same characteristic curve as the actual force in the stick.

**Pilot experience**

To evaluate how a glider feels during flight the pilot impressions needs to be quantified. Every pilot perceives the gliders' handling differently and a standardized method for extracting data from pilots has to be used. What pilots value as easy handling can also vary between pilots and the term "handling qualities" has to be defined.

This study concerns the easy handling qualities of a glider, and it is assumed that the gliders investigated in this study already have acceptable performance regarding safe handling and maneuverability.

**Handling qualities**

The impressions of handling qualities were analyzed by letting the test pilots do flight tests, and conducting a survey in form of a questionnaire and interviews. The main difficulty with a pilot survey concerning this subject is stating the aspects that are relevant for what can be defined as "handling qualities". The definition used in the Cooper Harper rating states that:

“Handling qualities” represent the integrated value of those and other factors and are defined as “those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role” [3].

According to this definition, handling qualities must be put in to respect with the purpose of the aircraft at hand, i.e. "handling qualities" will have a different meaning for an aerobatic plane than for an airliner. In general, it can be argued that easy handling qualities concerns with what effort the pilot can make the aircraft perform what he wants.

One aircraft role that is of great importance for gliders is curving. Since gliders, in general, never use any source of propulsion to climb, it is necessary for gliders to curve in thermal updraft in order to stay in the sky. This means that the pilot will spend a lot of the time turning and also that this is a very crucial part of the flight. While flying in thermals the pilot wants to stabilize the turn around the thermal center, which requires significant control

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effort compared to the rest of the glider tasks. Thus most of the pilot's impressions regarding the feeling of a glider will revolve around its performance in turning.

However, "handling qualities" can not only be quantified from the physical feelings perceived by the pilot, one must also take in to consideration the amount of mental effort required. For instance navigating, communicating, calculating different routes and metrological issues are examples of other tasks that are absolutely essential for the pilot (especially in competitions where this is the main part of the whole flight). From this it is obvious that a glider with easy handling is a glider that allows the pilot to direct more of his attention to these matters, instead of the actual flying and maneuvering. Which aspects that influence this can be both how often the pilot has to counteract an unwanted perturbation of the aircraft position, and how much force the pilot has to apply the corresponding control to achieve this counteraction. A glider that is stable in a state but also easy to change to another state can be said to be easy to handle.

Handling qualities is the combination of mental and physical effort the pilot has to use to make the aircraft do what he wants and are not definite for all aircrafts. Good handling qualities can also vary for the same aircraft performing different tasks in different configurations.

**Pilot psychology**

Another difficulty with the survey, apart from which questions the pilots should be asked in order to establish a definition of "handling qualities", was how to formulate the questions in such a manner that useful conclusions can be drawn. Also that they eliminate answers that are unclear or leaves room for interpretation. For instance; "On a scale from 1 to 5, how much effort is required to enter a 30 degree turn at 100 km/h with 50% control input?" is a better question than "How does it feel to enter a turn?" For the survey to be useful, it was important that the pilots interpreted the questions in the way intended, and that all pilots interpreted them in the same way.

To manage with these possible uncertainties in the results, there was a large focus on pilot interaction. Partly to make sure that the pilots were well informed of the flight mission and other matters of importance, but also how to share their impressions during and after a test flight. Before each test flight the pilot was briefed about the exact details of the flight mission in terms of maneuvers, flight configuration and purpose of the mission. Each mission was explained in several ways to give the pilot a clear picture of what was the goal of the test.

Pilots interpret words in different ways and both words and numbers have different meaning to different pilots. This interpretation of words and numbers will result in an uncertainty regarding the answers to a survey or an interview. How pilots relate words and numbers to each other, and how questions should be formulated to get useful information from the pilots was analyzed in the American study "Pilot rating techniques for the estimation and evaluation of handling qualities" [5]. The conclusions from this study were used in the design of the pilot survey.

