D/5

N85-16904

# SPACE SHUTTLE HANDLING QUALITIES

David W. Gilbert
NASA Lyndon B. Johnson Space Center
Houston, Texas

## ABSTRACT

This paper provides an overview of the initial Orbiter handling qualities requirements, their effect on the vehicle design, and how it all turned out through the first six orbital missions. Following this, there is a series of more detailed discussions of some specific areas consisting of hand controller considerations and the wheelie problem. Finally, there is a discussion which reviews the requirements for the pitch axis subsonic flight control system and provides some results of recent simulator evaluations to compare the existing system at landing with several other configurations.

## THE REQUIREMENTS

The original handling qualities requirements for the Space Shuttle were written more than 10 years ago. At the time, the magnitude of the task seemed overwhelming considering the size of the flight envelope the variety of control devices, control modes and control tasks. The existing MIL Spec. and user's guide run about 800 pages. This provides the requirements for conventional aerodynamic vehicles which correspond to a small part of the Shuttle mission/flight control matrix. Table 1 attempts to illustrate this. From a flight envelope viewpoint, most conventional aircraft experience lies in the lower right corner of the entry/ aerosurface control element in table 1. What were we to do with the rest of it? As a starting point, the Space Shuttle Flying Qualities Symposium was held at what was then the Manned Spacecraft Center in Houston, Texas in January 1971.[1] This was organized by Donald C. Cheatham (NASA, retired) to solicit industry-wide opinion on the subject. It was well attended by a cross-section of the guidance, navigation, and control (GN&C) community. The coverage, however, turned out to be limited to aerodynamic control of entry through landing. While most of the problem areas were recognized and discussed and systems concepts were presented, little design criteria was proposed except in the approach and landing area. In fact, one of the participants proposed that definitive criteria were not needed. Supposedly, the contractors knew what was good and bad. The simple statement "make it good" was the only requirement needed--an interesting concept. However, the flight control system designers said they needed some response criteria because of the closed-loop, fly-by-wire control concept and the unconventional airframe characteristics. After about six months of debate, all relevant information on handling qualities for the whole Shuttle mission were incorporated into 30 pages of text.

The basic reason for the relatively abbreviated set of requirements was that it was not intended to be a generally applicable specification for manned spacecraft or define the total boundary of acceptable conditions and the ultimate limits between acceptable and unacceptable. Instead, it was intended to present conditions that were thought to be easily achievable and fall well within the acceptable boundaries for a specific vehicle and mission concept. No theoretical rationale was provided. The requirements were based on simulations of the vehicle and mission as known at the time. One underlying assumption was that there would always be active, closed-loop control of vehicle response parameters with sufficient control power and parameter adjustment capability to get any type of response desired. In most cases, all that was specified was the control power or maneuver rate, the control modes, and a transient response envelope. The response requirement format chosen allowed the requirements for the whole mission to be specified on two pages. It was all quite arbitrary. However it represented something that worked on the existing simulators and was consistent with Apollo experience where it was considered applicable.

The remote manipulator system is shown as a control effector used during onorbit payload operations. This was not addressed in the original requirements, as it is in a slightly different class. Because of the flexibility of the arm, the limited force, and variable geometry and inertia it is not a trivial matter. It is a valid man-in-the-loop handling qualities consideration for payload operations, especially heavy payloads. Handling qualities had no significant influence on the design other than control mode and controller configuration. The task now is to accommodate the result.

To provide Shuttle-type vehicles with conventional handling qualities requirements during ascent, onorbit, and early entry is a very big job remaining to be done. One might debate whether it really needs doing. The need to compromise with the ideal handling qualities requirements will be much greater for this type of vehicle because of the potential costly impact on vehicle configuration and consumables. As a result, the need to define the minimum acceptable side of the requirement is probably where the real urgency lies.

