Why the Wings Stay on the Space Shuttle Orbiter During First Stage Ascent

Carl F. Ehrlich, Jr.
Retired, Calabasas, CA 91302

Wind tunnel tests of the Space Shuttle launch configuration conducted in early 1974 to determine if the elevons were going to exceed the load limits of their actuators. These expectations were confirmed but they also showed some even more disturbing results: i.e., the wings were going to exceed their design margins by a large amount and would potentially break off during mated vehicle ascent.

This paper documents the solution to these very significant problems. At that point, in the Shuttle development, the contracts for the Wing and External Tank designs had already been let to other contractors and any redesign could have led to very expensive contract modifications. An extensive series of additional wind tunnel tests were conducted which included a long series of oil flow visualizations to document the flow on the wing panels during ascent. These data were extensively plotted and cross-plotted over the ensuing months. The resulting "fix" turned out to be a very simple and elegant solution which, in short, was to fly in the now standard heads-down attitude: i.e., at negative angle of attack. Thus, the scheme was to fly the wings at near zero panel load and to deflect the elevons as a function of Mach number to track close to zero hinge moment. An avionics box on each of the Solid Rocket Boosters were later found to be the culprits.

These findings coincided precisely with separate trajectory studies to minimize drag losses during ascent. They also coincided with the astronauts recommending a heads-down attitude so that they could see the earth so as to maintain their visual orientation. These three separate findings resulted in the ascent flight attitude and post launch roll maneuver that have been used on all Shuttle flights. In the process, the wings and elevons did not have to be redesigned and the launch system received a welcome payload performance increase.

Nomenclature

CBW = Coefficient of wing bending moment
CTW = Coefficient of wing torsion moment
CNW = Coefficient of wing normal load
CHEI = Coefficient of elevon hinge moment – inboard
CHEO = Coefficient of elevon hinge moment – outboard
SRB = Solid Rocket Booster
δei = inboard elevon deflection – positive is trailing edge down
δeo = outboard elevon deflection – positive is trailing edge down
α = angle of attack
β = angle of yaw

AIAA Associate Fellow

I. Introduction

The heads-down attitude (i.e., crew heads pointed toward the ground) during the ascent flight of the Space Shuttle launch configuration has been the standard ever since the first flight in 1981. This attitude is attained after the vehicle clears the launch tower and is directed toward the azimuth of the target orbit. This was not the way it was planned at the outset: heads-up was the original plan. That way the lift vector would be directed to assist the ascent trajectory. The events that led to this change and their resolution are the subject of this paper.

II. The Test and Subsequent Program

I was newly arrived at [then] Rockwell International in early 1974 and was asked to conduct a wind tunnel test of the elevon hinge moments during first stage boost as they were beginning to show signs of being marginal with respect to the elevon actuators. During the test planning process, the suggestion was made that we incorporate a wing load balance into the test program. This suggestion was endorsed and added to the test program. The two elevon balances, one for each elevon, are shown in Fig. 1. The wing load balance was installed at the exposed wing root; it measured the loads on the wing and glove as outlined in Fig. 1.

The test was conducted in the [then] Rockwell 7-foot Transonic Wind Tunnel. I came prepared as was normal for those days with graph paper ready for plotting data as it came from data reduction; Fig. 2 shows an example of these graphs ready to take data. Back then, the reduced data came quite a few runs behind the test itself as things were slow then and early test data needed some extra time to verify the computer reduction processes. Fig. 2 shows the approximate upper load limit (Note that the exact value used is lost but the value shown is roughly correct to the best of the author's memory), the nominal ascent angle of attack, and the expected data trend. This data trend was assumed to allow for some angle of attack overrun before reaching the design limit.

[Note that many of the specific data plots presented in this paper have been lost over time. The plots denoted by "reconstructed data" have been generated from what is available in Ref. 1 or recreated to the best of my knowledge and memory.]

