SUBSONIC LONGITUDINAL PERFORMANCE COEFFICIENT EXTRACTION FROM SHUTTLE FLIGHT DATA -- AN ACCURACY ASSESSMENT FOR DETERMINATION OF DATA BASE UPDATES*

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SUMMARY

Longitudinal performance comparisons between flight derived and predicted values are presented for the first five NASA Space Shuttle Columbia flights. Though subsonic comparisons are emphasized, comparisons during the transonic and low supersonic regions of flight are included. Computed air data information based on the remotely sensed atmospheric measurements as well as in situ Orbiter Air Data System (ADS) measurements were incorporated. Each air data source provides for comparisons versus the predicted values from the LaRC data base. Principally, L/D, C_L, and C_D comparisons are presented, though some pitching moment results are included. Similarities in flight conditions and spacecraft configuration during the first five flights are discussed. Contributions from the various elements of the data base are presented and the overall differences observed between the flight and predicted values are discussed in terms of expected variations. A discussion on potential data base updates is presented based on the results from the five flights to date.

INTRODUCTION

The NASA Space Transportation System (STS) entry flights offer aerodynamic researchers unique opportunities to extract aerodynamic coefficients from flight data for comparisons with pre-flight data base values (refs. 1, 2). In this sense, the Space Shuttle is utilized experimentally as a "flying" wind tunnel throughout the entire speed regime. Results from this so-called Aerodynamic Coefficient Measurement Experiment (ACME) have been widely published in the literature, as examples, see references 3, 4, and 5. Though considerable subsonic analyses have been performed by aerodynamicists throughout the aerospace community, some of the results of which are reported in references 6 and 7, most of the published results have emphasized comparisons in the supersonic/hypersonic regime. Here, flight determinations are potentially limited by the accuracy of the remotely sensed atmospheric density, ρ, and the requirement to translate same in time and over rather large global areas to conform to the spacecraft ground track and vertical profile. The third (STS-3) and fifth (STS-5) flights permitted an alternative in situ density determination. These

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in situ ρ determinations were obtained by processing the Development Flight Instrumentation (DFI) fuselage pressure measurements (ref. 8).

In the subsonic regime, alternate air data are always available. Air data can be computed based on remotely measured atmospheric information or obtained directly from the Orbiter Air Data System (ADS). Use of both sources is assumed herein. Discussions are presented which summarize the use of both and quantify the differences which one could expect since both sources result in different flight extraction and predicts generation. One must consider the actual flight/data base comparisons obtained based on both sources in terms of the expected pre-flight data base accuracy, the so-called variations (refs. 9, 10) based on aerodynamicists' consensus. Also, subsonic data base prediction becomes more complex in that additional elements of the overall model are introduced, e.g., rudder, speed brakes, gear effects, and ground effects. Refer to figure 1 for a schematic of the actual control surface configuration of the Orbiter vehicle. The expected contributions from the various elements of the data base are presented and discussed in view of the flight differences. Repeatability in terms of flight conditions and spacecraft configuration across flights is investigated. Such results provide a precursor analysis to enhance more rigorous flight extraction for data base update determinations, i.e., for control surface effectiveness, stability, and performance determinations using regression methods.

DISCUSSION OF AIR DATA SOURCES

The necessary air data information required to extract flight coefficients and enable determination of predicted values can be computed from the measured atmospheric parameters or obtained from the ADS directly. The first method has conventionally been utilized at Langley Research Center (LaRC). Though some of the ADS parameters have been utilized for wind evaluation/estimation in generating the LaRC results as discussed later, direct use of the ADS angle of attack (α), Mach, and dynamic pressure (q) permits independent flight determinations and predicts generation.

Throughout the region investigated herein, conservatively below Mach ~2.5, complete air data are available from the ADS. These data are derived using pressure measurements from the ADS, which consists of two side probes deployed at Mach ~3.5. Each probe is configured with three pressure orifices, each orifice instrumented to provide redundant pressure measurements. Four static ports are also available on each side. These data are processed on/board using a reduced set of calibration coefficients to provide operational air data (except for sideslip angle, β) for spacecraft flight control. Though these on/board ADS parameters are available from the Operational Instrumentation (OI), researchers are able to utilize postflight results which incorporate more rigorous calibrations. These include updates based on Shuttle experience and further analysis of the data obtained during the Approach and Landing Test (ALT) flights for which nose-boom measurements provided additional calibration information. Use of the sensed air data for flight extraction and predicts generation is straightforward. The majority of investigators throughout the community have utilized and recommended use of the ADS in a similar manner.

Use of the remotely measured atmospheric data is discussed next. Subsonically, remote atmospheric measurements available from rawinsonde soundings are more optimally located (time and spatial) and ambient parameters should be more accurate considering the correspondingly lower altitude regions. These measured atmospheres are assembled as Langley Atmospheric Information Retrieval System (LAIRS) files as discussed in reference 11. Reference 12 discusses the merging of these data with the inertially reconstructed trajectory (BET) to obtain the air relative parameters.

Of considerable importance throughout this region are the winds encountered. Figure 2 depicts the drastically different wind environments for the various flights to date. Uncertainties in the available wind measurements, both magnitude and direction, contribute almost entirely to the flight determination uncertainties. The winds are utilized directly to compute the necessary air data parameters: α , β , and air relative velocity, V_A. The latter is used in conjunction with the measured ρ to compute the dynamic pressure. In view of this direct dependence, alternate source data (jimsphere measurements) and information from the postflight calibrated ADS data have been utilized extensively at LaRC to evaluate the remotely measured winds as discussed in reference 13. Basically, atmospheric independent algorithms have been developed which estimate winds using 1) α and β in a deterministic sense to derive winds on a point by point basis, or 2) α , β , and the true air speed, V_T , to obtain wind profiles at break point altitudes with a batch smoother. Evaluations above Mach 1 have not been successful since the uncertainties in the wind estimates increase dramatically with Mach number when constant uncertainties in the ADS parameters are assumed. It is noted that the actual winds incorporated for STS-3 and STS-4 were batch winds in lieu of the measured data. This replacement was somewhat arbitrary for STS-4, but wind measurement problems on STS-3 left no alternative as discussed in reference 13.

FLIGHT EXTRACTION DIFFERENCES

Flight determined aerodynamic coefficients based on the computed (LaRC) and measured (ADS) air data are discussed. In both instances the flight values are computed utilizing the same measured spacecraft rates, accelerations, and mass properties. The measured accelerations and rates are obtained from the accurate Inertial Measurement Unit (IMU) data. For example, the acceleration information is accurate to 1 mg and the angular rates are accurate to 0.01 deg/sec for the nominal 1 sec time homogeneous data. Mass properties are obtained post-flight as time histories. For all intents and purposes, the mass and inertias can be considered accurate to 1 percent or better. An important concern is the knowledge of the spacecraft center-of-gravity (c.g.) required to compute the moment coefficients. A sensitivity to reasonable c.g. errors is discussed later in terms of the resultant effect on the pitching moment, C_m .

Body axis coefficients, normal (C_N) and axial (C_A), are determined directly from the accelerometry and dynamic pressure. The LaRC q utilizes the inertial velocity from the reconstructed trajectory, the measured/evaluated winds, and, of course, the measured ρ . Stability axis coefficients, lift (C_L) and drag (C_D), are obtained by transforming the body axis coefficients through the angle-of-attack. The latter is computed from the inertial orientation of the spacecraft and the orientation of the air relative velocity vector, V_A , which requires knowledge of the wind magnitude and heading. Thus, the influence of the winds are twofold as they affect both q and attitude. For the ADS, the α and q are directly available. The q affects the computed body axis coefficients directly, which then are rotated through the ADS α for stability axis computations. Clearly, differences in the flight extracted coefficients from the two sources can be expected dependent on the observed differences between the α and q.

Figures A1(a) through A1(e) in the attached Appendix present plots of the flight conditions (α, M, and q) for both air data sources for the first five Shuttle flights. They are plotted versus the BET altitude which is utilized as common to both. These data are shown as composite plots for all five flights as figure 3 (LaRC) and figure 4 (ADS) in this paper. These data are plotted from the Aerodynamic Best Estimate Trajectory (AEROBET) files generated using the particular air data source. Reference 14 discusses the contents of these data files. Figures A2(a) through A2(e) show expanded plots of α and q versus Mach number from both sources for STS-1 through STS-5, respectively. Mach number from both sources is seen to be multi-valued in some regions. Though Mach number doesn't affect the flight extraction per se, any differences versus Mach number are most relevant for predicts generation as discussed later. Except for STS-4 and 5, there are noticeable differences between the two sources near Mach 1. Clearly the most pronounced differences occur for STS-2 and STS-3. Readers will recall from figure 2 that the winds encountered during these missions were considerably larger than those occurring on the other flights. Also, the profiles exhibited extremely large gradients, particularly for STS-3 in the vicinity of 10 and 55 kft. The measured winds which were utilized for STS-2 were never sufficiently substantiated using the estimation algorithms, at least in the vicinity of h ~24 kft and h ~50 kft (Mach ~ 1). Though estimated winds were incorporated for STS-3 as discussed, large differences in both the winds and dynamic pressure resulted when either the deterministic (α, β) or batch (α, β, V_T) algorithms were employed. This suggests an inconsistency between the attitude angles and true air speed which ostensibly depends on the actual environs. Indeed, an inconsistency among these parameters and the sensed Mach and q is suggested. Though the true air speed is utilized in the batch wind algorithm, it is recognized that this is a derived quantity based on the calibrated Mach number and derived ambient temperature. For STS-1, 4 and 5, this has not been indicative of a problem. However, true air speed/attitude inconsistencies were noticeable for STS-2 and pronounced for STS-3. In any event, one must be impressed with the performance of the ADS, recognizing that the in situ nature of these data might well represent the best air data available. It is noted that Mach and q differences could be a manifestation of ambient atmospheric measurement errors from the rawinsonde data.

The differences shown in the attached Appendix are of some concern. Referring back to either figures 3 or 4 for discussion purposes, considerable repeatability of flight conditions is evident, most noticeably above Mach 1.1 (h ~55 kft). One can sense the development of a flight data base permitting multiple opportunities for data base update determinations. For example, the total spread in α is essentially less than 2 degrees, with dynamic pressure within ± 25 psf about some average curve. These results are somewhat misleading in terms of α since some α differences between the two air data sources for any one flight are approximately the same magnitude as the total spread across flights. A trend exists in this interval as well. The computed α tends to be somewhat higher in the interval though there are exceptions. Additional analysis is required to further substantiate both sources though, as stated, wind estimation or evaluation at these altitudes is improbable. Below Mach 1 the variation in flight conditions is seen to be considerable, particularly for the STS-2 flight below 20 kft. Again, significant air data parameter differences are observed in some instances in the subsonic region as well. More repeatable conditions will result after additional flights but these will be selected cases restricted to very narrow intervals. For example, conditions at 20 kft (Mach ~ 0.6) for the five flights suggest reasonably similar conditions for regression purposes.

Though the figures presented in the Appendix best show the actual difference signatures for each flight, it is of interest to summarize these differences statistically. Table I shows the actual difference statistics for α and q for the two sources as these differences relate directly to the flight extraction accuracy. Data presented in this table were generated for three different Mach intervals as shown. It can be seen that mean differences (μ) in α are generally less than 0.2 degree for the five flights, the LaRC values being slightly larger on average in all instances. Standard deviations (σ) of these differences vary between 0.2 and 0.5 degrees. Locally, differences in excess of 1 degree are seen to occur in the figures. Dynamic pressure differences, tabulated as percentage differences, are less than 1 percent (μ) in most instances though as much as 3 percent occurs for STS-3. Differences of nearly 20 percent occur, though generally the differences locally are less than 10 percent as evidenced by the computed σ for each flight which varies between 1.3 and 4.4 percent. These differences can relate to ~ 2 (±3) percent differences in L/D and C_L. Mean differences in C_D are somewhat less though random differences exceed 5 percent. Peak differences for each performance coefficient can exceed 10 percent locally.

DATA BASE PREDICTION DIFFERENCES

A LaRC version of the Orbiter aerodynamic data base (ref. 15) has been utilized throughout. This data base, though vintage 1978, is essentially representative of the final pre-operational data base (ref. 16). Some six updates have occurred and thus it is difficult to quantify the differences in terms of actual percentage changes. More recent versions utilized revised fairings of some of the longitudinal performance data in the Mach interval from 1.2 to 2. These revised fairings were the result of correlating (fitting) various wind tunnel data sets such that the implied variations were reduced. Another update which resulted was the inclusion of theoretical body flap effects (in the presence of the ground) on longitudinal performance and trim characteristics. Beyond these changes, it is understood that most of the changes were for Mach numbers above that interval considered herein. Any lateral directional updates which have evolved would, of course, have no influence on the results presented.

The complete data base model provides for effects due to Mach, $\bar{V}_\infty$ (in the hypersonic regime), control surface deflections, reaction jet (RCS) contributions, and air relative attitude angles, α and β. Ground effects and landing gear contributions are also modelled. Control surface deflections and RCS activity are obtained from the OI recorded data. Figure 5 presents a composite plot of the longitudinal control surface deflections versus the BET altitude for the five Shuttle flights. Plotted are the elevator (δ_E), body flap (δ_{BF}), and speed brake (δ_{SB_A}) deflections, the latter with respect to the aerodynamic reference line and not about the hinge line of the swept tail configuration. The aerodynamic reference line is utilized for both speed brake and rudder for consistency with the data base as modelled. Figure 5 suggests reasonable repeatability of spacecraft configuration above 50 kft which should permit multiple opportunities for data base update determination studies. Evident below this altitude are the ample opportunities for control surface effectiveness studies. The control surface deflections are plotted individually for each flight in the attached Appendix. These data are plotted versus the Mach number from both sources as figures A3(a) through A3(e) for STS-1 through STS-5, respectively. Keeping in mind that the control surface deflections are the same versus time and/or altitude, differences shown thereon merely reflect the Mach number differences. Lateral control surface deflections (δ_A, δ_{RA}) as well as side-slip and vehicle roll angle (with respect to the air relative velocity vector) are included in the Appendix for each flight as figures A4(a) through A4(e). The β curves basically reflect the differences between the computed and ADS values though the Mach number differences contribute to the difference signature. Differences in any of the other parameters only reflect the slightly different Mach number from the two air data sources. These figures are included in the Appendix for information only. These parameters have no influence on the longitudinal performance parameters considered in this paper.

Since the data base is Mach and α dependent, the predicts from all elements of the data base will vary when either the ADS or computed air data are utilized. Angle-of-attack differences have been shown previously. Mach number differences need be quantified. The LaRC AEROBETs utilize the LAIRS temperature profile to compute the speed-of-sound. This, in conjunction with the inertial velocity and measured/evaluated winds, permits Mach determinations. Differences between the measured (ADS) and computed Mach numbers are ~0.01 (±0.03) with local differences of ~0.1. Again, these differences can be seen in the attached Appendix. Mach differences, in conjunction with the α differences previously discussed, can result in prediction differences comparable to the flight extracted differences.

FLIGHT/DATA BASE COMPARISONS

Performance Overview

An assessment of Shuttle performance between Mach 2 and landing is presented as Figures 6 through 10 for STS-1 through STS-5, respectively. These data were generated based on the LaRC AEROBETs as typical, i.e., the computed air data parameters were employed. Shown on each figure are the flight (O) and predicted (Δ) performance coefficients; L/D, C_L, and C_D. Variations (V) are also shown thereon as indicated. These variations are a representative estimate of the pre-flight accuracy of the data base. Though more detailed flight/data base comparisons are later presented, it is shown on these figures that the flight C_L agrees with the data base values to well within one variation above Mach 1. Flight L/D essentially is within one variation of that predicted over the same interval, indicating slightly more performance than predicted. Flight computed drag for all five flights agrees within one variation of the predicted values over a more restrictive Mach interval, namely, above M ~1.4.

Pitching moment comparisons are presented as Figure 11. Five strip charts are presented, one for each flight. These figures show results with respect to the best available flight c.g. and include thereon flight (O), predicts (Δ), and variations (V). This figure is concluded by showing the composite five flight pitching moment comparisons. Plotted are percentage errors ((flight - predicts)/flight) referenced to a c.g. of 65 percent of the body length, the reference c.g. utilized in the data base. As shown, the differences in terms of percentage are considerable, indicative of misprediction of either longitudinal control surface effectiveness or basic pitching moment. Even the suggested mean differences are large and, it is felt, not consistent with (reasonable) expected flight c.g. errors. For example, a one inch $X_{c.g.}$ location error should contribute approximately 5 percent as a mean error. Similarly, a one inch $Z_{c.g.}$ error would relate to only ~ 2 percent. Since some of the differences shown could reflect the vintage data base utilized no further C_m analysis was performed. Thus, the influence of the Flight Assessment Deltas (FADS) (ref. 6) on C_m has not been investigated. In this interval the FADS do include a basic C_{m_o} prediction update and a ground effects update. The C_{m_o} correction (0.0075) for the 65 percent reference c.g. is in the direction to reduce the mean differences shown below Mach 0.75.

As indicated, the data base predicted results are comprised of the contributions from many elements of the model. Figures 12 and 13 show the expected contributions to the total predicted lift and drag, respectively. The LaRC AEROBET parameters were utilized to generate these typical results which are presented as information. Shown thereon are: basic aerodynamic effects (assuming undeflected controls except for the speed brakes which are assumed in this configuration to be deflected 25 degrees); incrementals due to elevator, body flap, and speed brakes; and gear and ground effects. All are plotted as a ratio to the total predicted coefficient to show, in essence, the percentage contribution of each to the total predicted value. An additional item modelled, i.e., the flexible airframe contribution, is sufficiently small and, as such, is not shown.

These figures are presented for completeness to, perhaps, identify sources for the actual flight/data base differences next discussed. In general, above Mach 1.2 almost all of the predicts are determined by the basic airframe characteristics which are, of course, Mach and α dependent. Below Mach 1, expected control surface contributions become very significant. Specifically, the lift contribution from the elevators varies between 20 and 60 percent dependent upon the different deflections for the various flights. It is observed that the expected body flap contribution to the predicted lift can be as much as 20 percent with an expected reduction due to speed brakes of a similar magnitude. No predictable lift increment is modelled for the deployed landing gear configuration. Control surface contributions to the predicted drag are: 10 to 20 percent from the elevators; generally less than 10 percent from the body flap; and as much as 30 percent from the speed brakes. The negative drag increment shown due to the speed brakes is for deflections less than 25 degrees, the presumed undeflected controls configuration. The expected incremental drag due to the landing gear is approximately 20 percent. Incrementals indicated for the ground effects show that the expected lift contribution is approximately twice that for drag. Readers are advised that the BET altitude accuracy is approximately 5 ft at touchdown. As such, the BET altitude is of questionable accuracy in the required altitude/span (h/b) computation for predicted ground effects based on the extreme sensitivity to this parameter. The last strip chart presents an estimate of prediction errors for an α error of 1 degree. These partials, C_{L_α} and C_{D_α}, are numerically derived based on a 1 degree perturbation in α from the nominal.

Flight/Data Base Performance Comparisons

Figures 14 and 15 show performance comparisons in terms of percentage differences. These composite plots utilize both the LaRC (figure 14) and ADS (figure 15) air data parameters. Figure 14 is, of course, the percentage difference equivalent of those differences seen in figures 6-10, respectively. For more detailed investigations, figures A5(a) through A5(e) are included in the Appendix of this paper. These figures show the flight/data base performance comparisons for each flight individually using both air data sources, LaRC (○) and ADS (□). The variations are shown thereon as the dashed lines. Tables II and III present the difference statistics (μ, σ) for each flight for the LaRC and ADS, respectively. Ensemble results for all five flights are also included thereon.

Comparison of figure 14 and figure 15 indicates the ADS results are more consistent in the differences across flights, particularly above Mach 1.1. This suggests, in view of the similarity in flight conditions, configuration, and expected contribution from same in this interval as shown in figures 12 and 13, that the ADS represents the best source for air data. However, neither air data source results in significant flight/data base discrepancies in this interval. Below Mach 1 the LaRC results show both STS-2 (0.7 < Mach < 1.0) and STS-3 (0.5 < Mach < 0.7) as potential outliers. Problems with winds for these flights have already been discussed. The ADS results, as stated, have the advantage of being based on in situ measurements. However, required calibrations to obtain air data parameters could conceivably introduce some systematic error in the process. This is only proposed as a possibility and is certainly not suggested in the results.

Detailed inspection of the expanded plots in the Appendix shows regions of comparable flight/data base differences for both air data sources. The biggest discrepancy for STS-1 is seen to be essentially a bias difference in all three performance parameters above Mach 1. The differences relate to the average α and q differences from the two sources (see table I). Near landing there are some sizable (~10 percent) lift and L/D differences suggested by the two sources. Figure A5(b) shows comparable agreement below Mach 0.7 for STS-2. Sizable differences occur near Mach 1 and in the vicinity of landing. Use of the ADS data indicates a large misprediction of the ground effects, particularly for C_L. Some similarities between the two sources for STS-3 can be seen in figure A5(c) though in very restricted regions, e.g., C_D differences below Mach 0.6. The differences observed for L/D and C_L between Mach 0.5 and 0.8 are most significant. These differences are the result of both the q and α differences shown in figure A2(c). Again, bias is seen in the lift and drag differences above Mach 1, on the order of 5 percent for both parameters. STS-4 and STS-5 differences shown in figures A5(d) and A5(e) show the results throughout are virtually independent of air data source to within a very few percent, differences near Mach 1 being the exception. For these flights the ADS q appears to have been linearly extrapolated between Mach 0.95 and 1.15.