TABLE I

| | Mission phase | | |
|---|---|---|---|
| Control effectors | Launch and Abort | Onorbit | Entry |
| SRB/M.E. - TVC | First stage ascent<br>Attitude control<br>Fly commands | ------ | ------ |
| M.E. TVC | Guided ascent and Abort - fly the Commands<br>RTLS, TAL, AOA, ATO | ------ | ------ |
| OMS TVC | Orbit insertion $\Delta V$<br>Fly commands | Orbit maneuver $\Delta V$<br>Rendezvous<br>Deorbit | ------ |
| RCS | Single engine OMS<br>Roll control<br>Fly commands | Attitude control<br>Stationkeep<br>Prox OPS<br>Payload OPS<br>Single engine OMS Roll control | $\bar{q} < 2$ PSF<br>Fly commands |
| RCS/AERO | ----- | ------ | $\bar{q} = 2$ PSF $\rightarrow M = 1$<br>Fly commands |
| Aero Surfaces | Trim for load relief | ----- | $M < 1$<br>Fly commands → OTW |
| RMS | ----- | Payload OPS | ----- |

## RESULTS

After five approach and landing test flights and six orbital missions, a major result is that the only significant handling quality concerns have been in that little area where we have vast experience--the landing maneuver--specifically, the final flare to touchdown and the derotation to lower the nose gear. In reviewing this ironic turn of events, it appears that the reason is that in designing a vehicle that performs well in all the other mission phases where we have less experience, we have so changed the inherent vehicle characteristics, the flight control system and the flight path that it is no longer representative of the experience we do have. Efforts to make it more conventional for landing failed due to the penalties in weight, performance, and complexity imposed on some other part of the mission. The factors we were driven to accept were the following:

1. Unpowered approach and landing
2. Lack of static stability
3. Elevon controls
4. Lack of direct lift control
5. Lack canard control surfaces
6. High landing speed
7. Massive redundancy
8. Digital flight control

These factors either by themselves or combined affect the handling qualities during approach and landing. The last two contribute to additional time delays in the flight control system.

From an overall standpoint, handling qualities did not have much effect in determining the configuration of a really new first-generation vehicle, such as the Orbiter. Some of the reasons for this are the following:

1. In a radically new first-generation vehicle, the uncertainties in performance and survival far overshadow the vagaries of handling qualities requirements. In terms of urgency, compromises are not likely to be made in favor of handling qualities. In a second-generation vehicle, the result might be quite different since both handling qualities and performance capability would be better understood.

2. With the advent of fly-by-wire and digital flight control, there is a tendency to assume that any handling qualities problem can be solved with software. There is probably even a lot of truth in that but it does not follow that we are instantly smart enough to know how to do it. We still have a lot to learn about the fine points of fly-by-wire, closed-loop control of statically unstable aircraft in situations where precise control relative to another near object (a vehicle or the ground) is concerned. Even with a more favorable vehicle configuration, it would be easy to end up with poor handling qualities due to the way the control loops are designed. There are a lot more choices but we do not understand the additional set of limitations that go with them. There are more ways to go wrong. The trend in vehicle design, however, seems clearly to optimize for performance and depend more on fully active computer dependent flight control systems to make up the deficiencies. The Orbiter took a giant step in that direction.

3. These are interesting and challenging problems--the kind that engineers like to work on. Sometimes we are too willing to accept the challenge rather than argue for the tried and true. So, in a sense, we tend to invite trouble.

4. Finally, there is the fallback argument that if handling qualities become too much of a problem, the auto mode is always available. However, the auto mode must be given equal priority in the design process as it was in the Shuttle. Each control mode has its unique problems. For a really new vehicle, providing both greatly improves the likelihood that at least one will always be available.

The reason there have not been more problems in other mission phases might be that so far they have not really been exercised in situations that are critical from a handling qualities standpoint. All launches have been in automatic control with no launch aborts. We have not done any rendezvous, stationkeeping, or docking yet. It is the operation in close proximity to another object that tends to stress the handling qualities. For the most part, however, onorbit operations are not time critical and proceed very slowly. Some can even accommodate repeated attempts; e.g., docking. So there really is no reason for concern at this time.

During most of entry, maneuver rates are very low. Most have been flown in the auto mode. However, enough has been done to indicate the pilot has adequate control to perform the required bank reversals manually and has done some pushover/pull-up maneuvers to gather aero data. The significant issue here appears to be RCS propellant consumption not handling qualities. The auto system tends to use less. The anomalies that did occur are the result of variations in the aero data from that used to design the system and affects both auto and manual modes.

Subsonically, the pilot appears to have no problem flying the vehicle manually to perform the heading alignment maneuvers, the steep approach and preflare. From there to touchdown, it appears necessary to exercise unusual care to avoid large control inputs which tend to produce pilot-induced oscillation (PIO) in the pitch axis. More about that later. One other exception is the effect of winds aloft. Since the Orbiter is unpowered, its trajectory and energy management can be greatly affected. In three of the first six missions, there have been winds outside of the environmental design specification. Some last-minute modifications to the approach trajectory were required. There has been a continuing effort to develop ways to make the system able to accommodate a wider range of wind conditions.