When the actual data became available and plotted, I saw that the loads were very different from what were expected. The data suggested that the wings would exceed their normal load limit at attitudes far below the nominal flight attitude: about two deg. angle of attack versus six deg. as shown in Fig. 3. This trend was repeated for several more runs.

At that point, I stopped the test to verify the data and the wing balance calibration. This recheck of the calibration showed no change. We made several more runs at similar conditions. The job now was to thoroughly check everything in the test system to make sure that all was working properly or to determine what was not working. The wind tunnel crew calibrated the wing balance in the tunnel, out of the tunnel, on the model, off the model, right side up, and upside down. The matrix inversion process was rechecked and the data reduction procedures were verified to see if there had been any changes – there were not.

My concern was that once the Shuttle program and the various contractors heard of this problem; the news would travel from coast to coast, raising many design, performance, and contractual concerns. The only group that would have been happy to hear this was the wing contractor who was well into their design work and had probably been realizing that it was a bigger job than they had expected so they would have been pleased at receiving a big contract change order. Also, if this news and its ramifications were shown to be based on bad data, the wind tunnel itself would have a bad reputation for a long time. These concerns were the

Figure 1. Shuttle launch vehicle with the wind tunnel load balances shown (NASA photo).

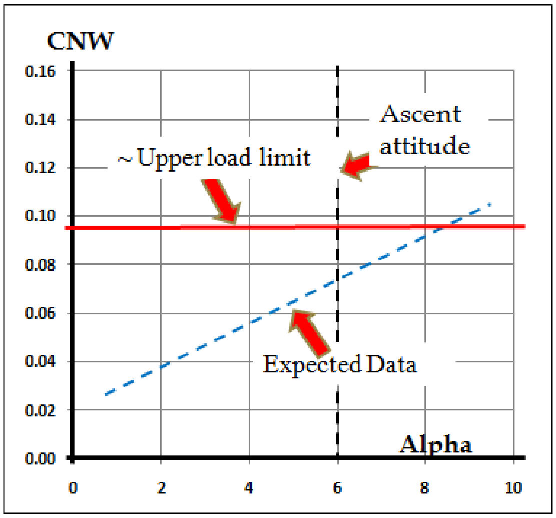


Figure 2. Example of a prepared graph showing data limits and expected data trend (reconstructed data).

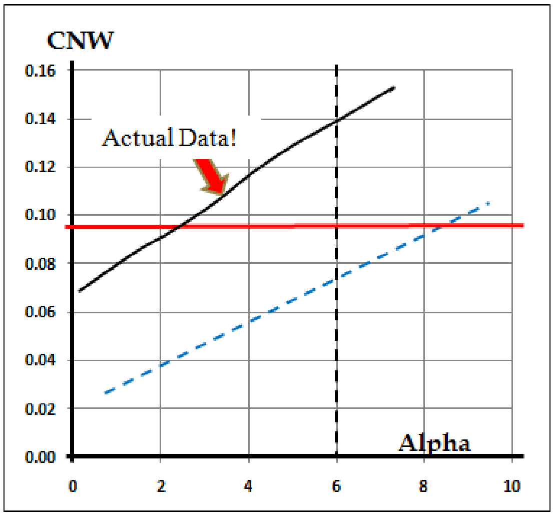


Figure 3. Actual data greatly exceeded the load limits at the nominal flight attitude (reconstructed data).

reason for undertaking the intensive recalibrations and verification.

This discussion has generally been referring to wing panel loads but a similar concern existed in the elevon hinge moment data.

Once we had verified the data in all respects, I made the call to my management. We decided to finish the test program but in an abbreviated version. The principal objective for the remaining period was to determine the extent of the problem as a function of Mach number and staging (we later found out that the problem went away with SRB separation.