In general the flight derived lift agrees with the predicted values to well within 1 variation throughout the Mach region investigated, with noted exceptions as discussed for STS-2 and STS-3. Drag is generally overpredicted by one variation below Mach 0.7 Exceptions are noted in the immediate vicinity of touchdown. Predictions due to ground effects are very sensitive to altitude and even for reasonable BET altitude errors, (~5 ft), are difficult to quantify.

DATA BASE UPDATE DISCUSSION

With only five flights to date it is felt that rigorous data base updates are premature. Rigorous updates herein imply refinements to all elements of the data base as modelled, i.e., Mach and α dependence for the basic aerodynamic characteristics, control surface incrementals, and gear and ground effects. More flights will enable development of a larger flight data base and permit more comprehensive updates.

Based on current results, simple predicts adjustments are plausible. However, throughout much of the region investigated herein, different results were obtained dependent upon the air data source utilized. Comparison of the results shown in figure 14 and 15 would indicate that the measured (ADS) air data would best serve for data base updates. If both sources are considered equally viable, the results of this paper can be interpreted as an error analysis defining accuracies of flight extraction, predicts generation, and resultant flight/data base update determinations. In that sense, it is relevant to focus on those regions wherein similar prediction deficiencies are noted independent of air data sources.

Table IV shows ensemble statistics for all five flights for the two air data sources. Below Mach 0.8 an approximate 10 percent overpredicted drag coefficient is independently suggested. This amount is essentially that decrement resulting from application of the FADS of reference 6. Therein, the functional form of the drag correction below Mach 0.6 is a constant drag decrement plus a constant and linear term when $h/b < 0.45$ for ground effect refinements. This total adjustment to the predicted drag will increase the predicted L/D and reduce the flight/data base discrepancies observed for that performance parameter as well. The results from table IV suggest that, beyond the noted plausible C_D correction below Mach 0.8, other predict refinements are questionable. In general, lift corrections would be small and perhaps not statistically significant, albeit dependent on the particular air data source utilized. The FADS do include some predicted lift changes which, when applied to the LaRC data base with ADS air data over the interval $0 < \text{Mach} < 2$, essentially remove the small mean error but only reduce the random error by 0.6 percent.

CONCLUSIONS

Flight derived and predicted longitudinal performance based on two independent air data sources vary on the order of 2 (±3) percent, with local differences in excess of 10 percent. Consequently, use of either air data source as the reference results in different flight/data base comparisons. More consistent flight/data base comparisons across flights were observed when the ADS parameters were adopted. In particular, STS-2 and STS-3 results exhibited the largest departures when the computed air data parameters were employed. Large winds were encountered during these two missions. Though estimation/evaluation of these winds versus some of the ADS parameters was performed, uncertainties in these winds would affect the resultant flight/data base comparisons. If both air data sources are considered equally viable, the results presented suggest statistically significant C_L prediction refinements are questionable for the Mach interval investigated. The FADS C_D decrement of ~10 percent below Mach 0.6 is substantiated independent of air data source. This decrement increases the predicted L/D and consequently improves comparisons of that parameter with the flight derived performance.

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TABLE I.-AIR DATA PARAMETER DIFFERENCES, LaRC - ADS

Flight	0<Mach<1				0<Mach<2				1<Mach<2			
	Δα (degrees)		Δq (percent)		Δα (degrees)		Δq (percent)		Δα (degrees)		Δq (percent)	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
STS-1	0.2	0.2	1.4	1.4	0.2	0.2	1.6	1.6	0.1	0.2	2.4	1.8
STS-2	<0.1	0.4	0.2	3.5	0.1	0.4	-0.1	3.8	0.1	0.3	-0.8	4.4
STS-3	0.2	0.5	1.0	2.5	0.2	0.4	1.6	2.9	0.1	0.3	3.1	3.1
STS-4	0.1	0.2	<0.1	1.3	<0.1	0.2	0.2	1.5	<0.1	0.1	0.5	2.0
STS-5	0.1	0.3	0.7	2.5	0.1	0.3	0.7	2.4	-0.1	0.2	0.6	2.0

TABLE II.-FLIGHT/DATA BASE PERFORMANCE DIFFERENCE STATISTICS, LaRC AEROBETS

Flight	0 <Mach <1						0 <Mach <2						1 < Mach < 2					
	$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)		$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)		$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
STS-1	6.1	4.6	-5.2	3.2	-12.2	4.7	5.3	4.5	-4.9	3.0	-10.9	5.0	2.8	3.0	-3.5	1.8	-6.5	3.3
STS-2	6.6	5.7	-0.7	6.1	- 8.0	6.2	5.8	5.6	-0.5	5.4	- 6.9	6.0	3.2	4.6	0.1	2.1	-3.3	3.9
STS-3	2.7	7.6	-5.2	11.2	- 8.1	7.4	2.6	6.7	-4.8	9.6	- 7.6	6.5	2.1	3.3	-4.0	2.0	-6.3	3.0
STS-4	6.0	4.8	-2.5	3.7	- 9.3	5.5	5.2	4.6	-2.3	3.3	- 8.1	5.3	3.0	2.9	-1.3	1.3	-4.5	2.8
STS-5	5.3	5.4	-3.8	5.6	- 9.8	5.2	4.7	5.1	-2.9	5.0	- 8.2	5.5	3.1	3.6	-0.7	1.7	-4.1	3.8
All	5.5	5.8	-3.4	6.7	- 9.5	6.0	4.8	5.4	-3.0	5.9	- 8.3	5.8	2.8	3.6	-2.0	2.4	-5.1	3.6

TABLE III.-FLIGHT/DATA BASE PERFORMANCE DIFFERENCE STATISTICS, ADS AEROBETS

Flight	0 <Mach < 1						0 <Mach < 2						1 < Mach < 2					
	$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)		$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)		$\Delta L/D$ (percent)		ΔC_L (percent)		ΔC_D (percent)	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
STS-1	7.7	6.0	-1.2	4.1	-10.0	6.2	6.8	5.6	-0.8	3.8	-8.5	6.3	3.9	2.4	0.6	1.6	-3.4	3.0
STS-2	6.5	5.2	0.6	5.5	- 6.5	6.3	6.0	4.9	0.8	4.9	-5.7	5.8	4.1	2.9	1.4	1.8	-2.8	2.7
STS-3	6.3	5.6	<0.1	5.4	- 6.9	6.4	5.3	5.1	0.2	4.7	-5.7	6.0	2.8	2.3	0.8	1.8	-2.2	2.8
STS-4	7.0	4.7	-0.9	4.6	- 8.7	5.0	6.0	4.6	-0.8	4.1	-7.4	5.2	3.6	3.1	-0.4	2.2	-4.3	4.5
STS-5	6.2	4.2	-1.5	4.2	- 8.3	4.0	5.3	4.1	-1.2	3.8	-6.9	4.7	2.8	2.9	-0.4	2.5	-3.5	4.6
All	6.7	5.2	-0.8	4.9	- 8.2	5.9	5.9	4.9	-0.5	4.3	-7.0	5.8	3.5	2.8	0.2	2.2	-3.5	3.8

TABLE IV.-ENSEMBLE FLIGHT/DATA BASE DIFFERENCE STATISTICS FOR MACH SUB-INTERVALS

Mach Region	$\Delta L/D$ (percent)				ΔC_L (percent)				ΔC_D (percent)			
	LaRC		ADS		LaRC		ADS		LaRC		ADS	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
0.2 to 0.4	8.2	4.9	7.6	4.6	-0.1	5.3	-0.2	6.7	- 9.1	4.9	- 8.5	4.7
0.4 to 0.6	3.7	5.7	6.9	4.6	-6.2	6.3	-2.9	4.5	-10.5	5.0	-10.7	4.3
0.6 to 0.8	8.8	4.3	9.8	3.5	-0.7	6.6	1.8	3.0	-10.4	5.7	- 9.0	4.7
0.8 to 1.0	3.8	5.9	2.5	5.2	-2.4	5.6	0.4	4.5	- 6.7	7.7	- 2.4	6.3
1.0 to 1.2	5.9	4.6	7.1	2.2	-1.6	2.9	-0.9	2.6	- 8.2	4.5	- 8.7	4.0
1.2 to 1.4	4.0	2.5	4.4	0.9	-2.4	1.6	-0.2	1.4	- 6.7	3.0	- 4.8	1.0
1.4 to 1.6	2.6	1.2	3.2	1.9	-0.5	1.7	1.4	1.6	- 3.2	1.6	- 1.8	1.3
1.6 to 1.8	0.9	1.4	1.8	1.0	-1.6	1.8	1.7	1.2	- 2.6	1.5	- 0.1	0.8
1.8 to 2.0	-0.8	1.1	0.1	1.1	-4.2	2.0	-1.6	1.5	- 3.3	1.3	- 1.6	0.7

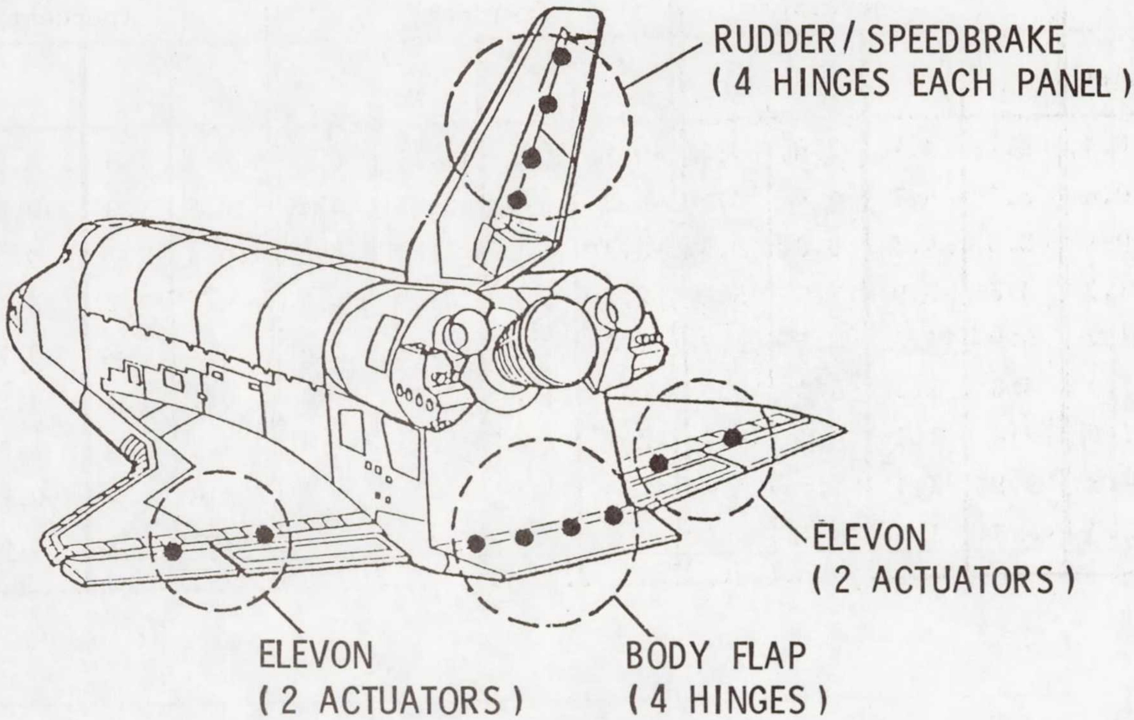

Figure 1.- Schematic of Orbiter control surface configuration.

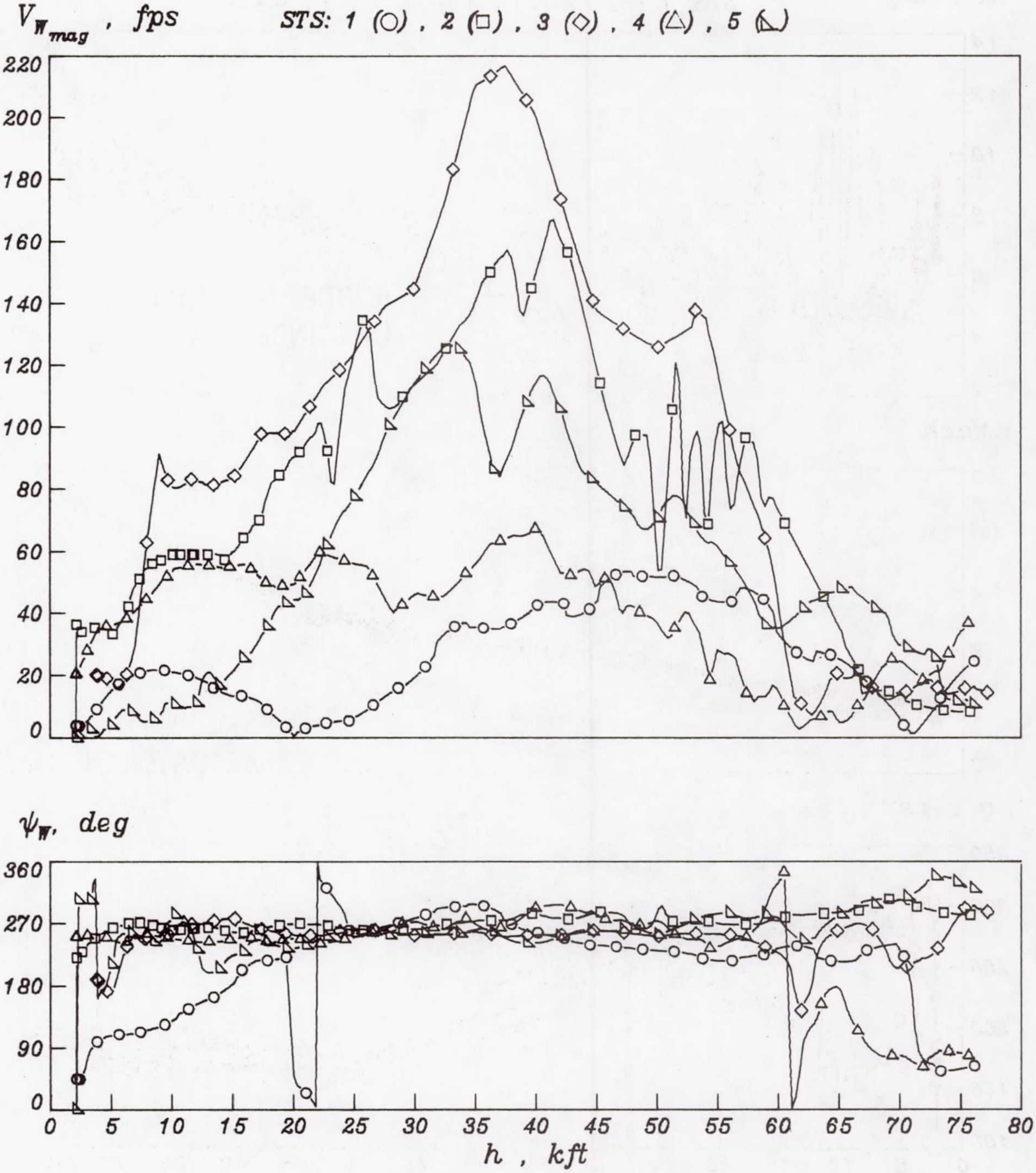

Figure 2.- Wind profiles over lower altitude region.

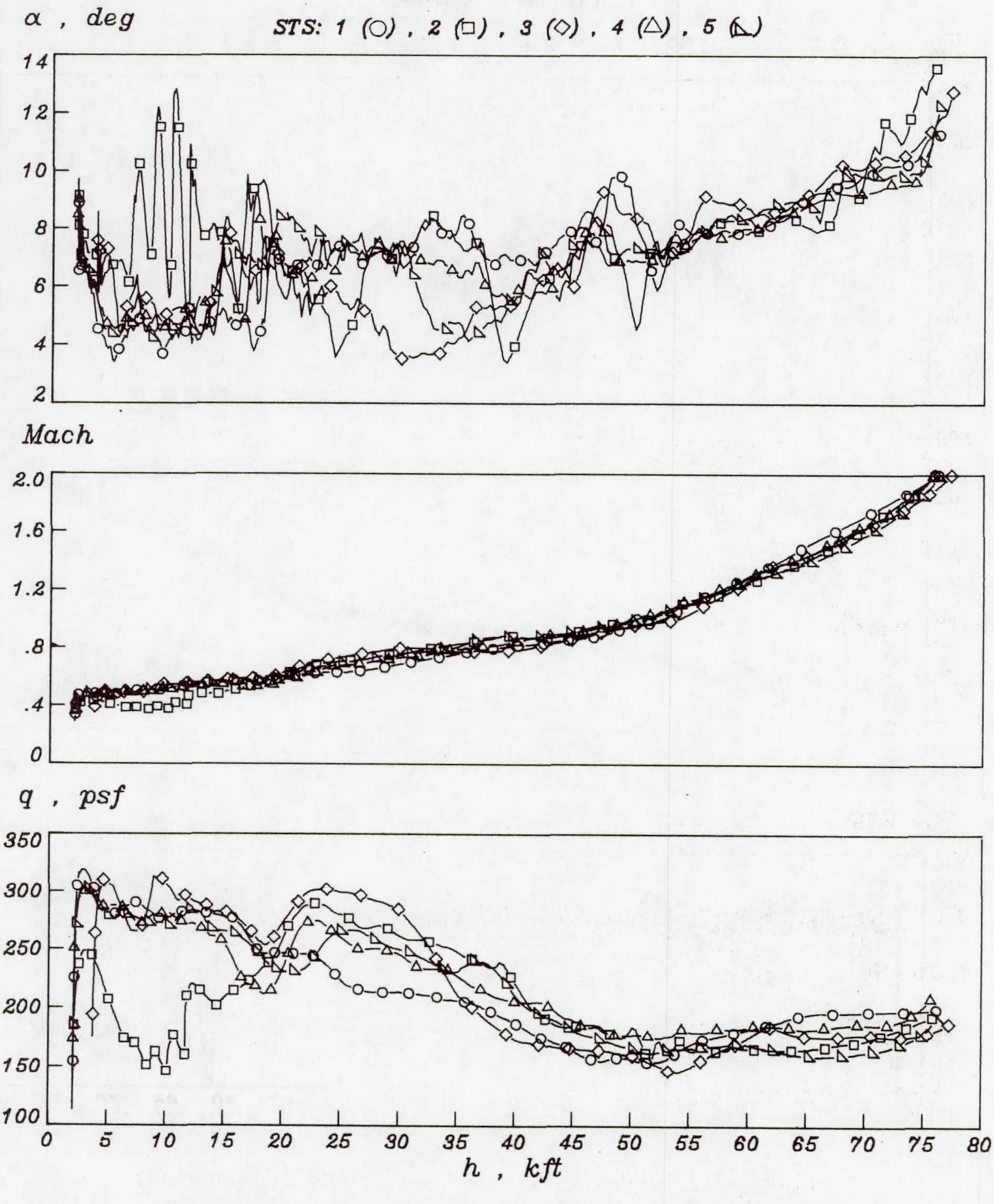

Figure 3.- Composite flight conditions, LaRC AEROBETs.

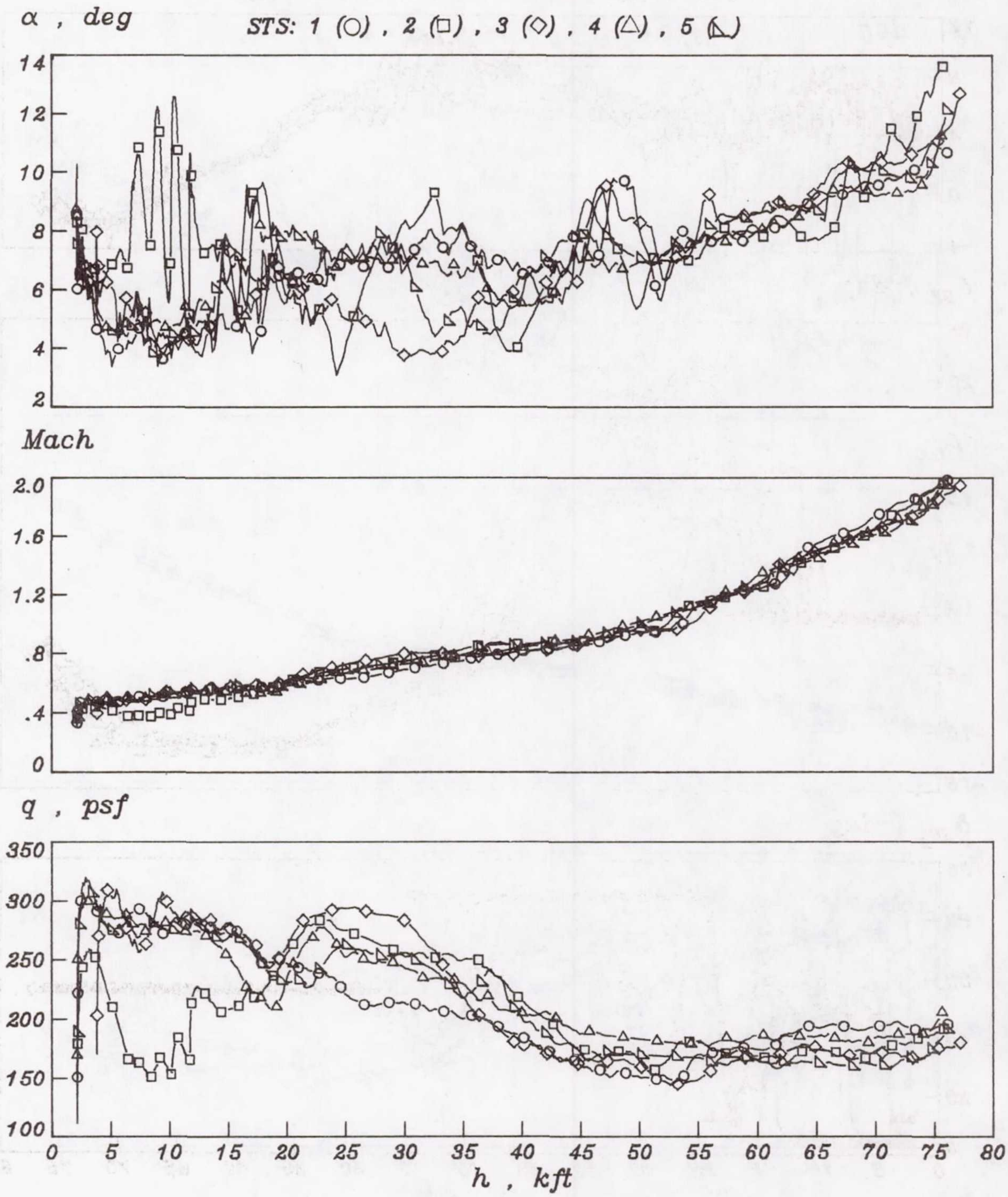

Figure 4.- Composite flight conditions, ADS AEROBETs.