## SOME PROBLEMS AND CONCERNS

Several other topics warrant some further discussion with respect to handling qualities. These are hand controller configuration, the derotation control problem or "wheelie", and the pitch axis flight control system tendency toward pilot induced oscillation at landing. This section will address each of these.

## HAND CONTROLLER CONCERNS

The Orbiter uses the same Apollo-type hand controller for both aero control and onorbit reaction control system (RCS) attitude control. The latter is essentially an on/off control function. Ideally it should have a different type of feel than that required for good aero control. We optimized as much as possible for good aero control and accepted the result for RCS control. As a result, it is impossible to tell by the feel force exactly when the jets fired. Consequently, there is a tendency to make sure the control input is big enough. There has been some concern, but this is apparently acceptable, although some of the more demanding tasks like docking have not been done yet. The alternative is more mechanical complexity, such as having two controllers or adjustable feel. Although this area could be developed further, it doesn't appear necessary.

Another peculiarity of this most simple fly-by-wire hand controller is the aero trim function. In a conventional mechanical system, the stick force can be trimmed without moving the stick. In the Orbiter, the manual trim signal goes into the control loop. This causes the vehicle to respond unless one backs off on the controller as the trim is applied. In general, this cannot be done perfectly but there have been no complaints. This is probably because the manual trim is hardly ever used since automatic trim follow-up is available. It would complicate the controller greatly to make the trim function appear conventional.

Controller location was also of some concern. It is in the center (not side stick) and canted some 19 degrees left to be comfortable for right-hand use. It provides better access and room for displays and switches. However, there was concern about the possibility of control cross-coupling since it is not aligned mechanically with the vehicle axes. To keep it in the center and aligned with vehicle axes would make it misaligned with natural arm motion. Either way some cross-coupling is likely. It does occur at times but not to a large degree and apparently has not been objectionable.

In the Orbiter, the hand controller is only connected to some electrical transducers and feel springs. It is easy to move the controller faster than the surface can respond without knowing it. When this happens in one control axis, a small input in the other axis will be ignored in an elevon system unless some special limiting is provided in the software. We did not have this limiting initially because it did not appear that the problem ever arose during simulations. During the last approach and landing test (ALT) flight however the situation occurred. Small lateral inputs were ignored until the pilot put in a big one provoking a lateral PIO when the vehicle suddenly responded. We subsequently added a series of limiters in the aileron/elevator/elevon mixer logic. This insured that control in one axis was never completely locked out due to rate saturation in the other.

This resulted in getting by with a very simple and light-weight hand controller configuration relative to what it might have been.

## THE "WHEELIE"

The wheelie that occurred on STS-3 was a bonafide handling qualities problem even though it occurred after main gear touchdown. The external symptom was the unintended pitch up during rollout after the nose had started down. The problem is caused by the change in geometry that takes place when the vehicle touches down. The center of rotation shifts from the center of gravity to the main gear. This aft shift in the center of rotation, coupled with a vehicle that is already statically unstable, results in a rapidly increasing nose down moment as the nose is lowered. The control system configured for the inflight situation could not keep up with the rapidly changing elevator trim requirement. Nor could it provide a stable pitch rate control loop. This was recognized analytically early in the program. However there was a reluctance to accept the required switching of control system parameters at touchdown that is necessary to compensate for the change in geometry. Instead, the pilots demonstrated during simulations that they could handle the problem. The procedure was to hold the nose up at the touchdown attitude until the speed decreased to an acceptable value. Then the nose gear is let down. Pitching over can cause full-up elevator and if started at too high an airspeed can result in excessive gear loads. Once the nose starts down, the trim changes so fast that is is almost impossible to stop it without overcontrolling. That's what happened on STS-3. It was not too difficult for the lightweight ALT Orbiter. However, at today's heavier landing weight and especially combined with a forward center of gravity, the control task is considered unacceptable.

The problem was reevaluated on a fixed base simulator and several fixes were developed. They involved changing the flight control system for landing or switching parameters at touchdown. Fortunately, this problem was quite obvious on the simulator and it was also quite noticeable when an improvement was made. The simulator evaluation included a sequence where the nose was lowered then raised again to evaluate controllability under the worst weight and center of gravity conditions. We ended up choosing the fix that was simplest to implement. This consisted of switching the pitch axis hand controller output through the same signal path that the autoland system uses. It switches parameters at touchdown. Most of the software was already there.