After this information was digested at the Rockwell Downey site, I was put in charge of a team to determine what was going on and how to fix it gracefully. The word "gracefully" translated to finding a way out of this problem without affecting the program any more than necessary. Primary to that was to minimize changes to the outstanding contracts to Grumman, for the wings; Martin, for the external tanks; and Thiokol, for the boosters. We embarked on a long series of exploratory wind tunnel tests, principally at the 14-Inch Trisonic Wind Tunnel at NASA/MSFC using a small-scale model of the launch configuration. We instrumented the model for force data on the full model, wing panel loads, and hinge moments on the two elevons. In addition to force and moment data, we did extensive oil flow studies to help determine what was going on. This entailed making a run at a single condition, taking the model out of the tunnel, dismounting the orbiter, photographing the oil steaks generated by the flow conditions, then cleaning the model, re-oiling it, and replacing it in the tunnel. We eventually developed an extensive digital and photographic database covering critical regions of interest determined from the initial test program.

Figure 4 presents a sample carpet plot of data from Ref, 1 developed during these tests. These were completed for the five major parameters of the test program for a range of Mach numbers and elevon deflections. As these plots became available, the generally linear characteristics of the data became obvious. Since the ascent trajectory folks were looking for some way to explore trajectories

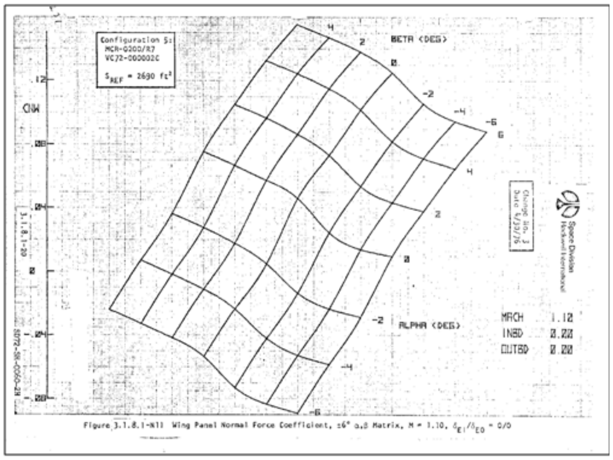


Figure 4. Typical carpet plot of data developed during the testing; note the relative linearity of the data (Ref. 1).