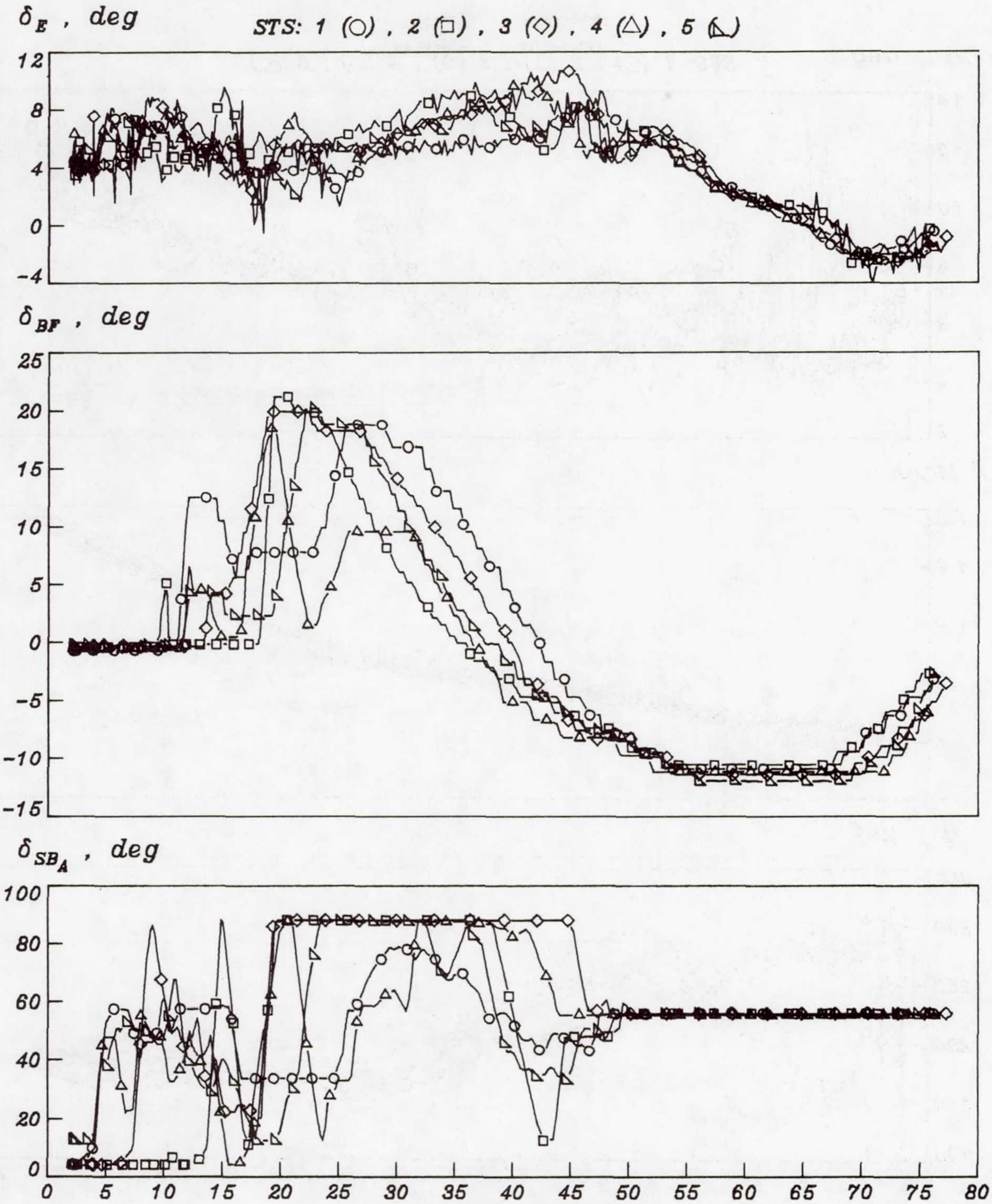

Figure 5.- Composite of control surface deflections versus h.

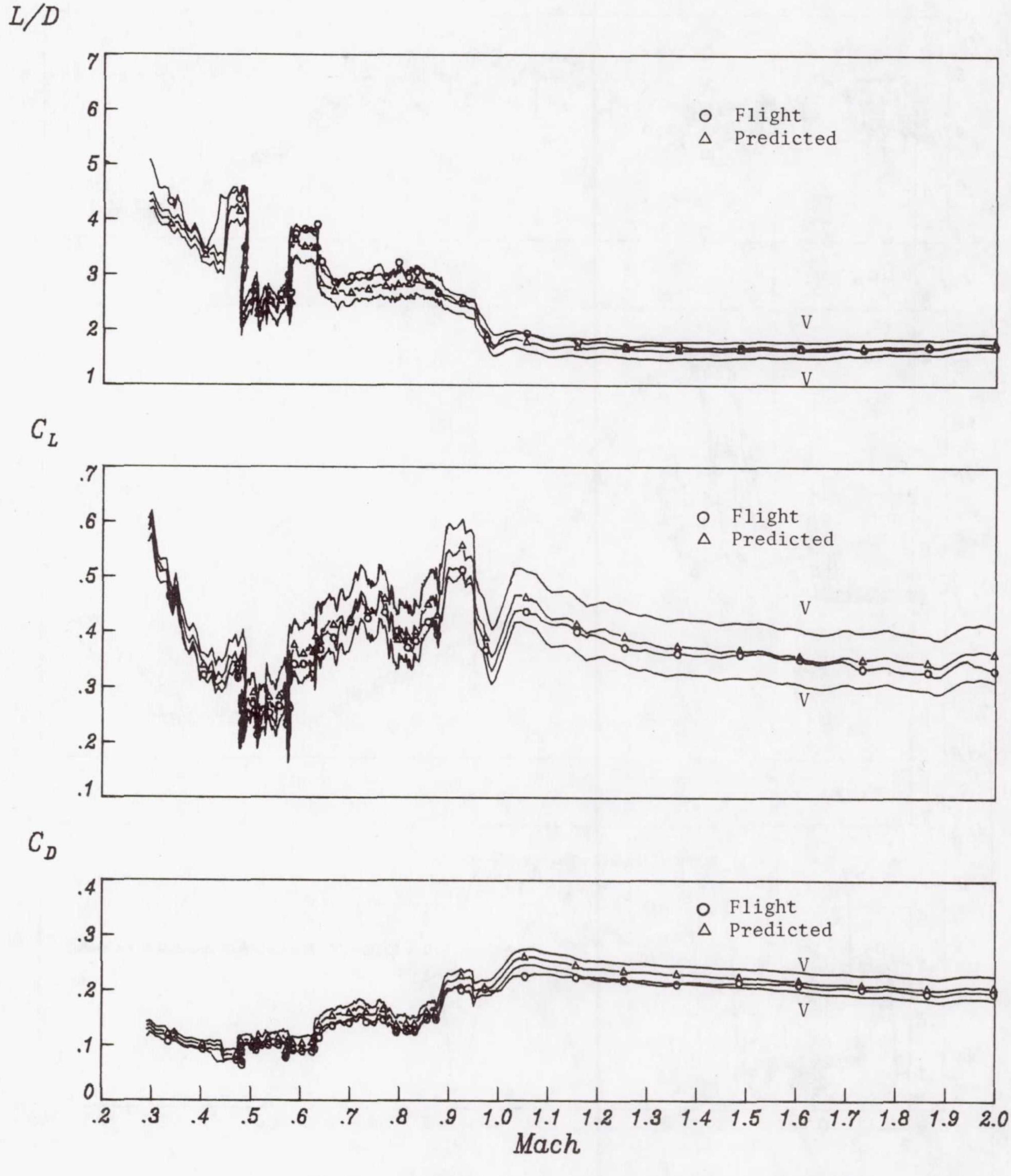

Figure 6.- STS-1 longitudinal performance for LaRC AEROBET.

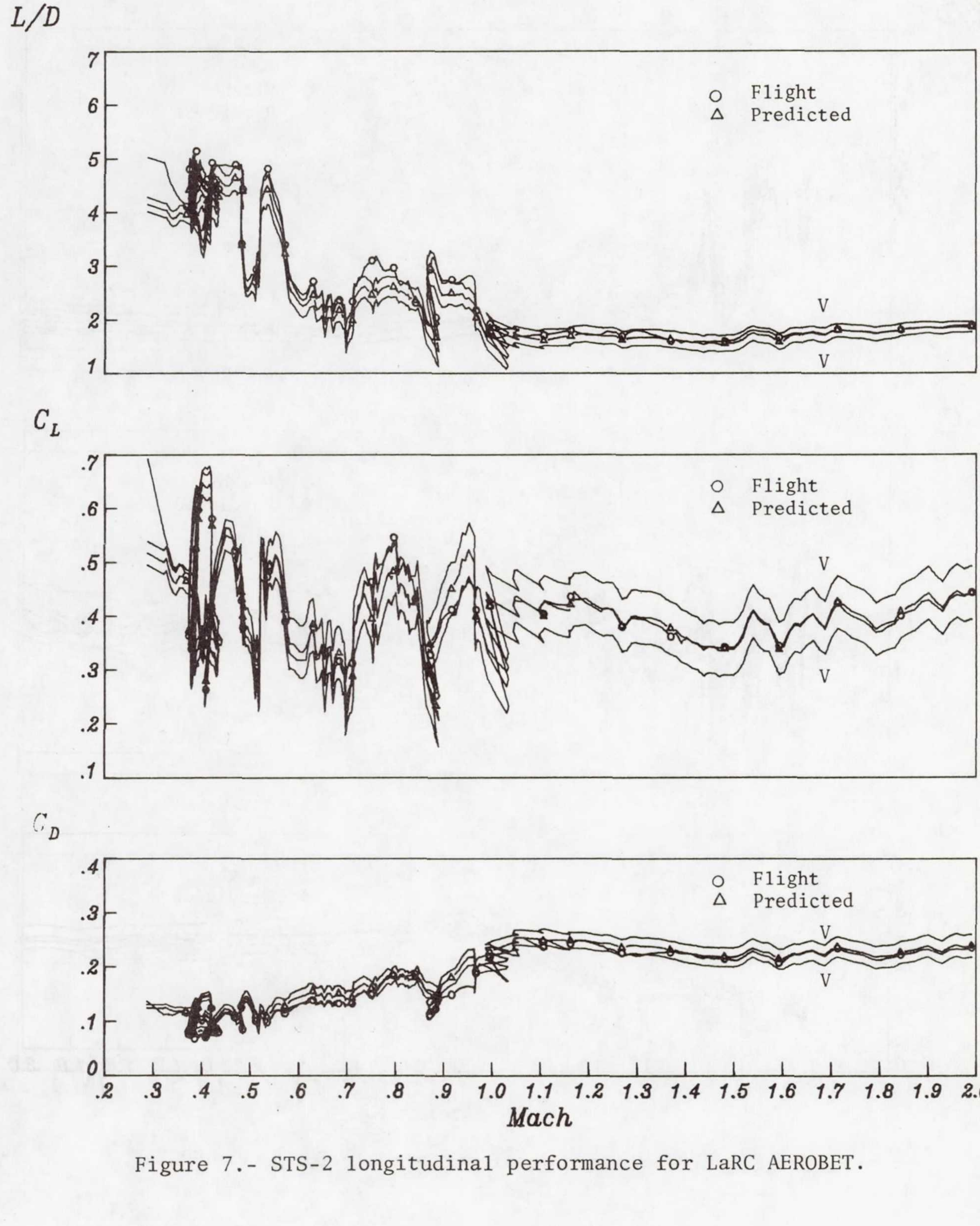

Figure 7.- STS-2 longitudinal performance for LaRC AEROBET.

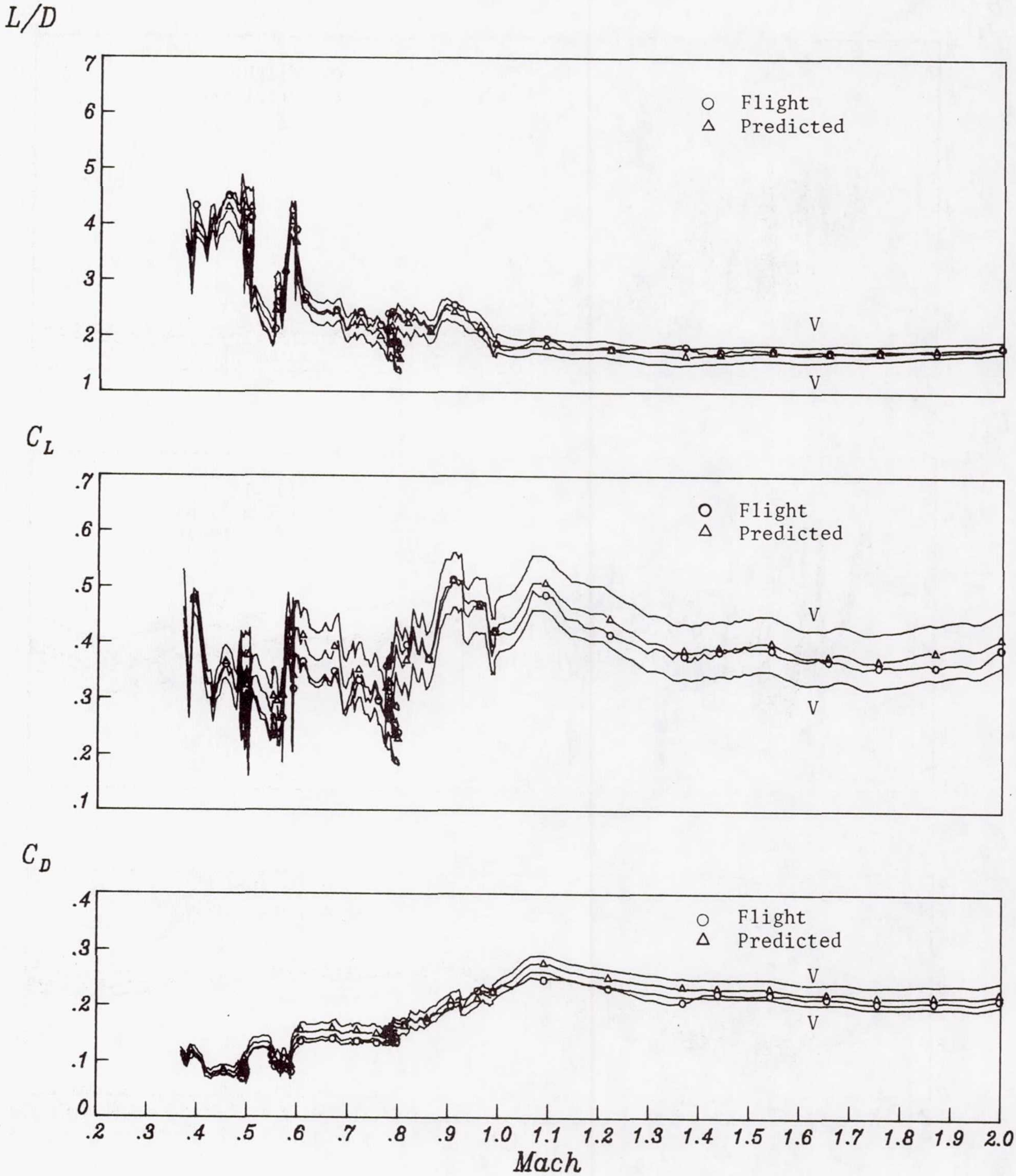

Figure 8.- STS-3 longitudinal performance for LaRC AEROBET.

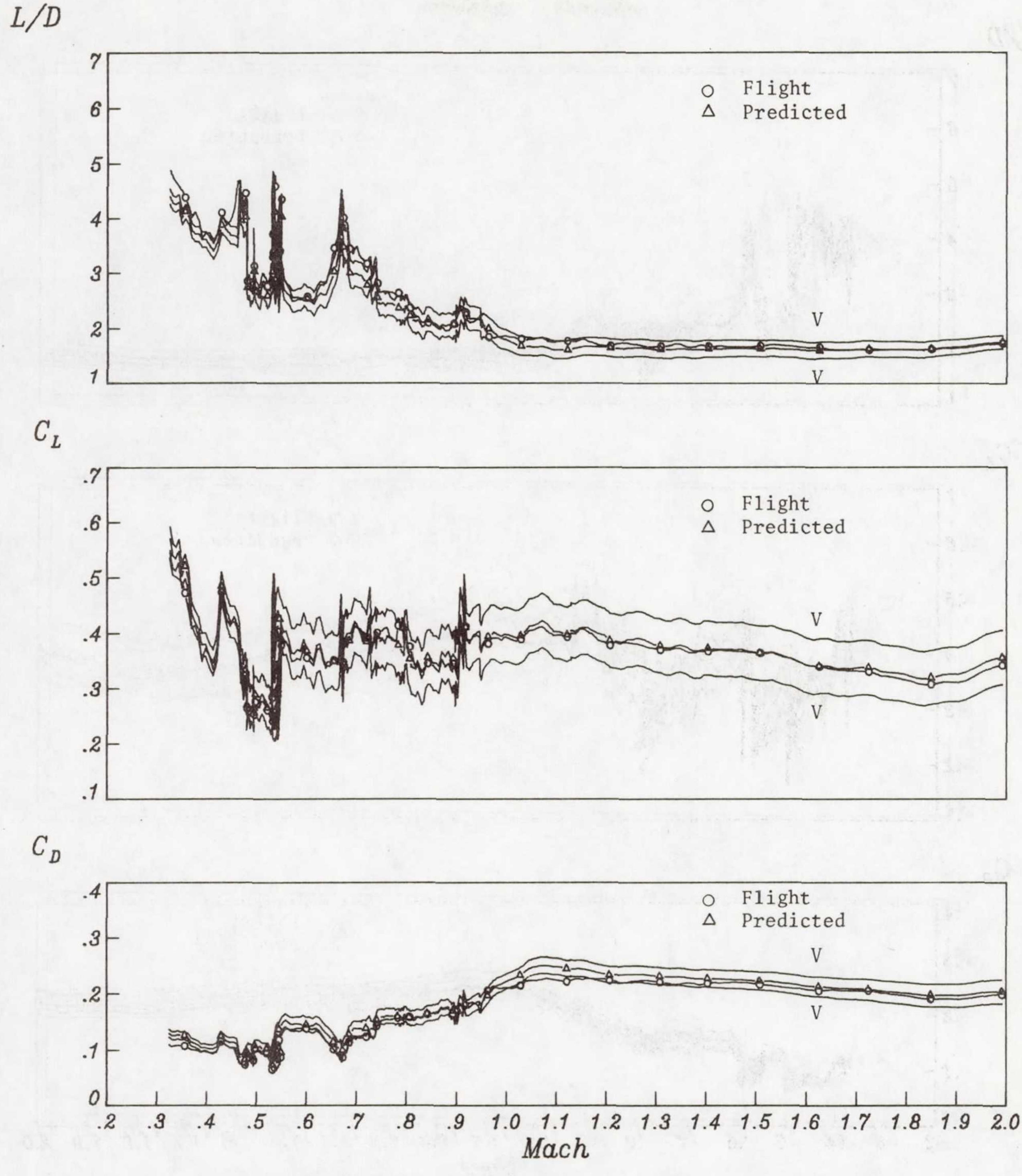

Figure 9.- STS-4 longitudinal performance for LaRC AEROBET.