## LANDING FLIGHT CONTROL

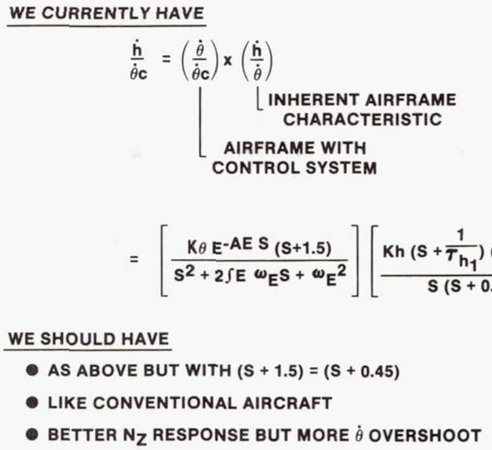
The Orbiter pitch axis control during landing has undoubtedly been the single most worrisome handling qualities problem. The symptoms are that if the pilot attempts to take very aggressive control of the vehicle close to the ground and force it to land at a specific point, there is a tendency to get into a pilot-induced oscillation. As a result, the pilots have learned to get the approach well set up early from an energy standpoint and take unusual care to avoid large inputs close to the ground. Gusts and crosswinds could aggravate this technique, hence, the concern.

The attitude control response has been consistently reported as crisp. Consequently there is something deficient in the path control; i.e., the control of altitude rate or normal acceleration. This always leads back to the same dilemma. It is obvious that the normal acceleration (Nz) response is sluggish. To quicken it significantly requires more overshoot in the pitch rate response and the pilots always object to that. Notice that the choice of feedback parameters ($\dot{\theta}$ or Nz) is not necessarily a significant issue here. The response to command can be made the same with either feedback depending on how it is shaped. But either way, to get faster Nz response means more pitch rate overshoot. Actually, pitch rate was selected as the specified response parameter. It was well behaved with no initial reversals or dependence on sensor location as is the case for Nz. This does not inherently limit any type of control system configuration but just judges them based on the pitch rate response. Other considerations for choice of feedback parameter in the actual system are based on the response to external disturbance. For a vehicle, such as the Orbiter, with zero or slightly negative static stability, pitch rate appears the safer choice. It is less demanding on surface rate in gusts and turbulence. To rate limit under these conditions could mean loss of control.

More analytical treatments in references 3 and 4 have pointed out that the existing pitch rate control system mechanization cancels the inherent zeros in the bare airframe pitch rate transfer function and replaces them with another term that does not completely cancel the corresponding term in the flight path response like a conventional unaugmented airframe. Figure 1 illustrates this. The result shown in figure 2 is an unnatural attentuation. There is also an additional phase lag in the flight path response relative to what it would be with perfect cancelation. There are, in general, two ways to correct this. One is to reshape the pitch rate control system to preserve the bare airframe short period zero as in reference 4. The other way is to add a lead/lag filter in the hand controller output. It is tuned to cancel the existing system zero and replace it with the natural airframe value. Since this is done outside the control loop, it does not change the stability margins of the inner control loop. It only changes the handling qualities as seen by the pilot.

A recent series of fixed base simulator evaluations examined these and other variations in the pitch axis control during landing. This was done to determine if improvement is possible by changes to the software. These simulations are still in progress. A complete treatment is beyond the scope of this paper but some of the findings have been the following:

1. None of the changes made more than a 0.5 improvement in the Cooper-Harper rating or a 26 percent improvement in landing performance with respect to the existing baseline system. Twice that much would be required to consider a change.



**WE CURRENTLY HAVE**

$$\frac{\dot{h}}{\dot{\theta}c} = \left(\frac{\dot{\theta}}{\dot{\theta}c}\right) x \left(\frac{\dot{h}}{\dot{\theta}}\right)$$

$$= \left[\frac{K\theta\, E^{-AE\, S}\,(S+1.5)}{S^2 + 2\zeta E\ \omega_E S + \omega_E{}^2}\right]\left[\frac{Kh\,(S + \frac{1}{T_{h_1}})\,(S + \frac{1}{T_{h_2}})}{S\,(S + 0.45)}\right]$$

**WE SHOULD HAVE**

- AS ABOVE BUT WITH (S + 1.5) = (S + 0.45)
- LIKE CONVENTIONAL AIRCRAFT
- BETTER $N_Z$ RESPONSE BUT MORE $\dot{\theta}$ OVERSHOOT

FIGURE 1.- WHAT DOES IT ALL MEAN?