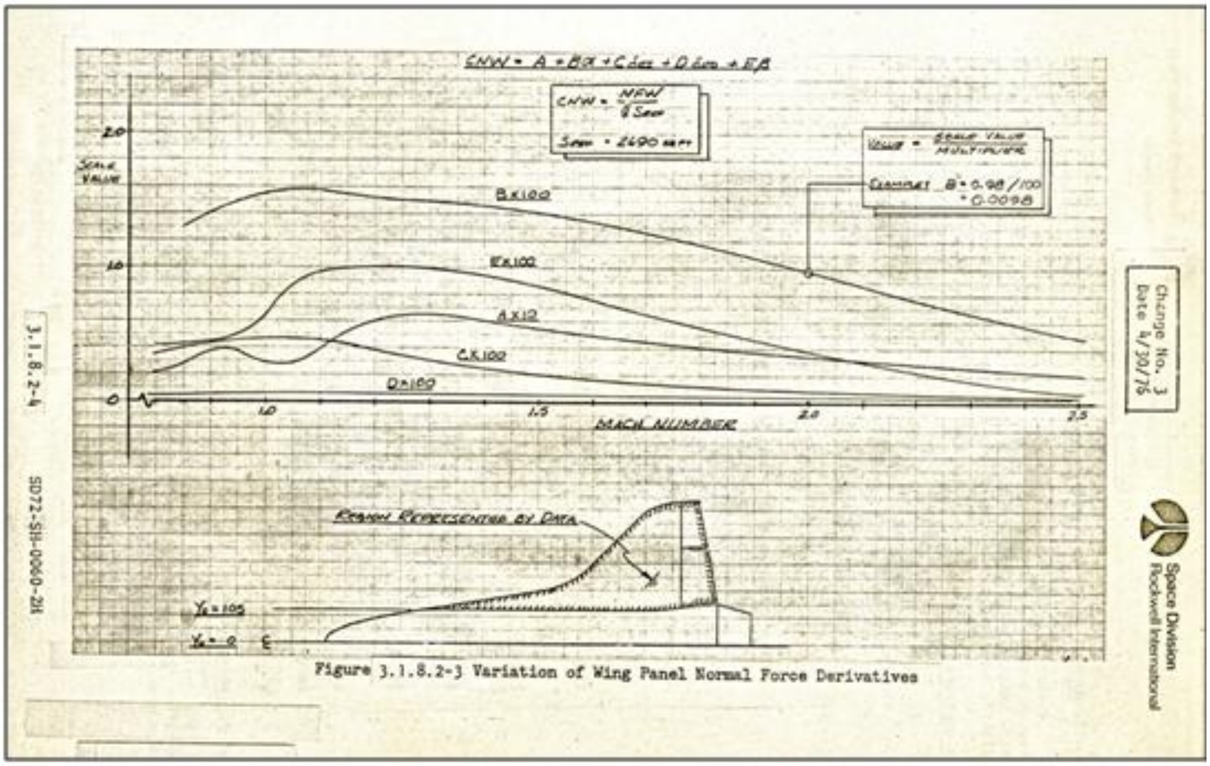


Figure 5. Example linearized plot of data developed during the exploratory testing (Ref. 1).

with these load limitations, I developed a graphical summary of these data by capitalizing on their generally linear nature. For each of the five principal coefficients, I developed equations for each in the form:

$$Cxx = A + B\alpha + C\beta + D\delta ei + E\delta eo$$

where the letters: A, B, etc. were derived from linear least squares curve fits. A sample of these plots from Ref. 1 is presented in Fig. 5 for CNW.

Meanwhile, the oil flow visualizations were revealing interesting and critical information. At supersonic speeds, shocks impinged on the lower surfaces of the wing from root to tip (Fig. 6). The cause for this shock was not indentified during this exploratory test period. I imagined that it was the result of flow inference between the orbiter and the external tank, particularly from interference of the aft external tank attach structure.

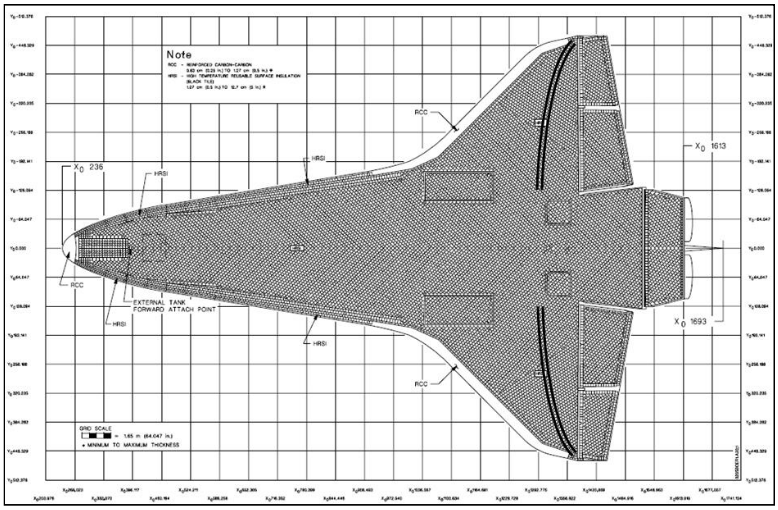


Figure 6. Oil flow data clearly showed that there was a shock running tip to tip (simulated by the black line) on the lower surface of the orbiter interrupted by the tank/orbiter flow field. (reconstructed data plus Ref. 3).

Flow streamlines seemed to support this theory.

During this test phase, we then looked at various candidates for fixing or relieving the problem. These included fences between the orbiter and external tank, ramps in front of the forward and aft attach structures, changing the cant angle of the orbiter relative to the external tank, and variations of each of these candidates. Most of these had little or no effect, although the full-length fence achieved a notable improvement but would have significantly affected the external tank contract.