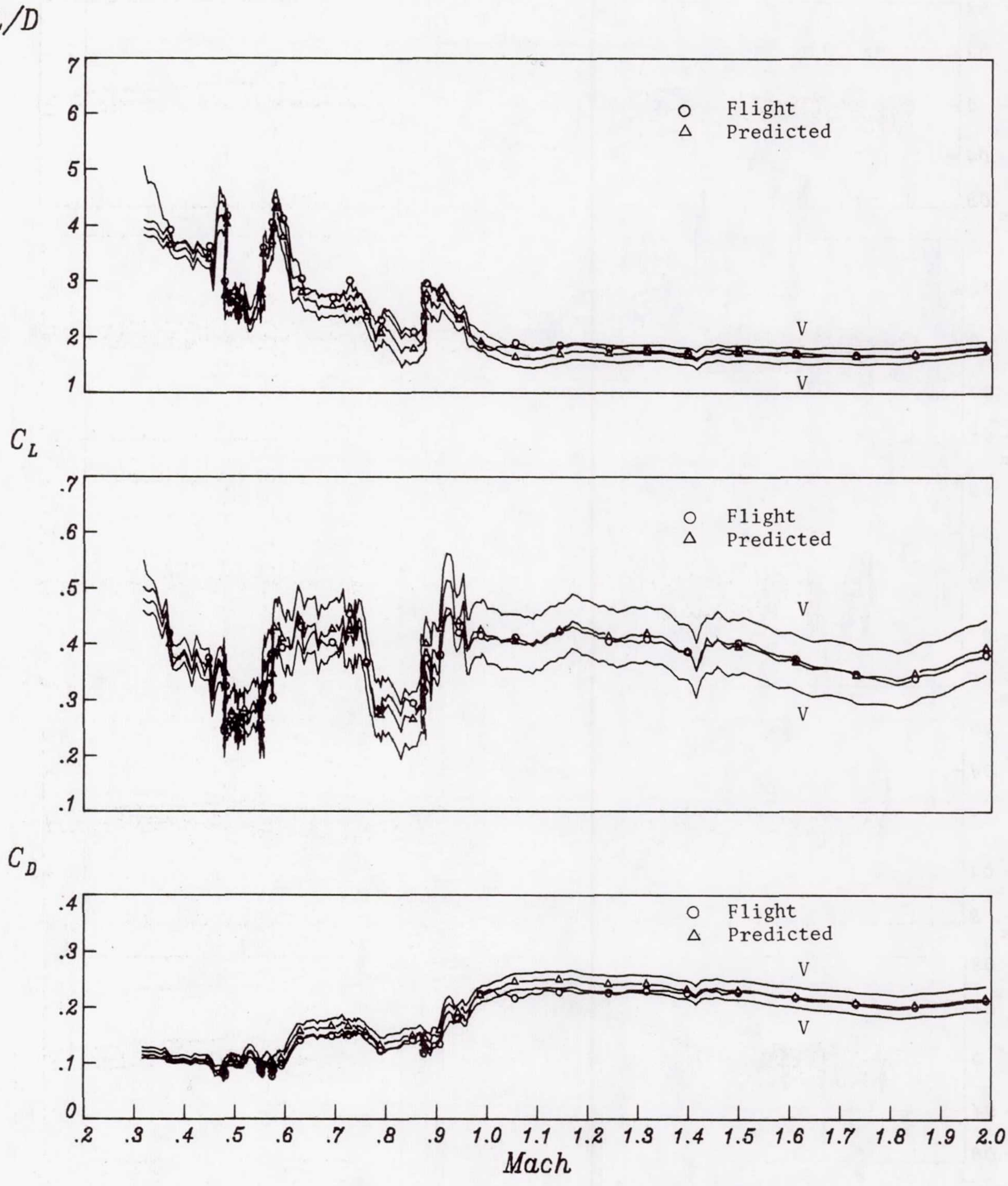

Figure 10.- STS-5 longitudinal performance for LaRC AEROBET.

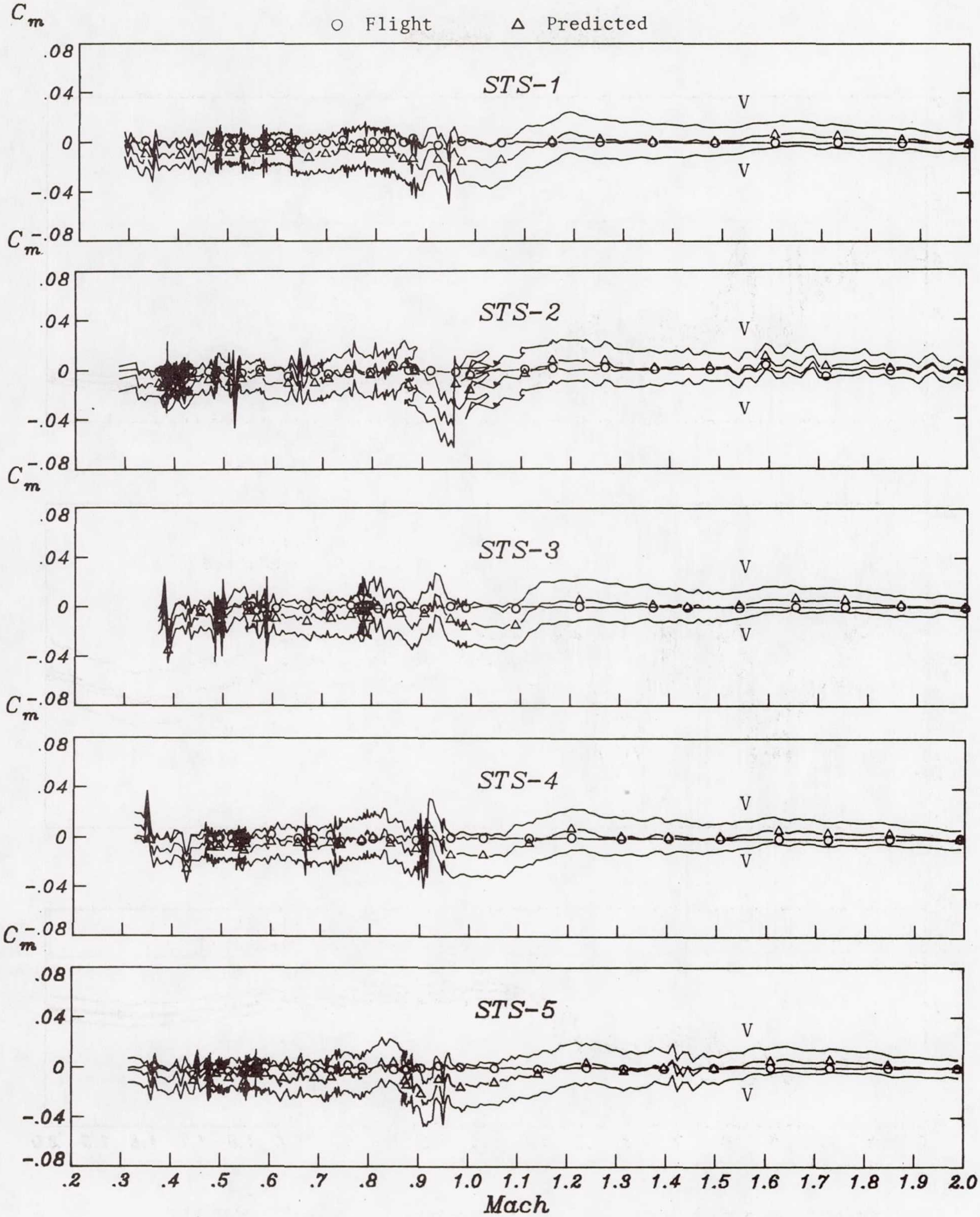

Figure 11.- Pitching moment comparisons for LaRC AEROBETs.

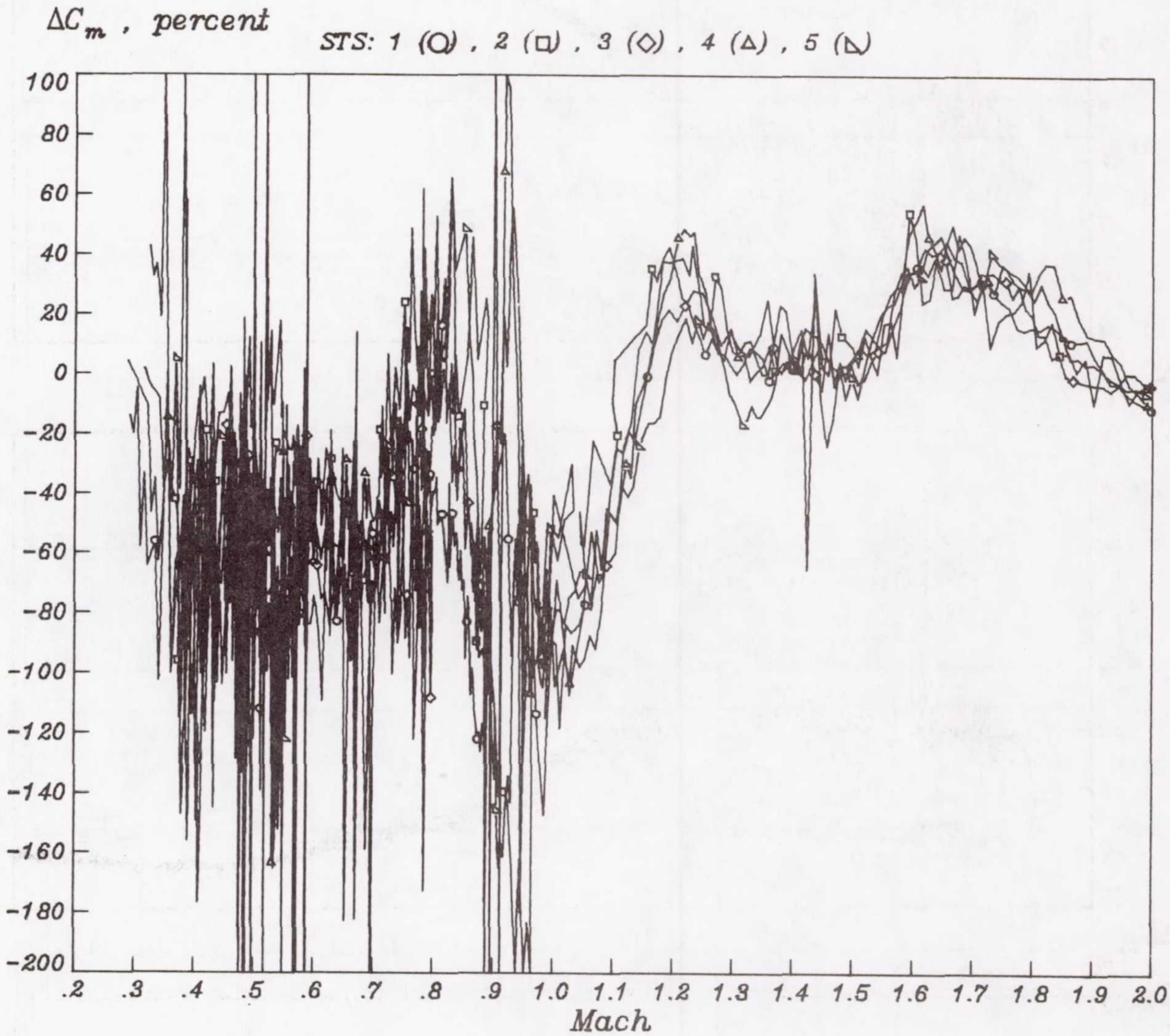

Figure 11.- Concluded.

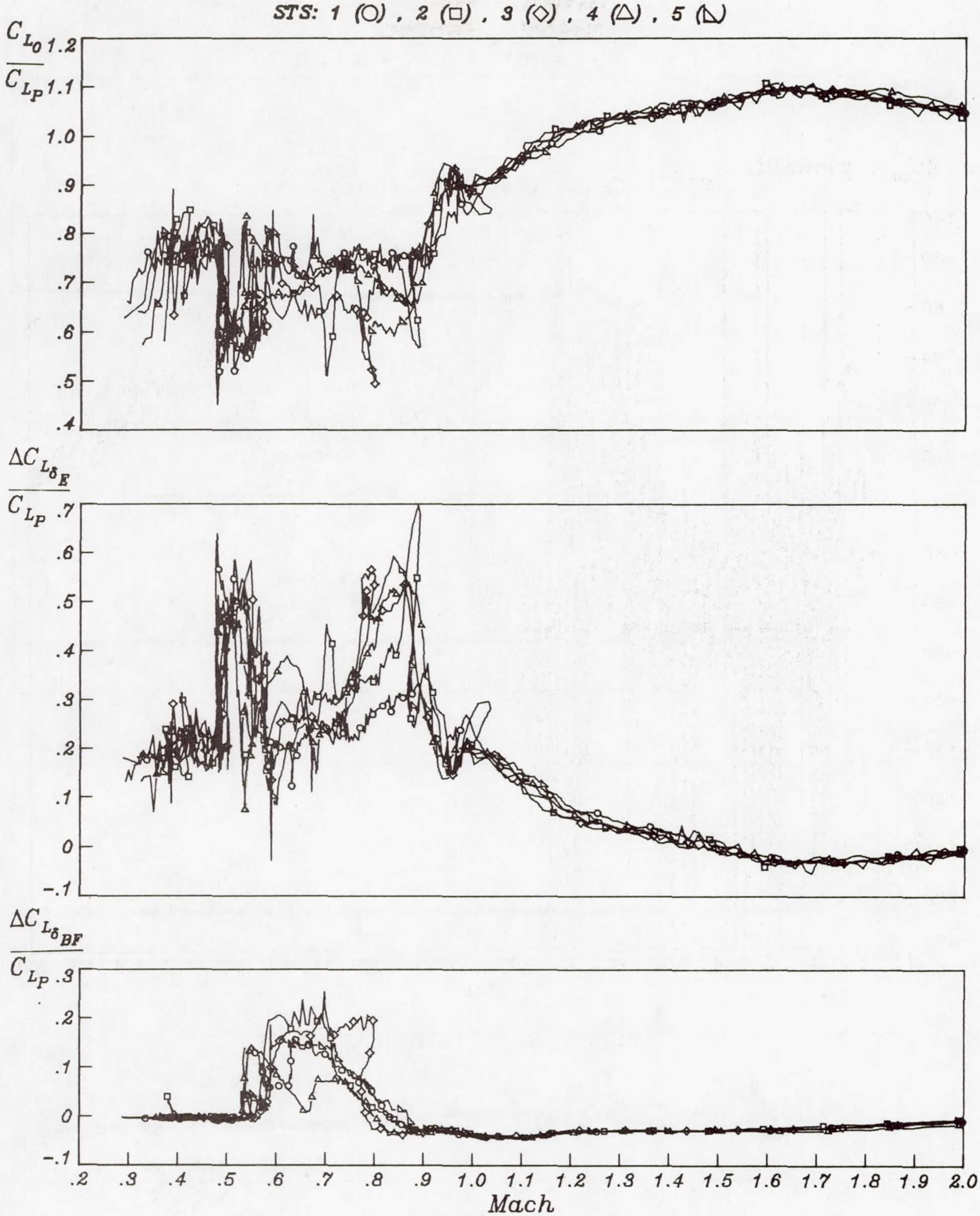

Figure 12.- Predicted C_L contributions.

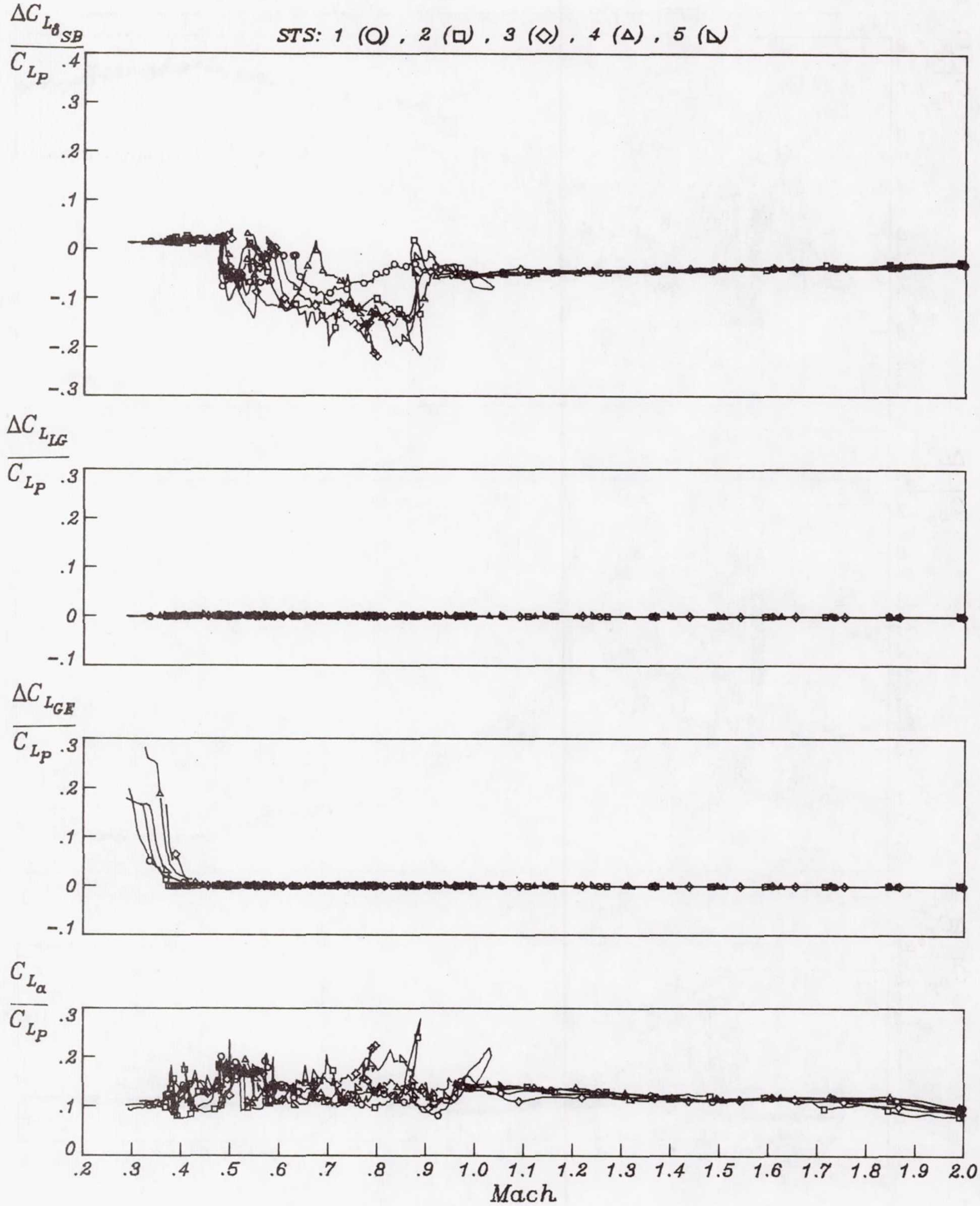

Figure 12.- Concluded.

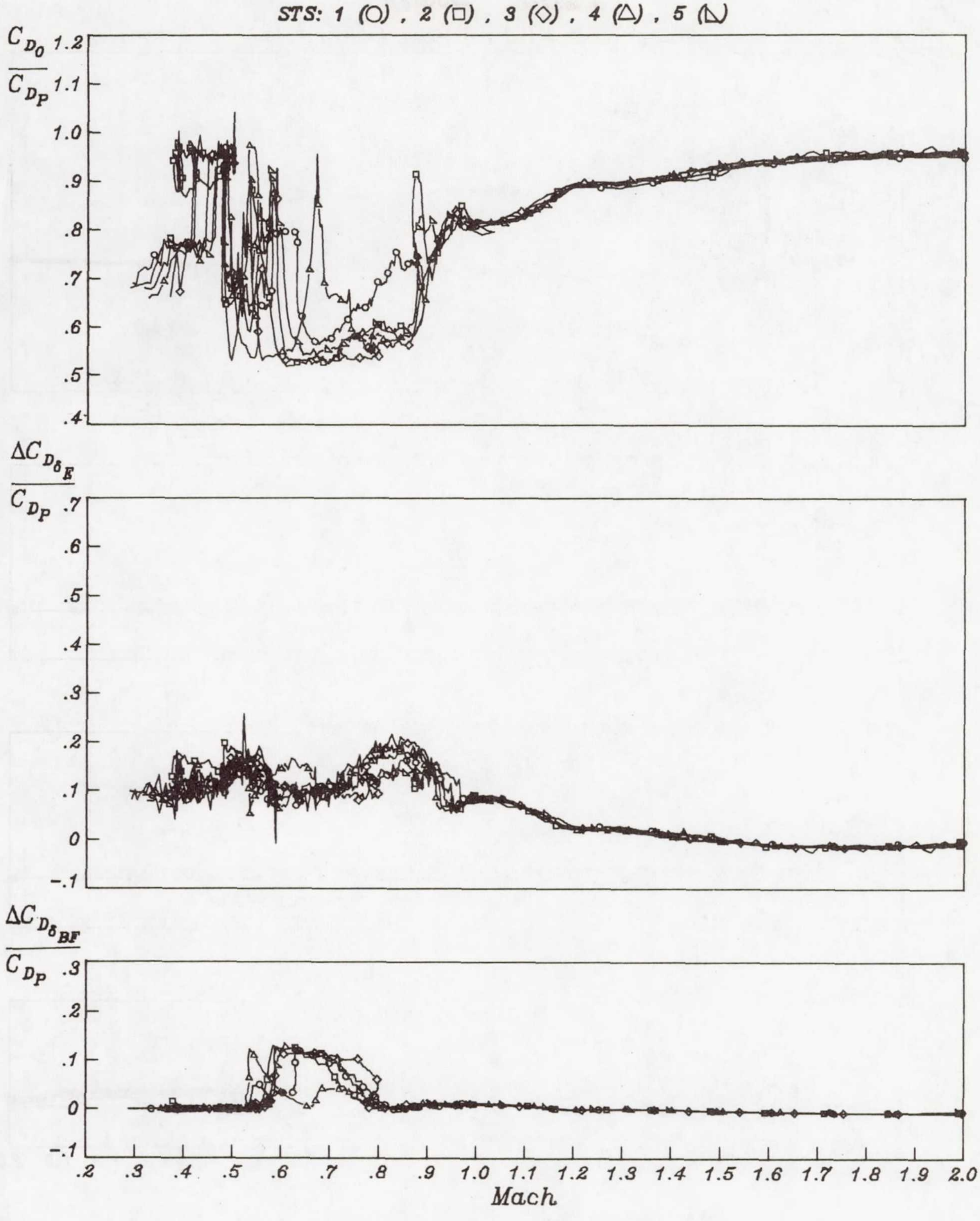

Figure 13.- Predicted C_D contributions.