Another already existing pilot survey treating pilot interaction and opinions of glider performance investigated for the project was the Zachern rating used by Idaflieg [6]. This study, as well as the Cooper Harper, mostly treated subjects that were not related to "easy handling qualities", but they both provided inspiration to the pilot survey used in this thesis.

Since words, questions and numbers do not have an absolute value to all pilots it can be misleading to compare ratings of a glider between pilots. But words, questions and numbers have in some sense an absolute meaning to one pilot. From this it can be argued that the difference between two
gliders rated from one pilot compared with the difference rated from another pilot, can be a more accurate measurement than the one pilot rating one aircraft.

The pilots’ physical and emotional states, like their level of hunger, weariness and happiness, will also affect how they experience a glider. It is therefore preferable to perform the test flights with the different gliders under the same conditions with the pilots in the same mood for all flights. How much flight time the pilots have in the respective gliders and how wonted they are to that glider will also have an influence.

**Flight tests**

Flight tests were performed to identify how the gliders were behaving in different situations. For every flight test performed the pilot had a number of missions, a mission could be for instance “turning” or “wing-rocking”. Every mission was then divided into tasks that described a smaller part of the flight mission. These tasks were designed in such a way that the behavior of the glider in specific flight position could be analyzed, for instance “enter a turn” or “holding a turn”. The pilot performed one task at the time, and directly after the task was performed the pilot filled in a questionnaire, expressing what he thought of the specific flight segment.

For most of the flight missions the pilots were given very specific instructions for how the maneuvers should be performed. Control inputs and flight states were decided beforehand and all pilots were briefed in order to perform the tasks in the same way. Each task instruction consisted of what flight speed (IAS*), control input, flap setting and angle of bank that should be used for the given task. One flight mission without restrictions was also performed where the pilots had no restrictions in how to fly.

Since the handling of the glider in turns or turn-like conditions was to evaluated, the flight missions used were 1. Wing-rocking 2. Turn 3. Flying near stall in turn and 4. Flying without restrictions. The first three missions had very specific sub tasks and a questionnaire was used to obtain the pilot experience from these missions. For the flying without restrictions segment, the pilots were interviewed with specific questions to obtain their thoughts about the mission.

The flying without restrictions test was used to evaluate the pilot experience when he could perform the maneuver the way he is used to. When the pilot was given strict instructions his impressions could have been affected by the execution itself rather than the properties of the glider, as intended.

The flight speed and flap setting for where the mission should be performed were decided in accordance with the manufacturer of the gliders [1][2] along with an experienced pilot [7].

As a measurement of a glider’s response in roll, the quantity “time to bank” was introduced. This quantity represents the time it takes from the point where the pilot makes a certain stick input in roll until the glider has reached the desired bank angle. This measurement was used to get an idea of how rapid the gliders’ responses were. The time to bank was measured with video cameras mounted in the cockpit for all turning tasks.

Both of the gliders were flown in a configuration with low wing loading, they were empty on water and the center of gravity was well within the specified range.

**Wing-rocking mission**

The wing-rocking mission was performed in 100 km/h with flap setting 4 for each glider [1][2]. The pilots were instructed to start with small stick inputs and rock the glider from 30 degree bank angle left, to 30 degree bank angle to the right, while maintaining the speed and keeping the nose of the glider straight.

*Indicated Air Speed*
The pilots were then instructed to increase the bank angle and control input until the pilot was performing 45 degree turns from left to right with full stick input in roll direction. The mission was performed in trimmed condition.

Turning mission
The Turning missions were performed for two different flight speeds and two different stick inputs, all turns were performed in flap setting 4. The flight speeds were 100 and 120 km/h and the stick inputs were 50 and 75 % of maximum deflection. The turning mission was divided into the three tasks: enter turn, holding turn and exit turn. The turn bank angles were 45 degree and the mission was performed in trimmed condition.