III. The Solution

We eventually collected enough data to get an idea of what was going on. The next question was what to do about it so that the "fix" would have a minimal impact on the program and subcontracts. While exploring the data, I made cross plots of the data versus Mach number at even angles of attack. This entailed interpolating between angle of attack data as the wind tunnel data (note that the wind tunnel data normally reflect the effects of sting bending, ending up with fractional angles). A sample of these data is presented in Fig. 7, which shows the variation of the wing bending moment (CNW) as a function of Mach number at constant angles of attack.

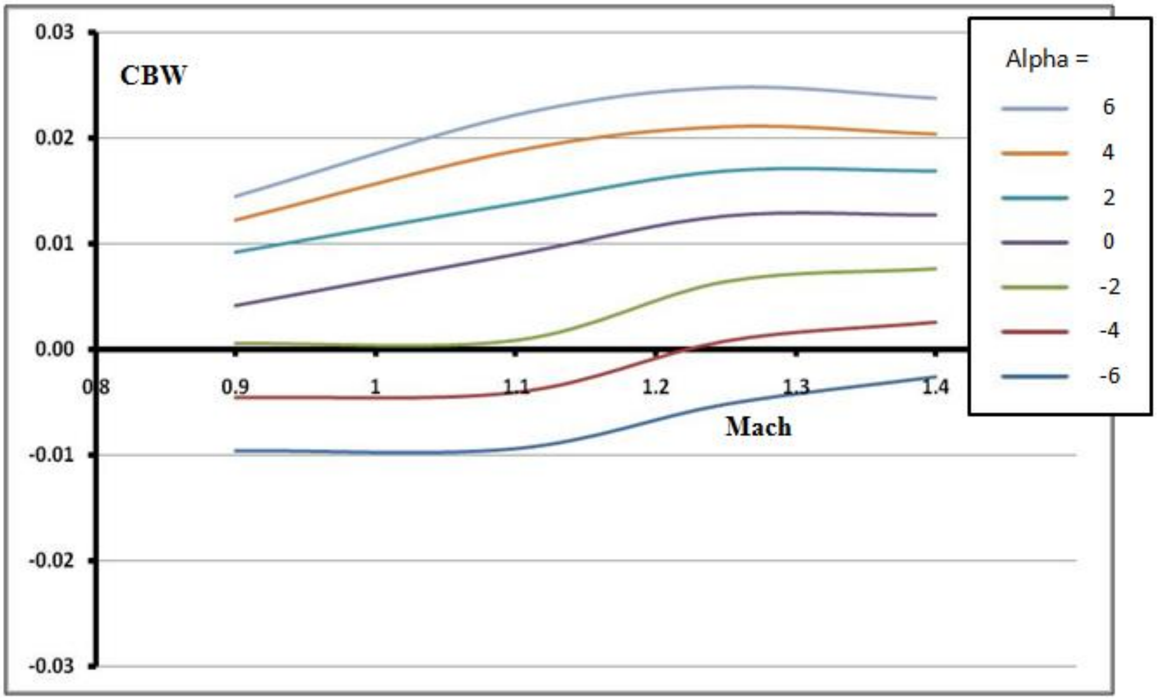


Figure 7. Crossplot of wing bending moment (CBW) data at constant angles of attack illustrating the Mach number trends of the data (partially reconstructed data from Ref. 1).

This proved to be a key presentation. When I added the load limit data to the plots and added the Mach number for maximum dynamic pressure, the solution became very clear. The angle of attack for zero loads was seen to be between minus 2 and minus 6 degrees across the Mach number range. This is made very clear in Fig. 8, where a "safe" zone is identified. Ultimately, an angle of attack of minus 5 degrees was recommended.

Later, recommended elevon deflections were developed by a similar approach. In this case, the limiting elevon deflections that corresponded to maximum positive and negative load limits were plotted versus Mach number. A more or less neutral path between these limits was sketched (from memory), as shown in Fig. 9. This nominal schedule has been carried along the entire Shuttle flight schedule since the first flight, as shown in Fig. 10. The two formal charts in Fig. 10 are reproduced from the STS-131 flight manual.