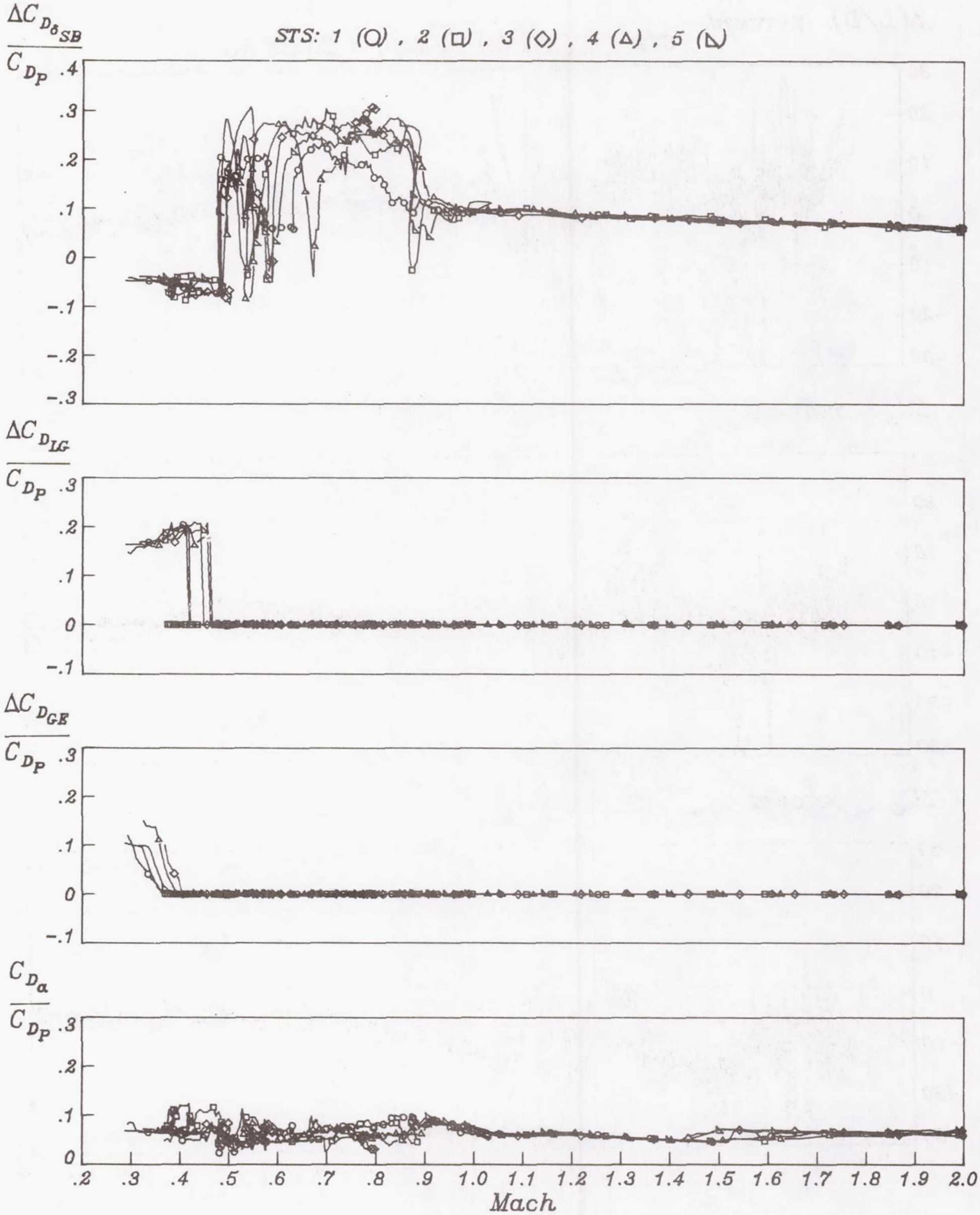

Figure 13.- Concluded.

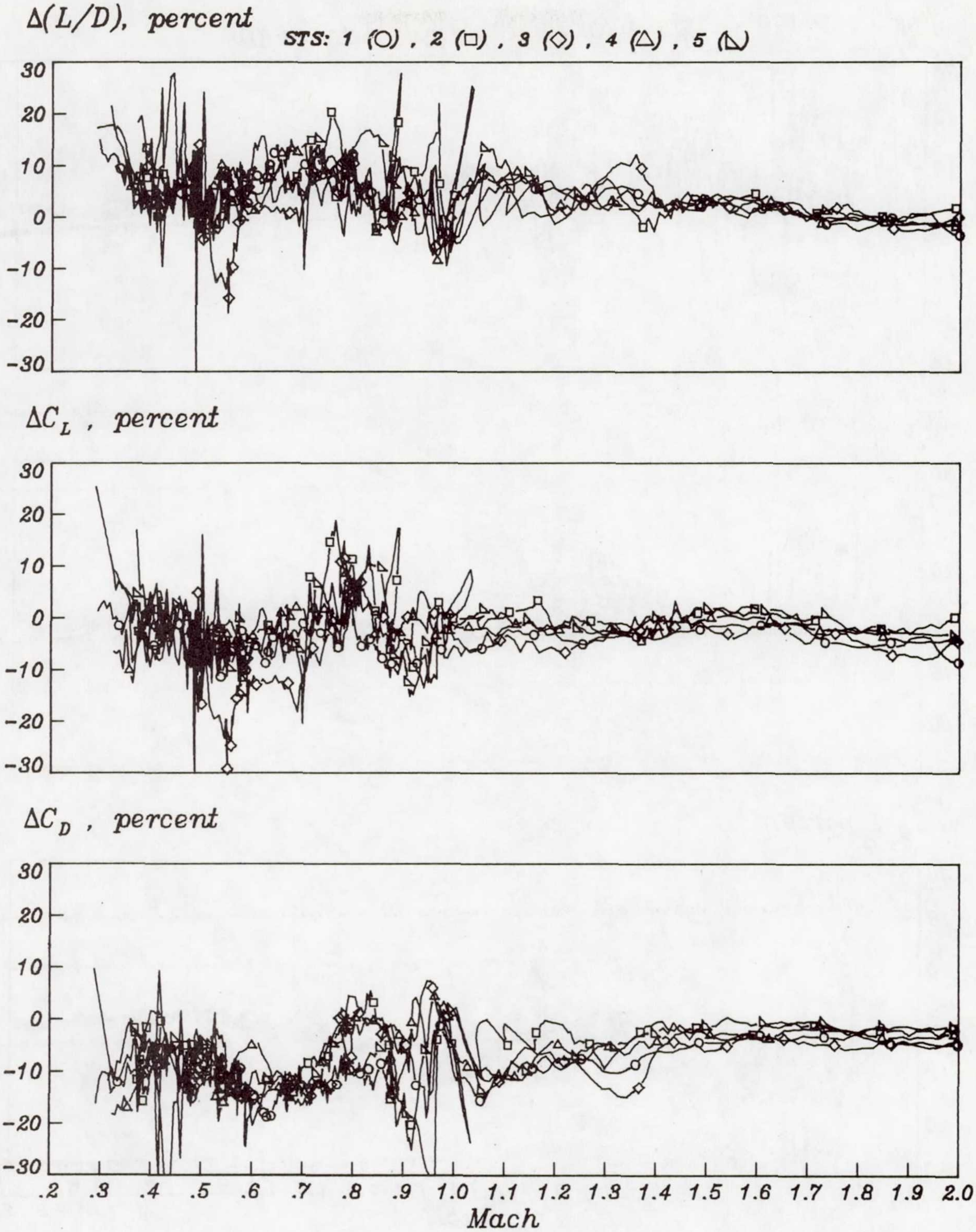

Figure 14.- Flight/data base comparisons for LaRC AEROBETs.

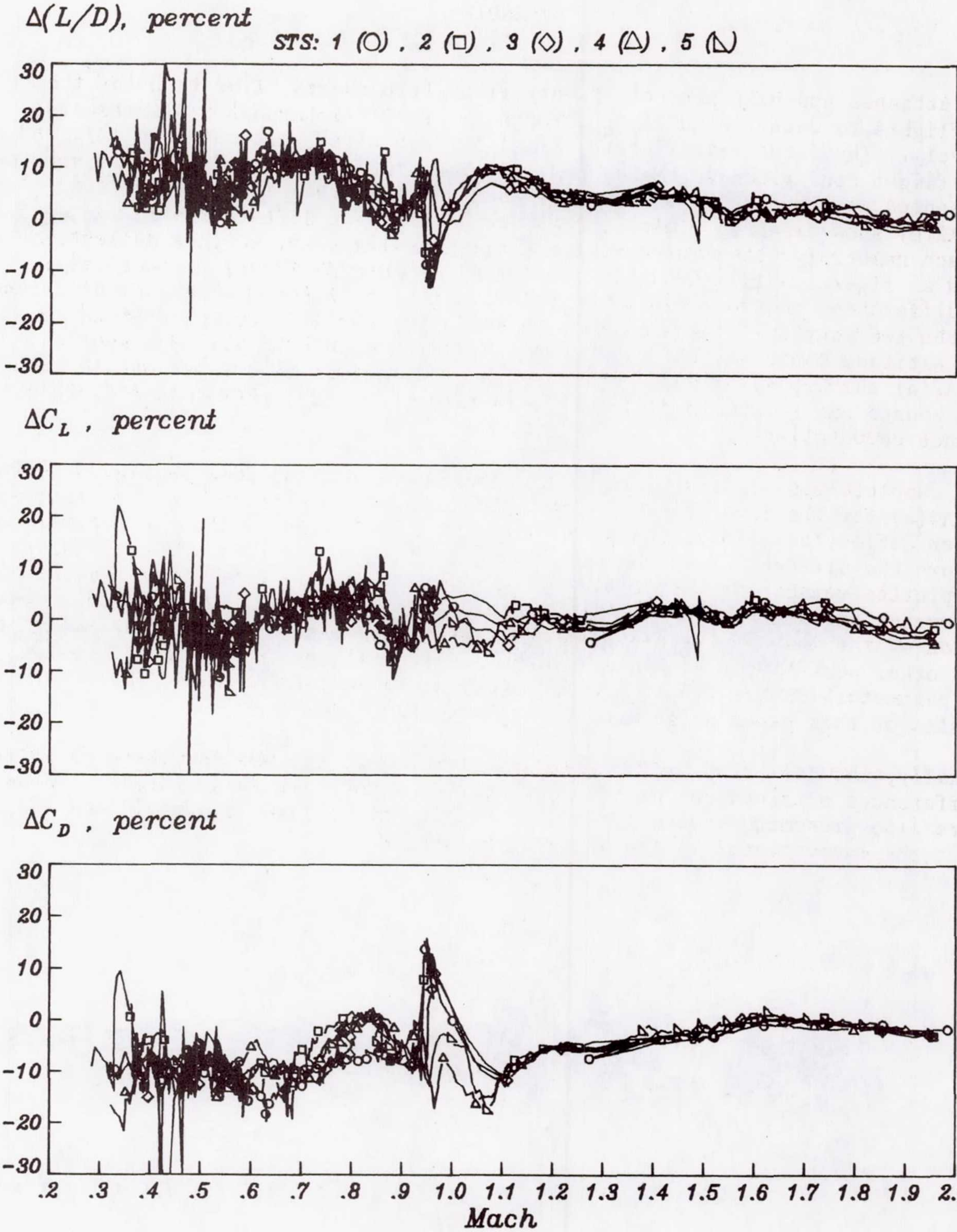

Figure 15.- Flight/data base comparisons for ADS AEROBETs.

APPENDIX

The attached Appendix presents twenty-five strip charts, five each for the Shuttle flights to date. Figures A1 through A5 are STS-1 through STS-5 results, respectively. The first five figures, A1(a) through A1(e), present LaRC (○) and ADS (□) flight conditions (α, Mach, and q) versus the BET altitude. These same data were presented as composite plots in figures 3 and 4 of the paper. Figures A2(a) through A2(e) show expanded plots of these very important differenses in α and q versus Mach number for the two sources. Longitudinal control surface deflections are presented as figures A3(a) through A3(e) for STS-1 through STS-5, respectively. Visible differences on these plots are a manifestation of the Mach number differences between the two sources. These deflection histories would be common plotted versus time and altitude since the BET altitude is utilized with both air data sources. Figures A2(a) through A2(e) and A3(a) through A3(e) exemplify the reasons that each air data source can result in differences in both the flight extracted and predicted performance computations.

For completeness, lateral directional parameters are included as figures A4(a) through A4(e) for the five flights. Included thereon are plots of β, σ, aileron and rudder deflections (about the aerodynamic reference line). The β curve principally shows the differences in the sideslip from the two air data sources, though each is plotted versus the respective Mach number which will contribute somewhat to the difference signature. Roll, aileron and rudder differences are entirely a manifestation of the Mach number differences. These data can be utilized by investigators for other post-flight analyses. There is no predicted influence of these lateral parameters on the longitudinal performance discussed in this paper, nor do the results of this paper suggest that there should be.

Finally, the last five pages, A5(a) through A5(e), are the resultant flight/data base differences obtained for each flight utilizing both air data sources. These data were also presented in the paper as composite plots (see figures 14 and 15) and represent the major import of the analysis presented.

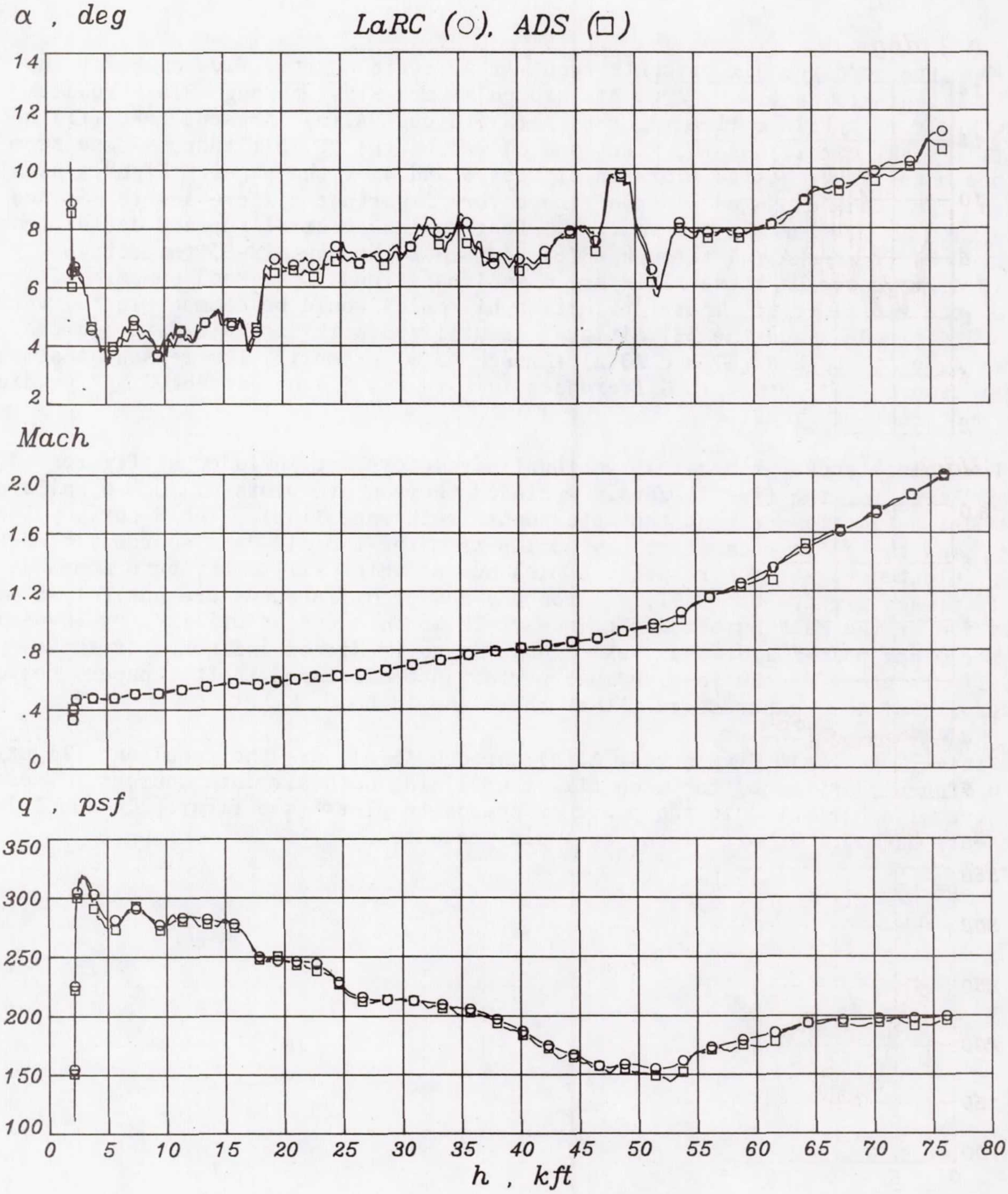

Figure A1(a).- STS-1 flight conditions.

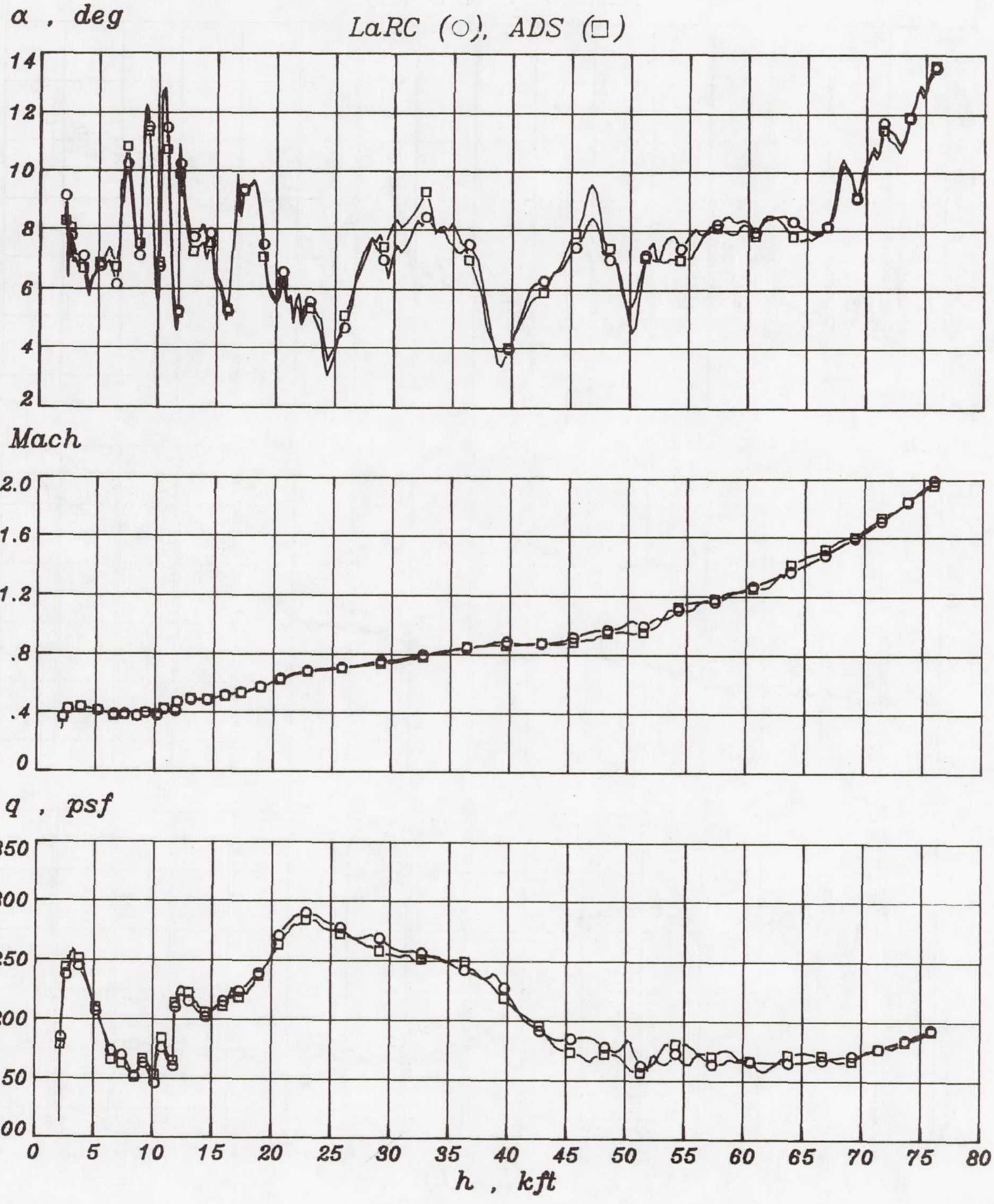

Figure A1(b).- STS-2 flight conditions.