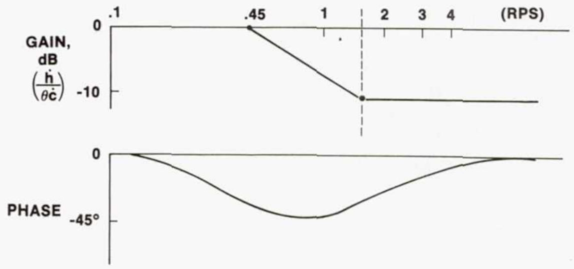


FIGURE 2.- FLIGHTPATH RESPONSE DEGRADATION WITH THE PRESENT SYSTEM.

2. The systems with the best landing performance were not rated the best by the pilots. In fact, the two systems with the best landing performances were both rated worse than the baseline.

3. The lead/lag stick filter addition to the baseline was one of the two best systems from a performance standpoint (group 1 out of 8) even though not properly implemented in detail.

4. The baseline system was in group 3 out of 8 from a performance standpoint. It was rated in group 2 out of 5 (C.H. = 3.5) by the pilots which is quite consistent.

These systems did not all have the same inner loop gain or gain margin. Consequently it is not immediately obvious what aspect of a given system caused a certain result. Also, from the pilots' comments, it is clear that there are many subtleties that affect the rating of a system. These subtleties include having to control across the hand controller detent or use push force right at touchdown. It is also clear that the pilots' first priority is attitude response. Systems with significant overshoot tended to be downgraded even though they might have better flight path response. This probably resulted from training and adjustment to accommodate the existing system. Changing the system response characterstics to achieve better landing performance would probably require a significant amount of retraining. The improvement needs to be significant enough to warrant the effort.

## CONSIDERATIONS FOR NEXT TIME

It is interesting to consider what should be done from a handling qualities standpoint if a second-generation Shuttle were to be designed. There are at least two major objectives to address. First, there should be an effort to provide more definitive requirements for mission phases other than approach and landing. A significant amount of basic knowledge is available that would be useful. However, it needs to be organized and written down. The effort would probably expose holes where further activity would be beneficial. Future missions will serve to increase the understanding of these requirements and allow a more knowledgeable compromise with new vehicle configurations if available at the outset.

The other major objective should be to improve the pitch axis handling qualities for landing. First, serious consideration should be given to arrange the vehicle configuration such that fast-acting direct lift control is available for landing. This could be by means of canard control surfaces or wing flaps if it is a tail-controlled vehicle. Possibly even the reaction control system could be used if it were designed with this in mind. Secondly, there needs to be a strong influence at the beginning of the program to keep the flight control system time delays to a minimum. Additional time delays tend to creep in and this is clearly detrimental though somewhat difficult to quantify. Specific requirements should be imposed for end-to-end system response delays. In addition, the design and development effort must be monitored closely. Aggressive action should be taken where necessary to ascertain that proper attention is given to meeting the requirements. The inner flight control loops should be processed at 50 cycles/second or more for landing. The redundant actuator design should be reviewed to quantify and determine ways to minimize the response delays to small signals. Finally, a hardware feed forward provision should be implemented so that small amplitude, high passed analog signals can be sent directly to the actuators from the hand controller or sensor summing junction to bypass the digital delays and overcome the small amplitude actuator nonlinearities. These improvements are relatively easy during the design process but nearly impossible to change after the hardware is built.

## REFERENCES

1. Space Shuttle Flying Qualities - Guidance and Control Division, Manned Spacecraft Center, Houston, Texas; January 20 and 21, 1971; Donald C. Cheatham

2. Flying Qualities Requirements for the Orbiter Utilizing Closed-Loop, Fly-By-Wire Control of Vehicle Response Parameters, MSC-07151; May 12, 1972; W. J. Klinar, D. W. Gilbert, C. T. Hackler, H. E. Smith, Jr., D. C. Cheatham

3. Space Shuttle Flying Qualities and Flight Control System Assessment; Myers, McRuer and Johnson, Systems Technology Incorporated (AIAA Paper 82-1608), 1982

4. Application of CALSPAN Pitch Rate Control System to the Space Shuttle for Approach and Landing; N. C. Weingarten and C. R. Chalk; CALSPAN Report No. 7102-F-1; December 1982