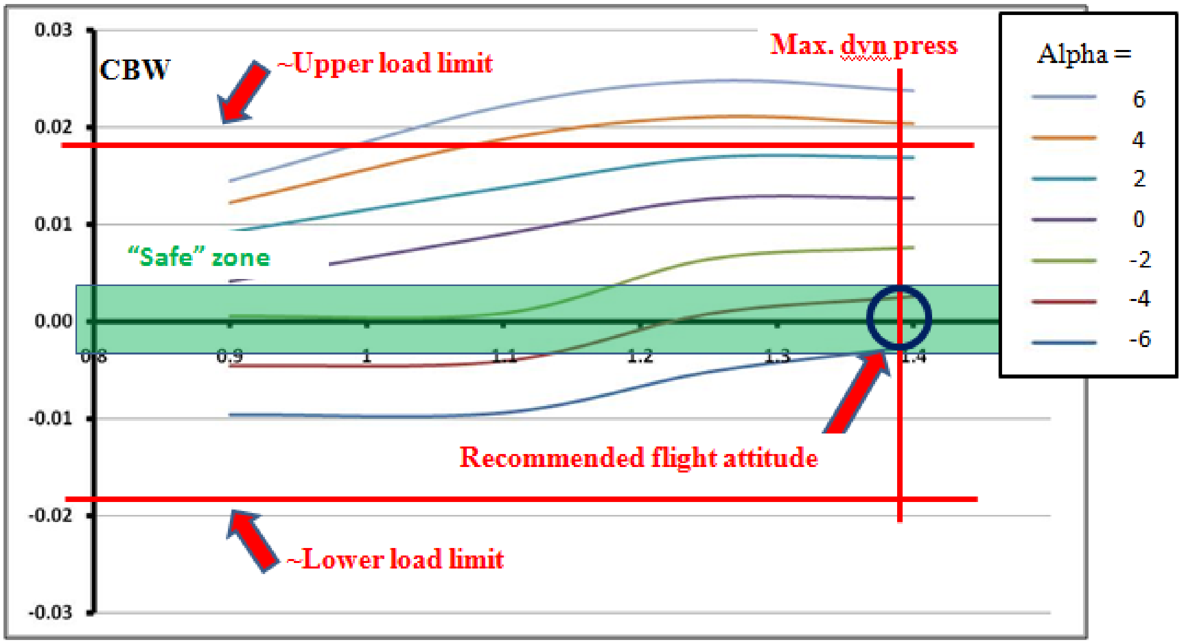


Figure 8. Wing bending moment data with load limits superimposed (partially reconstructed data from Ref. 1).