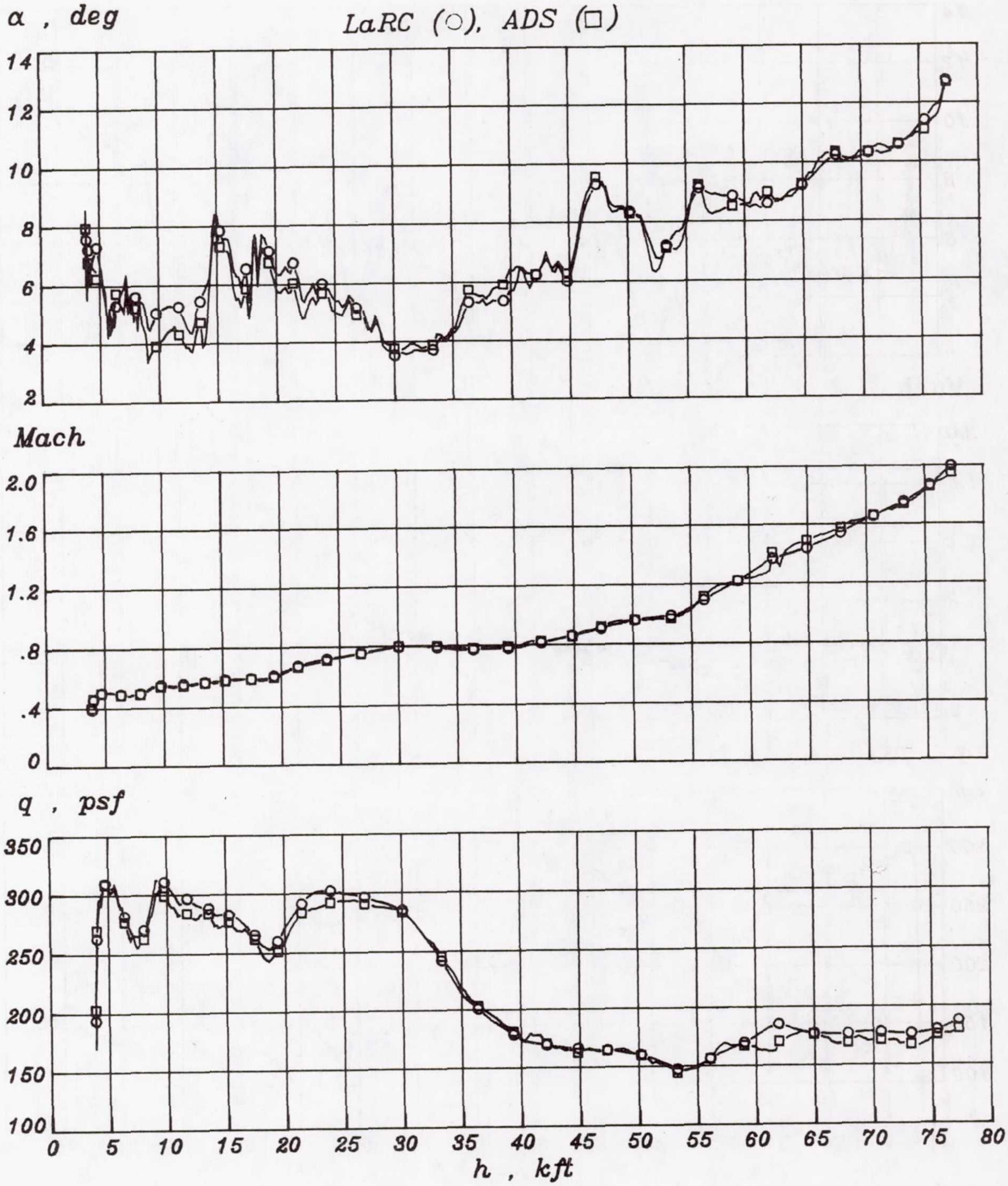

Figure A1(c).- STS-3 flight conditions.

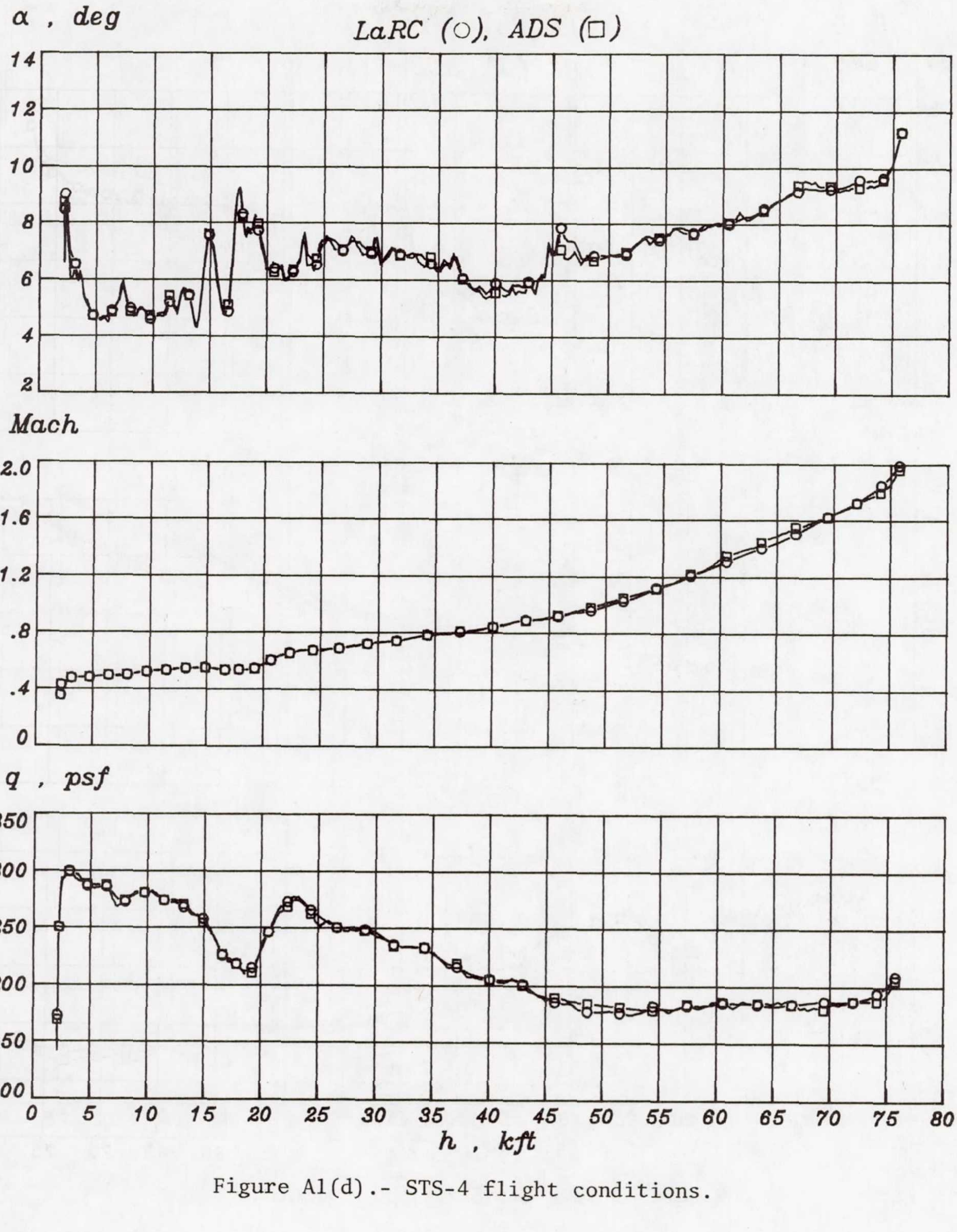

Figure A1(d).- STS-4 flight conditions.

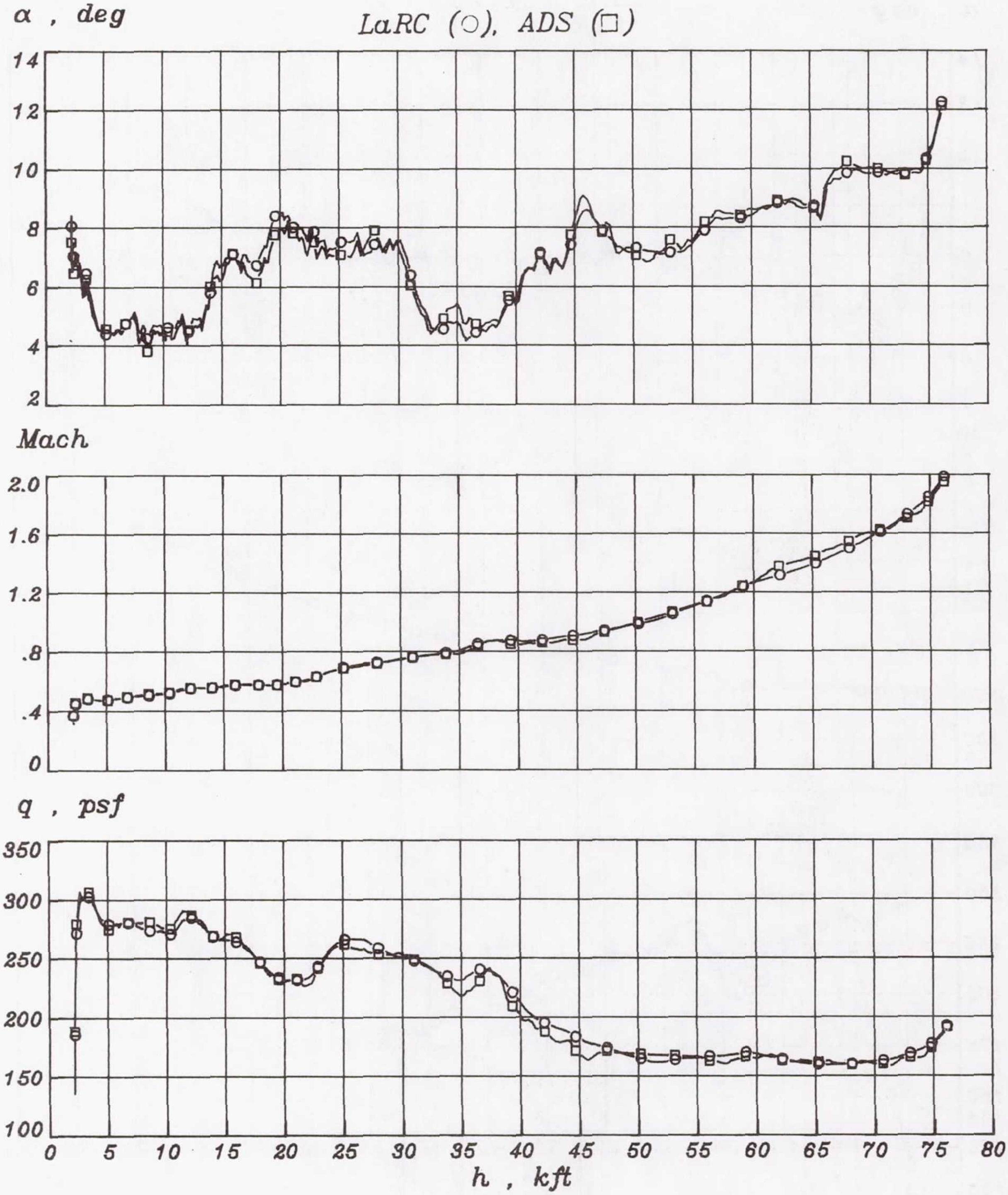

Figure A1(e).- STS-5 flight conditions.

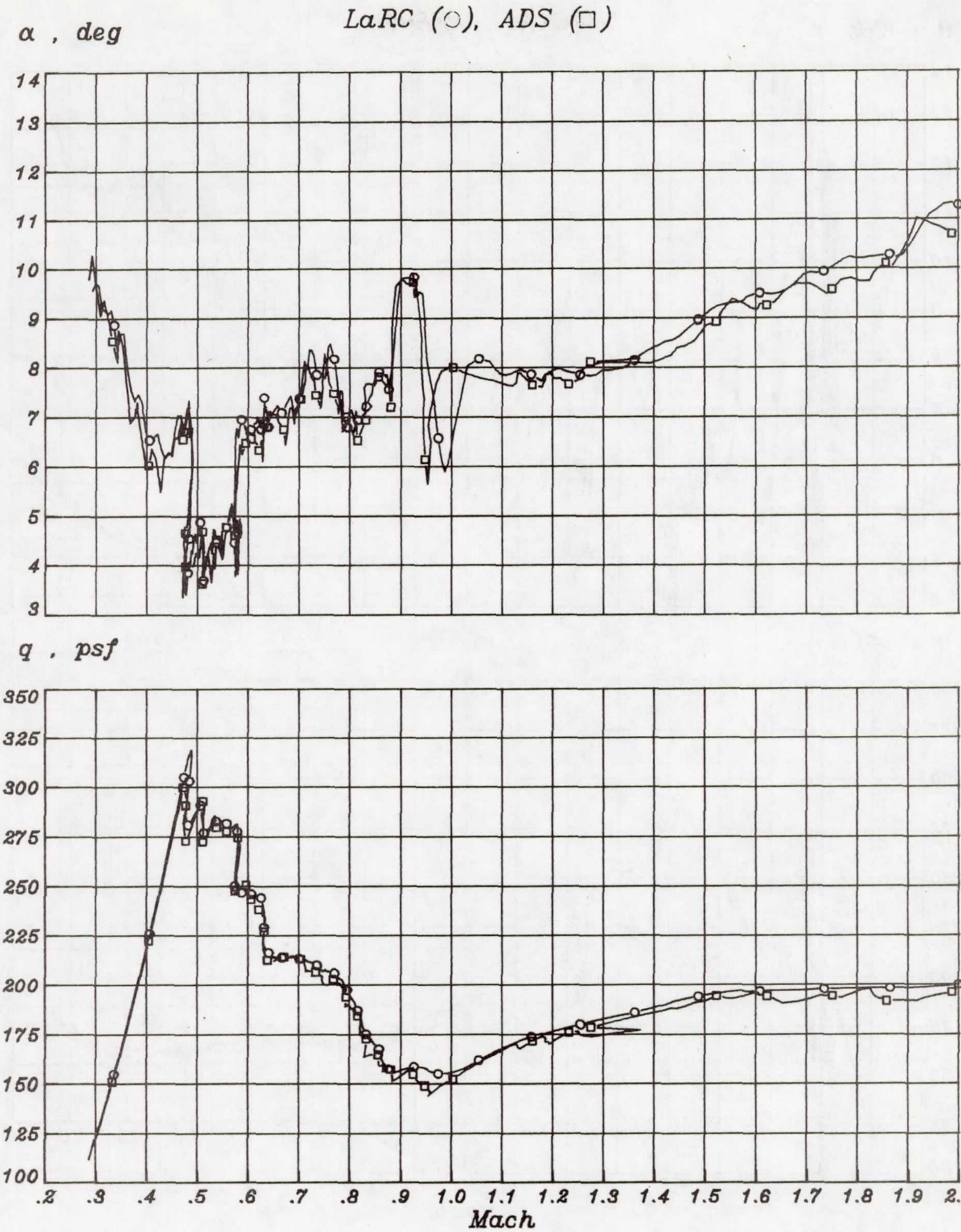

Figure A2(a).- STS-1 flight conditions versus Mach number.

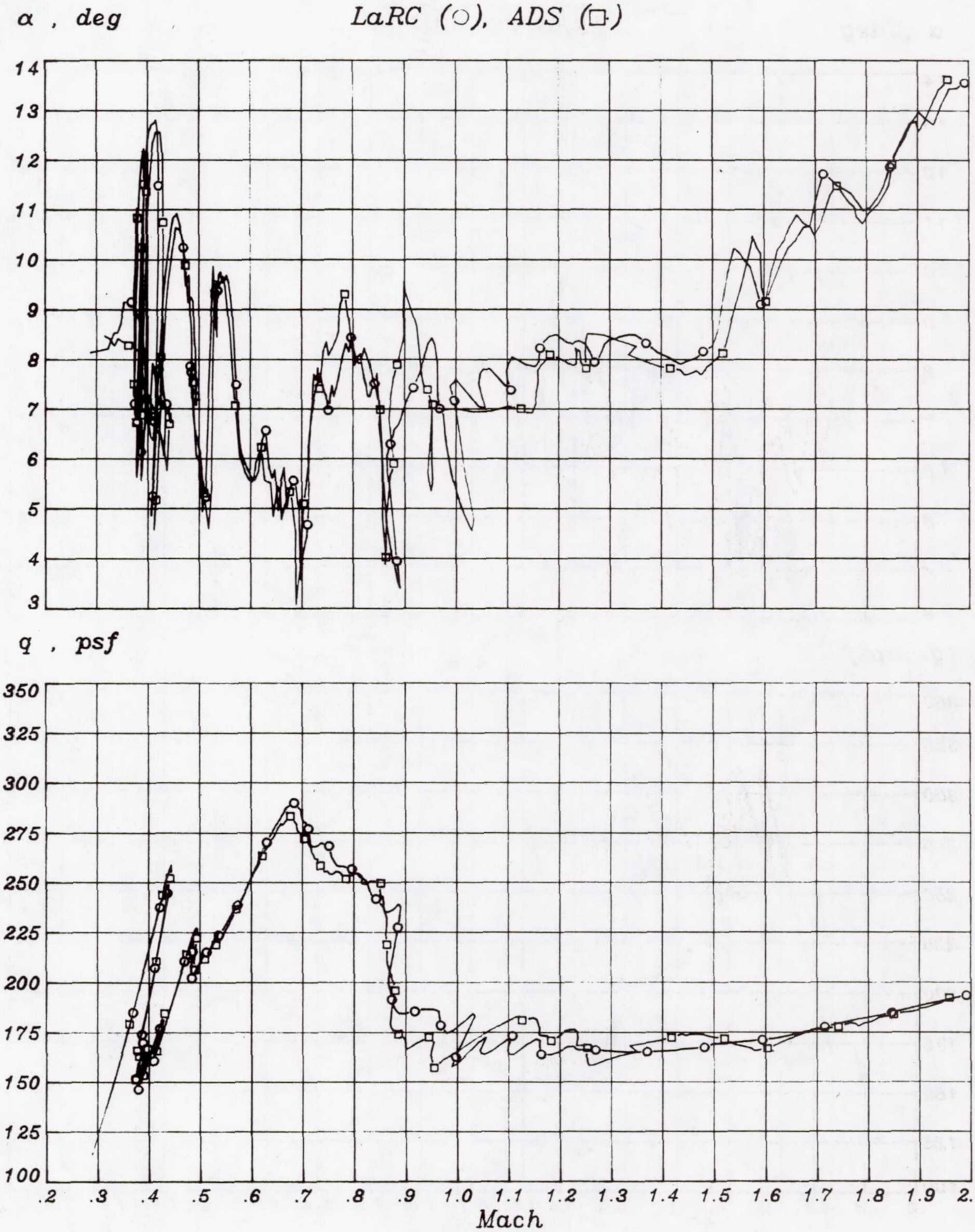

Figure A2(b).- STS-2 flight conditions versus Mach number.

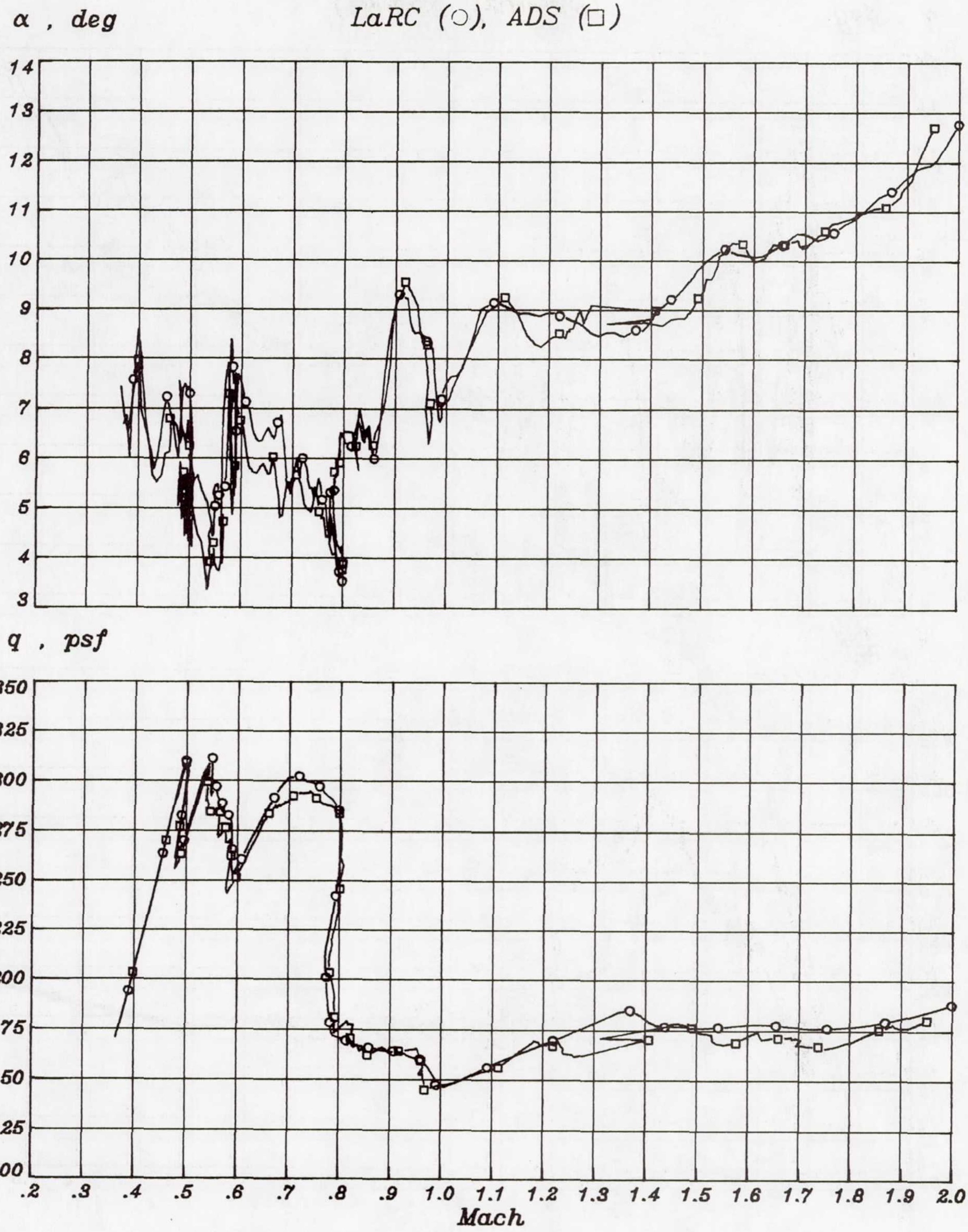

Figure A2(c).- STS-3 flight conditions versus Mach number.