Flying near stall in turn
The flying near stall mission was performed in a 45 degree turn and the goal was to evaluate the glider behavior when flying as slow as possible. The pilots were instructed to maintain 45 degree bank angle and fly as slow as they could, while still maintaining the 45 degree bank angle.

Flying without restrictions
For the flying without restrictions mission the pilots were simply told to fly a few turns at different speeds and bank angles, as they do while flying in thermals. The execution was completely free of choice, and the mission was used for the pilot to get an overall impression of the glider. The glider was flown in trimmed condition.

Results and conclusions
The flight tests were performed by four pilots during two days. In total 112 tasks were performed by all the pilots together. All flights were performed in calm weather. Directly after landing the pilot was interviewed and his answers and comments were recorded. This was used together with the answers to the questionnaire filled out by the pilot in flight, to establish the characteristics preferred by the pilots.

The results from the flight tests were compiled into tables and graphs, showing how the different characteristics of the gliders were perceived by the pilots. Both the answers from the questionnaire and the comments from the interviews were analyzed.

Pilot ratings
The answers in the questionnaire from the pilots were averaged for each glider and compared to each other. By taking the average between all pilots, the problem with pilots' different interpretations of words and numbers (as discussed in the section "Pilot psychology") will be reduced since every pilot uses his same "misinterpretation" for both gliders.

The questionnaire was designed to, in the furthest extent possible, separate and individually examine different flight segments and controls of interest. Meaning one could look at the entry, holding and exit of a turn individually, instead of a total credit for turning all together.

According to the pilot survey, following properties were concluded to have the biggest influence of pilots' perception of "easy handling qualities":

Harmonized controls; meaning that the control inputs for every axis are in correspondence with each other. For example, the input in pitch required for holding a turn should be of the same magnitude as the required input in roll. This criterion also includes that the pilot should not have to wait for the response in one axis before he can give the input for another.

Quick response time; especially high roll rate. One thing that was most disturbing for the pilots was the mental effort and focus required to prevent and counteract flight state perturbations. If the response time is short then it is easy for the pilot to correct, but if it is too long it is more difficult to adjust the glider and this requires that the pilot is more vigilant. It was also preferable to have controls
that are effective even for small inputs. The pilot does not want to "wait and see" if the input was sufficient, but rather feel that the glider are affected already at small changes.

One thing the survey revealed was that pilots disliked gliders where there is a range of stick positions, described as a "dead spot" in the center, where the glider did not have satisfactory response. This lead to some confusion regarding how much further input the pilot needed to give, and when the response eventually came the forces were higher than desired because of the bigger inputs.

**No crossed controls:** In order to stay in a coordinated turn without slipping, the pilots found it preferable if the inputs did not need to be crossed. Crossed controls means extra input, and are more demanding than controls closer to neutral.

The questionnaire that was used for the pilot survey consisted of two types of questions for each task; one regarding the actual magnitude the pilot considered himself to experience, and one regarding how pleased he was with this. Each mission also contained a third type of questions asking if the pilot would prefer more or less of the given magnitude. By asking three different types of questions that more or less treats the same properties of the glider, each with somewhat different approach, it was easier to draw conclusions of how pilots define handling qualities and what they wish for in a glider.

The charts presented in Figure 1 to Figure 3 represent the average value between all pilots for the two gliders. In all of these charts, it is the questions regarding how pleased the pilot was that has been averaged. The two other types of questions were used together with the interviews in order to establish the pilots' opinions of the properties of the gliders.

The pilots' opinions regarding the controls for all flight missions are presented in Figure 1. According to the questionnaire it was found that the pilots were more pleased with the JS1 for all controls. However, these results were in some cases in contradiction to what the pilots stated in the interviews. For instance almost every pilot said in the interviews that the ASH26 had a much more effective rudder, and that it was superior to the one of JS1 in many situations. Why the results from the questionnaire show the opposite may be due to other parameters that affect how the glider feels in maneuvers where the pilot is using the rudder, which makes the pilot less keen on giving the rudder a better score. So even though the rudder was appreciated, the tests show that it was difficult for a pilot to separate and individually rank each parameter.