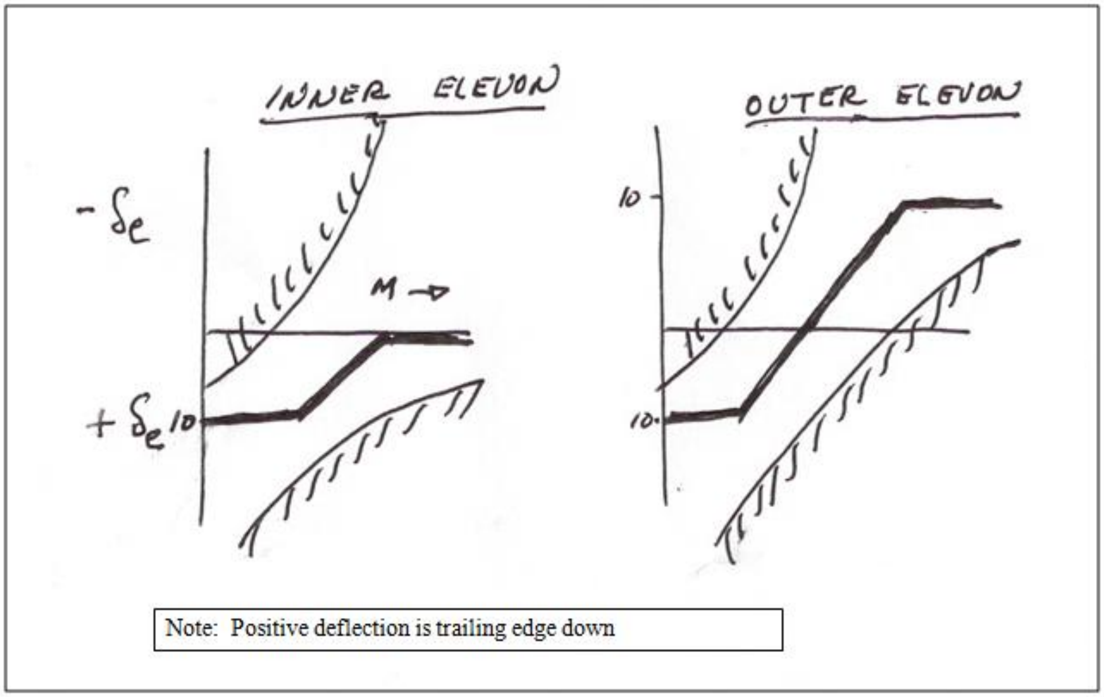
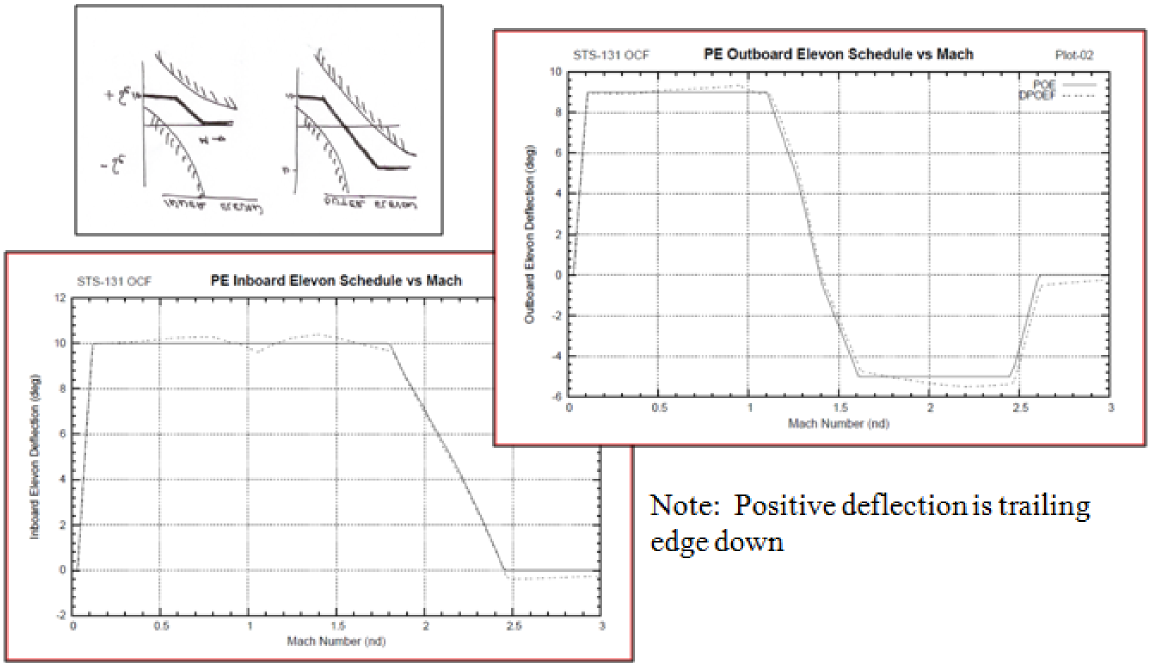


Figure 9. Limiting elevon deflections were identified to define the recommended deflection schedule versus Mach number (sketch is constructed from author's memory).