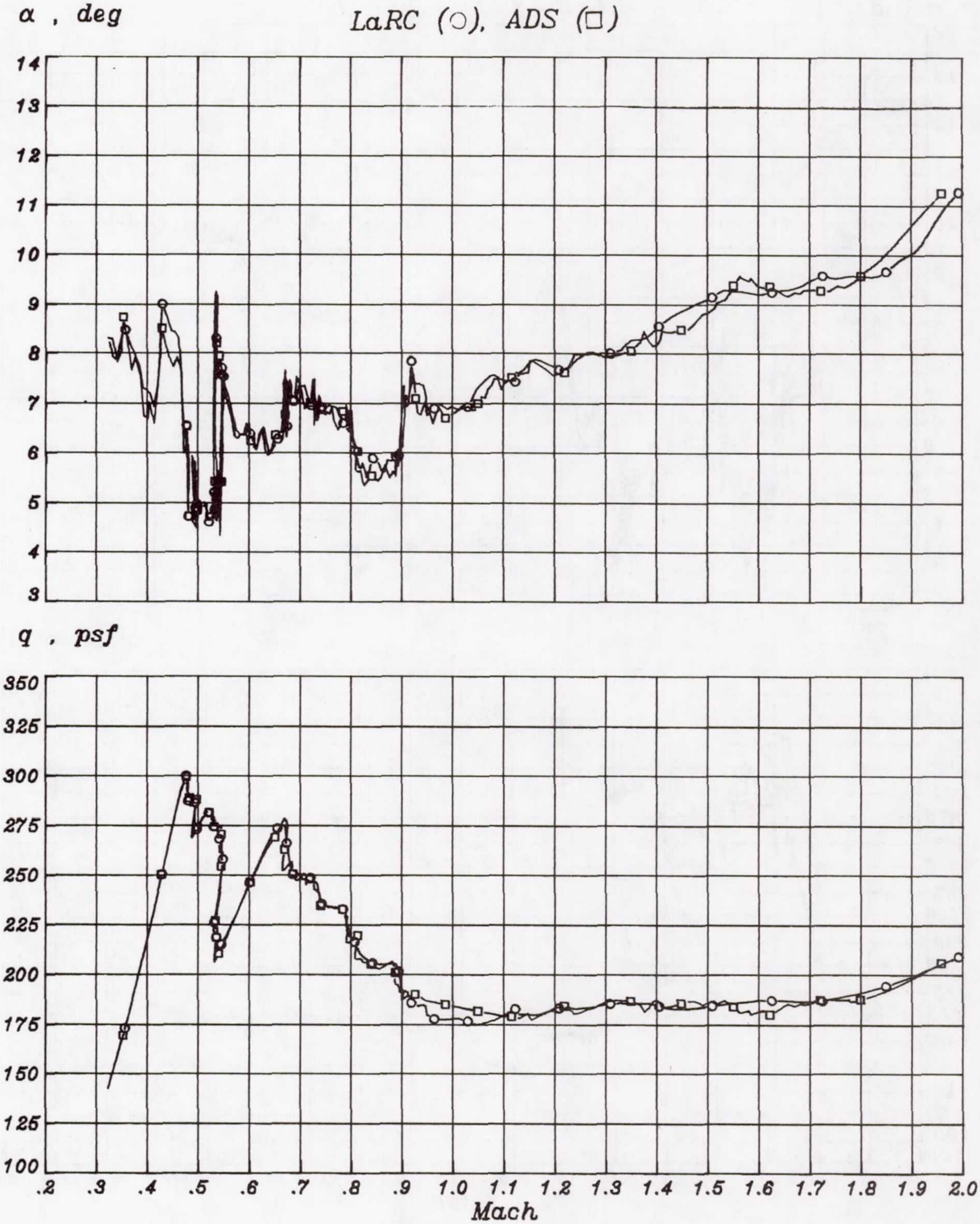

Figure A2(d).- STS-4 flight conditions versus Mach number.

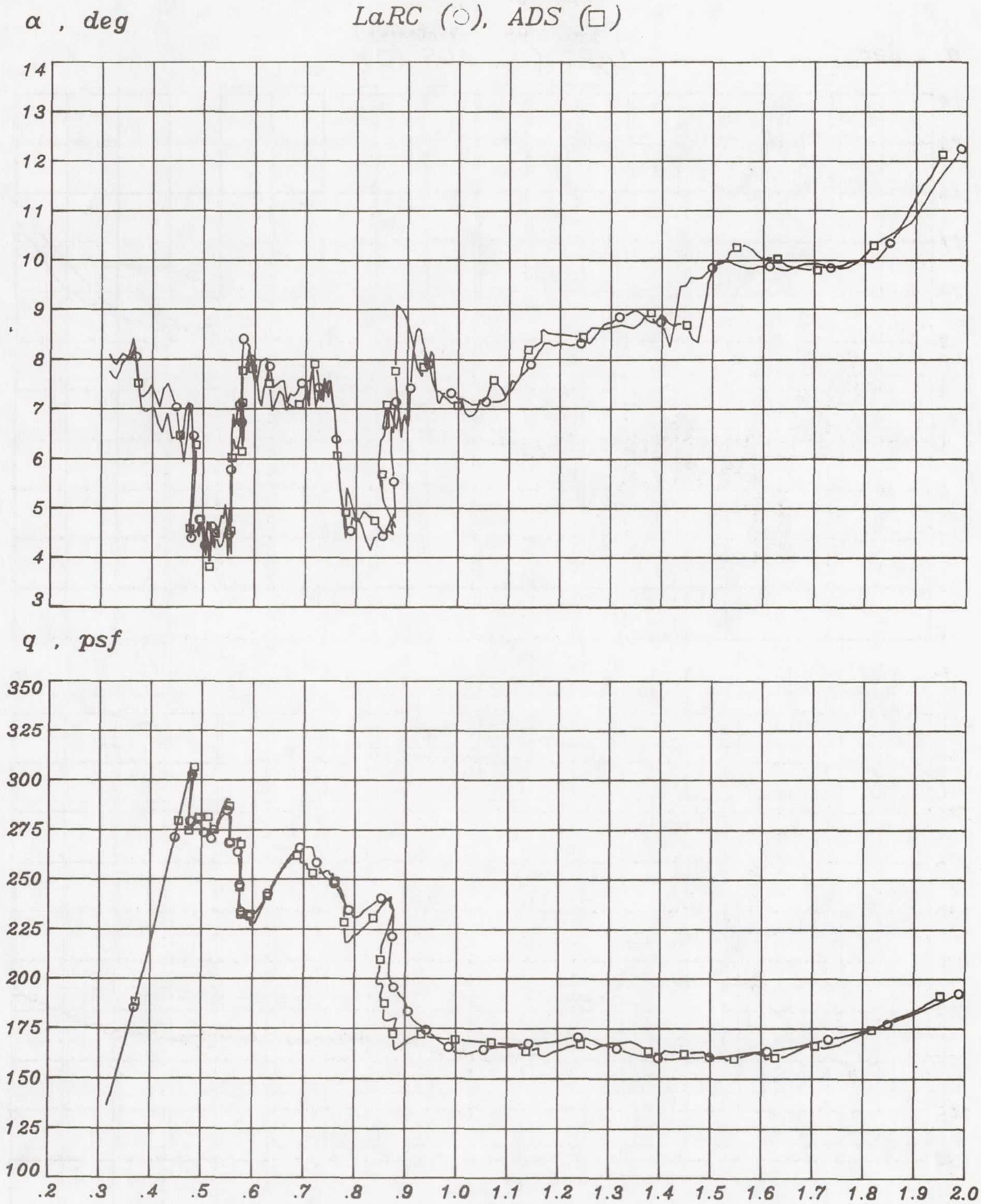

Figure A2(e).- STS-5 flight conditions versus Mach number.

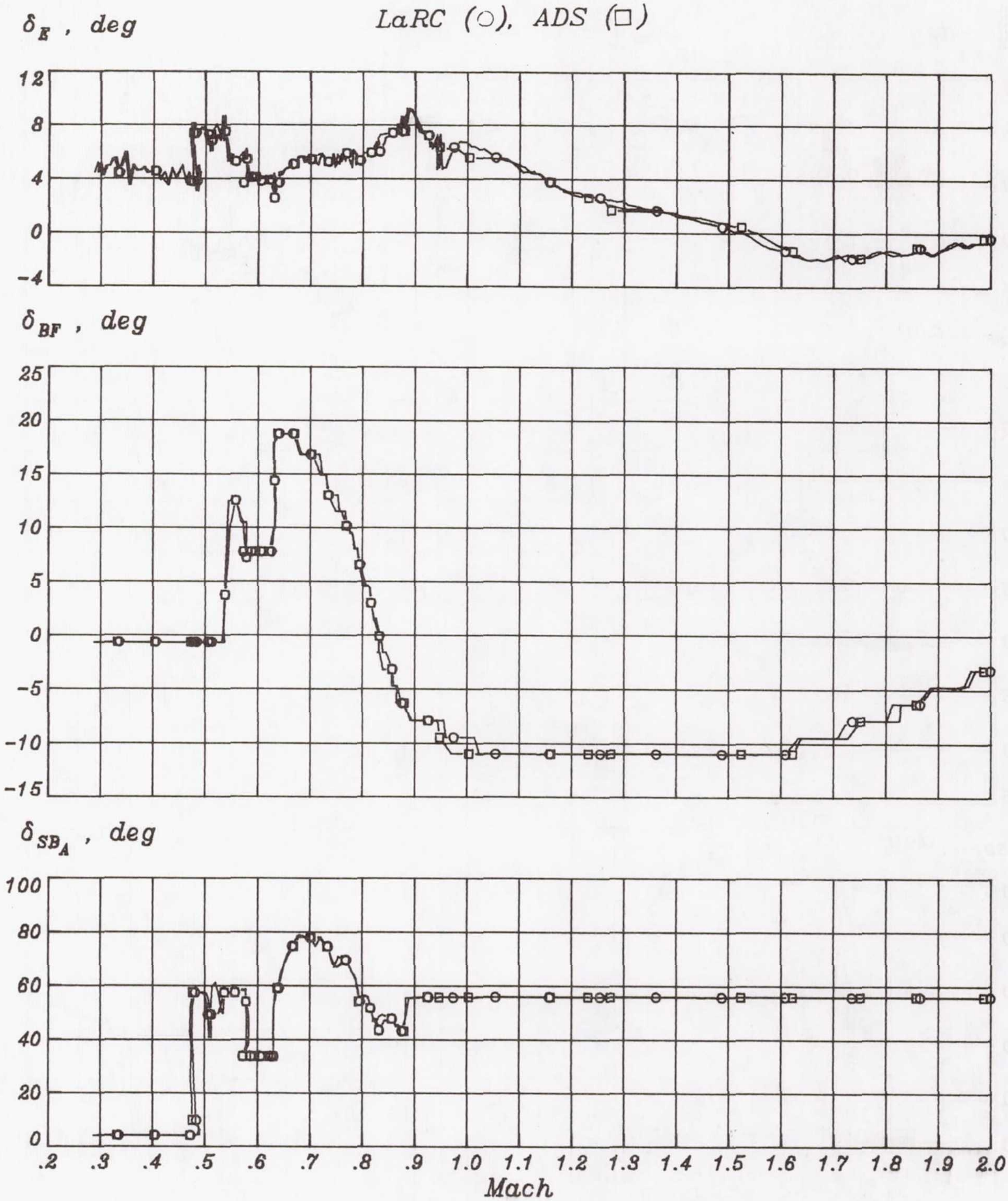

Figure A3(a).- STS-1 control surface deflections versus Mach number.

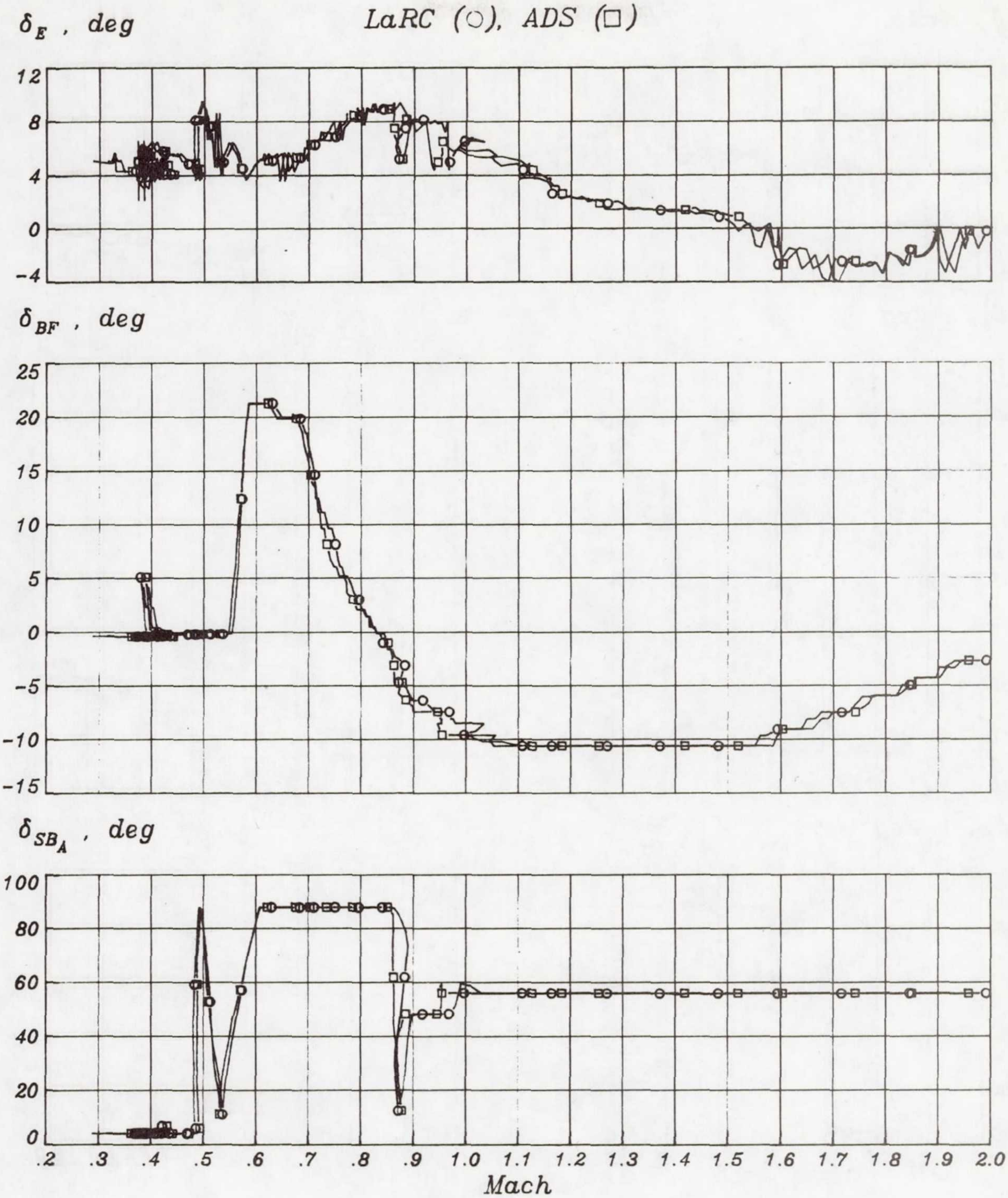

Figure A3(b).- STS-2 control surface deflections versus Mach number.

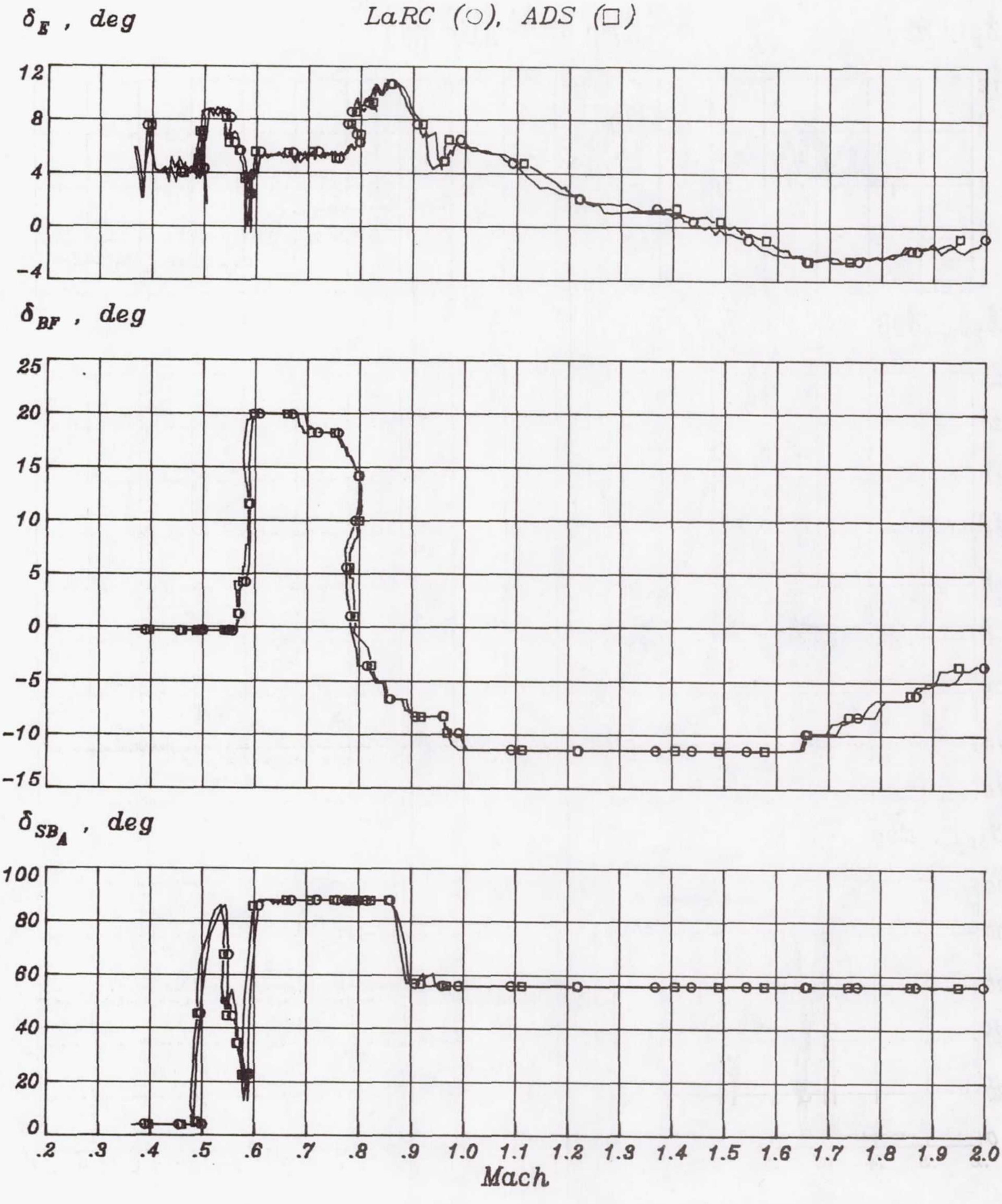

Figure A3(c).- STS-3 control surface deflections versus Mach number.