In Figure 2, the average scores for each phase of a turn for all turning missions are presented. As one can see both gliders got a higher ranking in holding a turn, compared to enter and exit. Both this chart and the one in Figure 1 show why separation is important, since the dissimilarities of the different controls or maneuvers would not show if the pilots were asked to rate the overall impressions of controls or turning performance.
In Figure 3 below, the results from the questionnaire for the three different flight tests (wing rocking, stall turn and turning) are presented. According to the pilots, wing rocking was the test that revealed most about the handling qualities of the glider.

![Figure 2](image1.png)

**Figure 2**, chart over the pilots’ average ratings of each task of the turning missions

![Figure 3](image2.png)

**Figure 3**, chart over the pilots’ average ratings of each flight mission performed

**Time to bank**
The values of the time to bank for the two gliders at the different flight speeds and control inputs used in the flight test were obtained by taking the average time to bank of all pilots and tasks. The results are presented in Figure 4.

![Figure 4](image3.png)

**Figure 4**, chart over the average time to bank to 45 degrees for the different flight speeds and control inputs used in the turning missions

The method of determining the quantity “time to bank” depend on many variables that have potentially high inaccuracy. Examples of these are how rapidly the pilot changes the stick to the intended position, with what accuracy the pilots and the cameras can measure the bank angle, and in what manners the pilots perform the turns. Despite all of these uncertainties, the time to bank can still be a quantity of interest when comparing different gliders. Since many of the variables are pilot related, each pilot will suffer from his same uncertainties for every task, and thus he will still experience the eventual differences of the two gliders. Especially if this information is used together with the pilots’ opinions and comments from the interviews, it can facilitate the conclusions of what the pilots preferred.

**Transfer functions**
The stick length is approximately the same for the JS1 and the ASH26. The leverage depends more on how the pilot holds the stick, rather than the actual length. Therefore, studying the moment acting on the stick attachment joint will give the same result as if studying the
actual force in the stick, i.e. the characteristics of the transfer function curve will look the same for the moment on the joint as for the feedback force in the stick. This curve was studied in respect to conclusions regarding control system design and pilots’ perception of handling qualities. The stick transfer functions in roll for two different flight speeds are shown in Figure 5 and Figure 6 below.

![Figure 5](image5.png)

**Figure 5**, graph over theoretical moment at the stick joint as function of stick position. Flap 4, dynamic pressure corresponding to 100 km/h at Sea level, ISA

![Figure 6](image6.png)

**Figure 6**, graph over theoretical moment at the stick joint as function of stick position. Flap 4, dynamic pressure corresponding to 120 km/h at Sea level, ISA

The transfer functions were compared to the result of the pilot survey in order to relate transfer function characteristics to pilot perception.

The stick transfer functions for roll show slightly different characteristics between the JS1 and the ASH26. The two transfer functions each have the same shape respectively for the different flight speeds, only the magnitude of the moment (stick force) differs. The JS1 transfer function has a steeper slope for small stick deflections than the ASH26, and for larger stick deflections the slope of the transfer curves becomes more similar, only that the JS1 requires a larger force for the same stick deflection. From the characteristics it looks like the JS1 would have a more rapid force response to control input. The pilot should get a larger feedback force for small stick inputs, which could be beneficial for small adjustments in roll. This stands in correspondence with the results from the pilot survey. According to the pilots, the JS1 had a faster response for small stick inputs whereas the ASH26 felt like it had a "dead spot" around the neutral stick position, i.e. the pilots experienced that the ASH26 needed larger stick inputs for the same response as the JS1. This can be due to the steeper slope of the transfer function of the JS1, which leads to a larger stick force for smaller deflections.