Note: Positive deflection is trailing edge down

Figure 10. Actual elevon deflection schedule for STS-131 with Fig 8 sketch shown inverted to depict more recent plotting formats (Ref. 2).

After I had made my recommendations for the elevon deflections and the ascent angle of attack, there was a detailed verification and certification program bythe full Shuttle program. By that time, I had been assigned to another emerging problem, that of the SRB ignition overpressure concern, and was not involved in that process. Later still, I rotated off the Shuttle program but was able to follow the launches from time to time.

The recommended deflections at launch were actually used in practice and are clearly visible in flight, Fig.11, and have been since the inception of Shuttle flights.

Figure 11. In-flight photograph showing the deflected elevons (NASA Photo).

IV. The Aftermath

The basic culprit in all this was not well understood while the load relief solution was being developed. I found out some twenty years later in a chance conversation that during the verification and certification process the problem had been attributed to an avionics box mounted on top of the SRBs at the aft attach points, Fig. 12. At the time, I questioned this because we had tested orbiter/ tank fences that followed the flow streamlines noted from the oil flow tests. We noted at the time that the fences provided notable improvements in the wing and elevon loads.

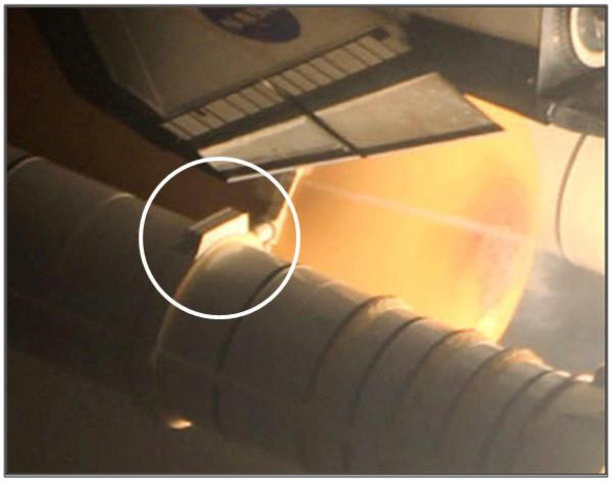


Figure 12. In-flight photograph showing the Integrated Electronics Assembly box on the SRB (NASA photo).

V. Concluding Remarks

Meanwhile, there were other program events unfolding:

The ascent trajectory group was experimenting with means to reduce drag losses during ascent in order to maximize payload delivered to orbit. Notably, I understood that they were using a different database than we were developing in the wing loads program. In their work, they were coming up with the conclusion that flying heads-down at a slightly negative angle of attack would achieve their goal. Then the ascent trajectory design became, in part, a balance between minimizing the wing loads, minimizing the elevon hinge moment loads, allowing for the loads induced on the wings by the elevon deflections, and minimizing induced drag.

At the same time, the astronauts were beginning to fly more and more sophisticated simulators. They were discovering that, by flying at the then nominal heads-up attitude, they could not see the Earth’s horizon and were losing their orientation. They started experimenting with a heads-down attitude and realized that this was a solution to their concerns.

Ultimately, these three separate studies came together very nicely and got us out of a potentially expensive problem. Our initial elevon concerns were resolved by establishing a deflection time history that would position them in an nearly zero hinge moment condition, the wing loads were minimized by flying them also in an essentially minimum load condition, the astronauts were able to maintain their orientation, and the program payload delivery performance was improved.

The recommendations made during the studies have been used during the entire Shuttle flight history to this day. I note during each launch that I had a piece of that action; that was, and remains to be, very gratifying.

References

[1] “Aerodynamic Design Data Book - Volume II Mated Vehicle,” Contract NAS9-14000, Space Division, Rockwell International, SD 72-SH-0060-2H, February 1975.

[2] STS-131 OCF

[3] *Shuttle Operational Data Book*, July 30, 2007