From the wing rocking mission, the pilot survey showed that both gliders are perceived heavy in roll for stick inputs close to maximum. The ASH26 was perceived heavier than the JS1, which does not correspond to the transfer functions. If only studying the transfer functions, theoretically, the ASH26 should be lighter in roll since the moments are lower compared to the JS1. From this one can draw the conclusion that the actual amount of force the pilot needs to apply to the stick, in order to achieve a certain response, is not the main concern for easy handling qualities. What matters is the response of the glider related to the feedback force. The reason why the pilots thought that the ASH26 was heavier in roll might be because they have to work and struggle with large stick deflections, even though the force itself is low.

Overall the JS1 felt lighter in the controls than the ASH26, the pilots felt that both the force and the amount of stick deflection used in the JS1 was less than in the ASH26.
The results obtained show that the initial assumption, that the pilot's inputs in roll will have the main influence over his opinions of a glider's handling qualities in turns, was insufficient. The survey showed that a pilot will base his opinions on more than just one control, and the conclusion from this is that it is difficult to separate the different controls. All controls have to be analyzed for every flight missions in order to obtain a more complete understanding of what affects a pilot's perception.

**Flight testing**

To draw more complete conclusions relating the control system design parameters to handling qualities, more flight tests need to be performed. The flight tests performed showed that it is of most importance to define the task at hand in detail; the pilot survey has to be perfectly defined and explained to the pilots. In this study it has been shown that pilots make different interpretations even though a lot of time was spent describing what the questions and answers meant.

Another source of human error is that the pilots' habit of how to handle a glider can take the upper hand over the instructions for the tasks. The task at hand has to be explained before every flight and it could be preferable to walk through the flight sequence on ground with all the pilots. Another issue is that the pilots do not necessarily see the flight tests from a scientific point of view. If they do not exactly understand the reason why something has to be performed in a specific manner, they can tend to do it in a way they are used to instead.

A lot of knowledge for future flight test has been documented and methods of how to perform flight tests for evaluation of handling qualities have been established. According to the conclusions drawn in the previous section, the control inputs in all axes affect the pilots' perceptions for maneuvers and it can be difficult to separate them and study only one control at the time. In the same way it is difficult to design flight tests that investigate only one control at the time. Thus, when investigating the easy handling problem, the flight tests should be designed such that all controls are used and measured in the same task, but they are still treated individually in the survey.

Another note for future flight testing is that the flight tests should be executed for a considerably wider range of flight configurations. The influence of parameters such as position of the center of gravity and wing loading were not investigated, but they were kept as constant as possible for each test pilot. Different positions of the center of gravity and different wing loadings could have significant effect on the handling, and they should be investigated in future studies.

One other parameter of interest that should be modified in future tests is the flight speed. For this project the same speeds where used for both gliders since this meant that the transfer functions were calculated for the same dynamic pressure. However, it is unfair to compare two gliders if one of them happens to be within its intended range, but the other one is not. For this reason, the flight speeds investigated should instead be relative to each glider. For instance the different speeds should be a factor multiplied with the stall speed of each glider.

In order to improve the results and further investigate the influences of the control system design on handling qualities, it would have been beneficial to use more well-performing equipment. For this project, the only physical property measured in flight was the time to bank. If the forces and positions for all different controls could be measured and documented in flight, and compared to corresponding flight data such as angular velocities and accelerations, it would have been possible to make a more extended investigation of how to design for easy handling.
**Conflict of interest**
This project was executed at the facilities of Jonker Sailplanes in Potchefstroom, South Africa. 75% of the test pilots have an employment at JS, and are also very used and familiar to the JS1 glider. The ASH26 used in the project is privately owned by one of the test pilots.

This over representation of JS-pilots could easily be seen as if the pilots are biased and the results are therefore disputable. However, the project has no intention what so ever to advertise or promote the JS1 in any way, but simply investigate the engineering aspects of handling qualities. Thus everyone involved has nothing to personally gain to falsify or tamper the results.

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**References**