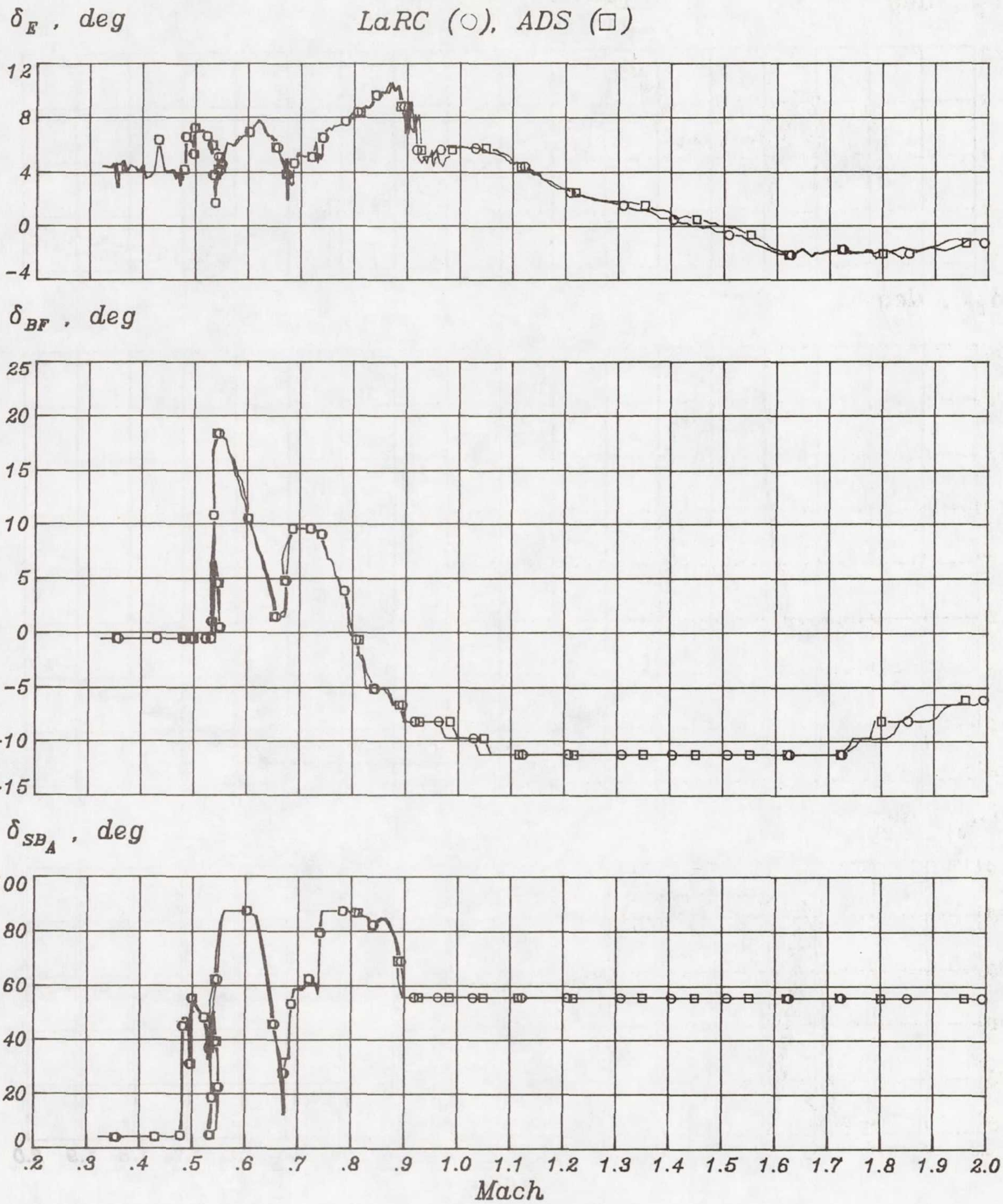

Figure A3(d).- STS-4 control surface deflections versus Mach number.

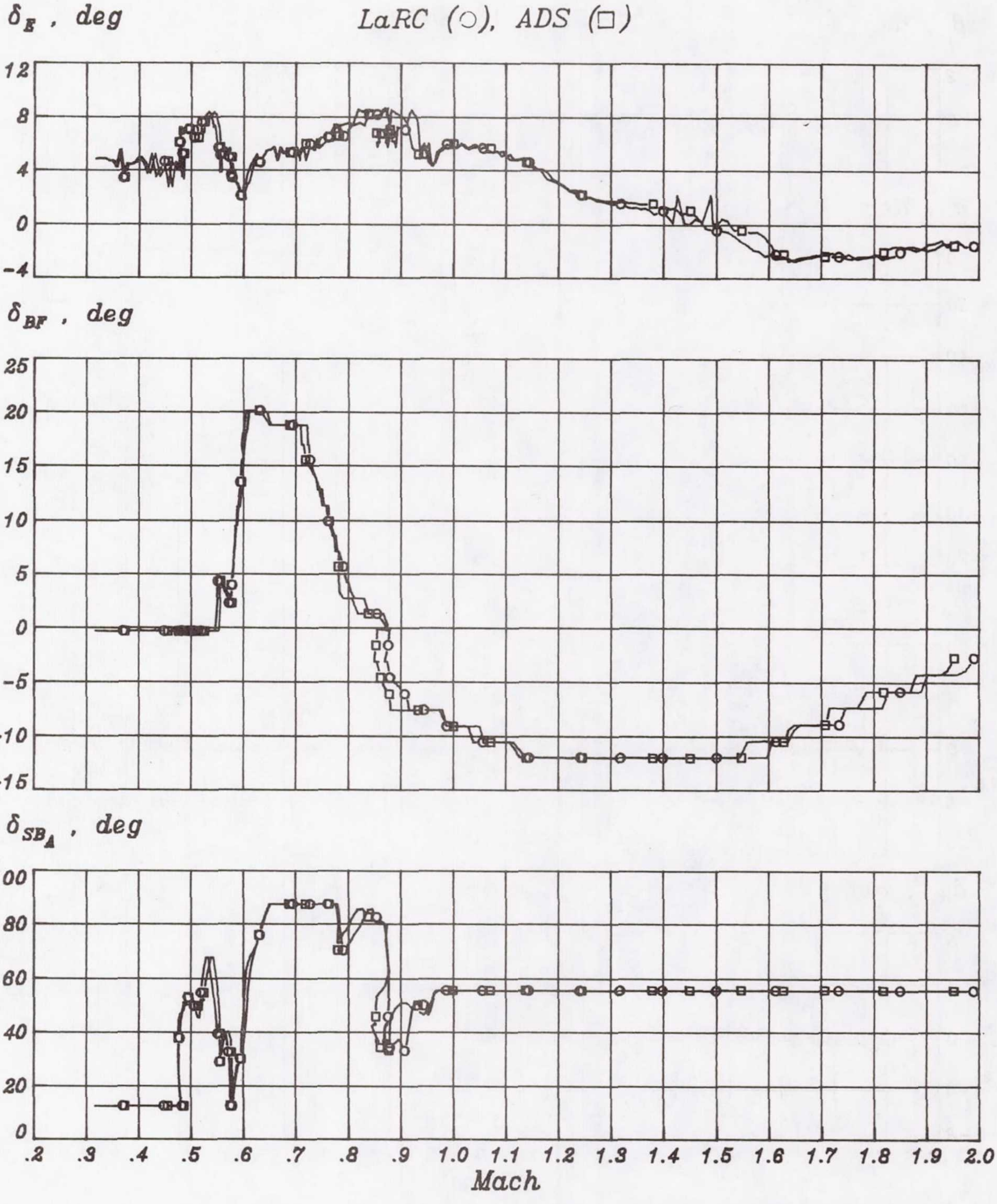

Figure A3(e).- STS-5 control surface deflections versus Mach number.

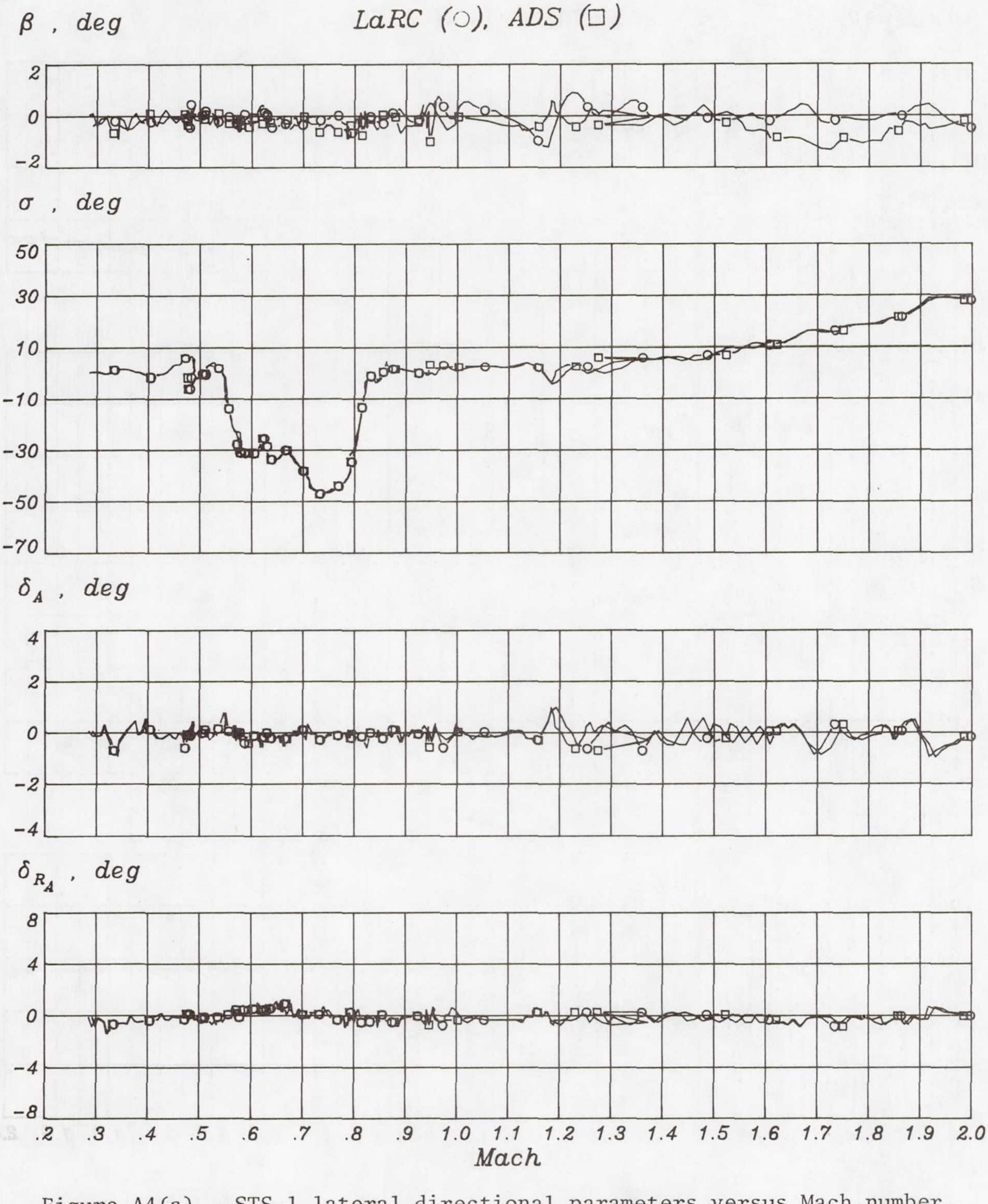

Figure A4(a).- STS-1 lateral directional parameters versus Mach number.

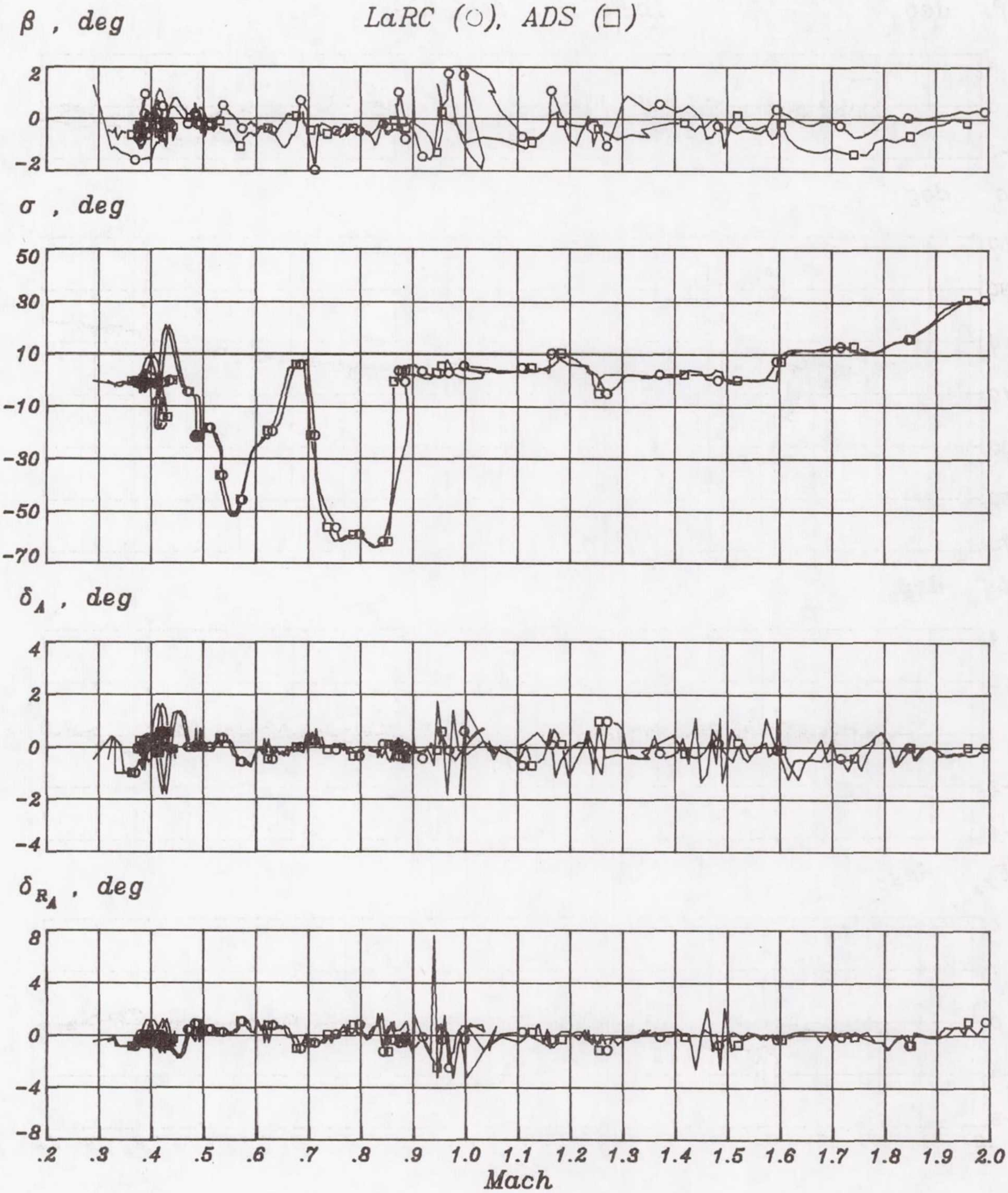

Figure A4(b).- STS-2 lateral directional parameters versus Mach number.

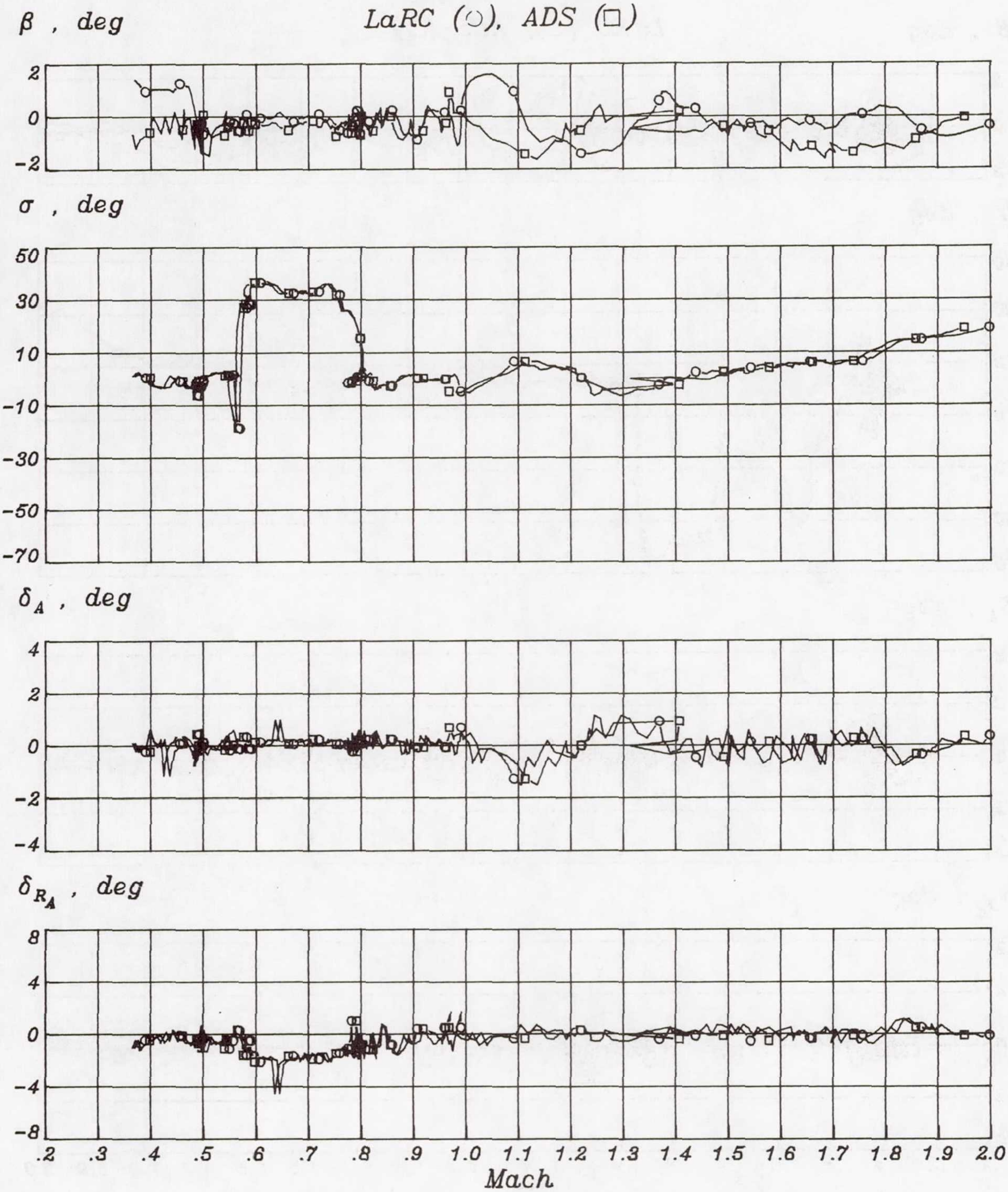

Figure A4(c).- STS-3 lateral directional parameters versus Mach number.

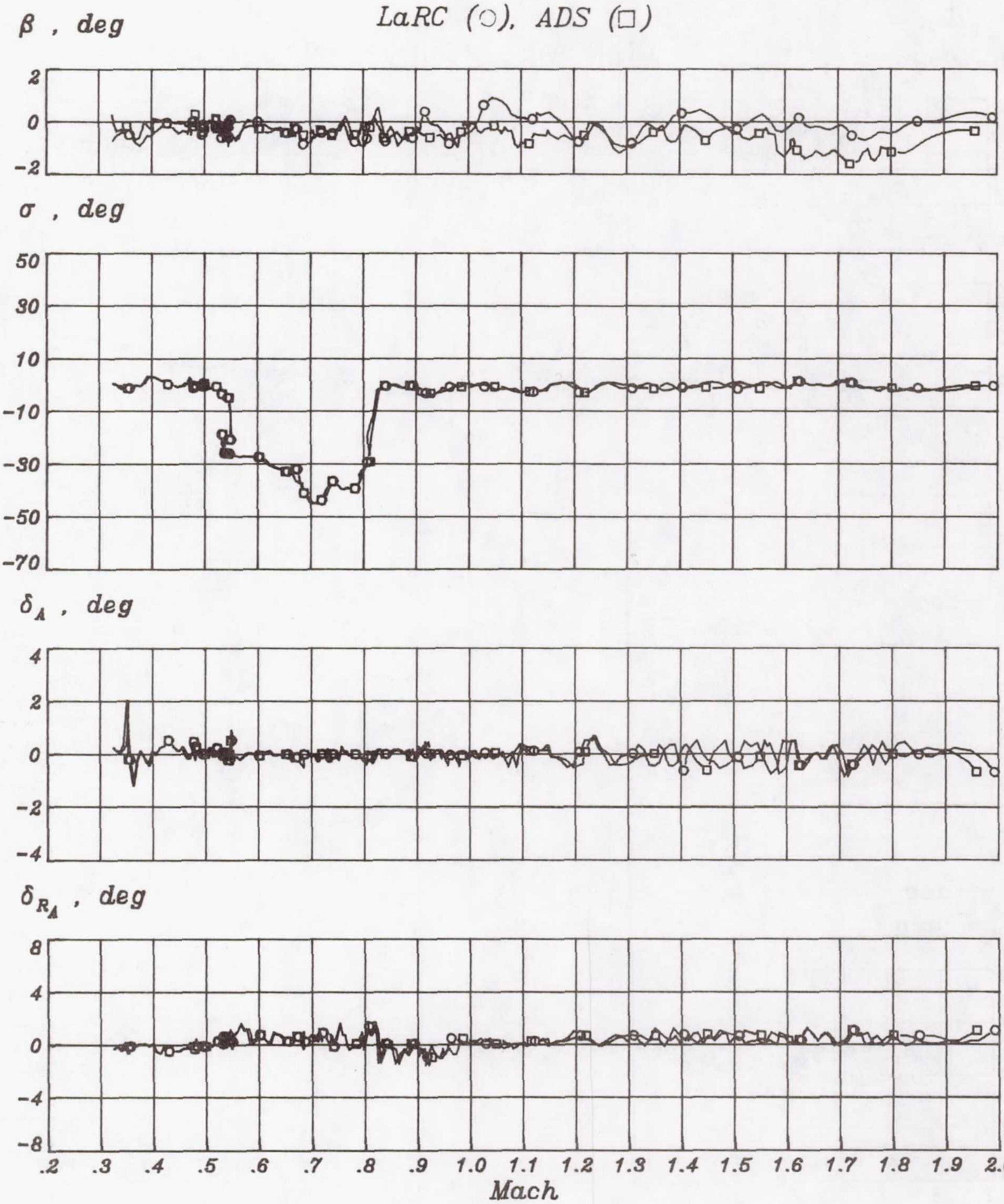

Figure A4(d).- STS-4 lateral directional parameters versus Mach number.

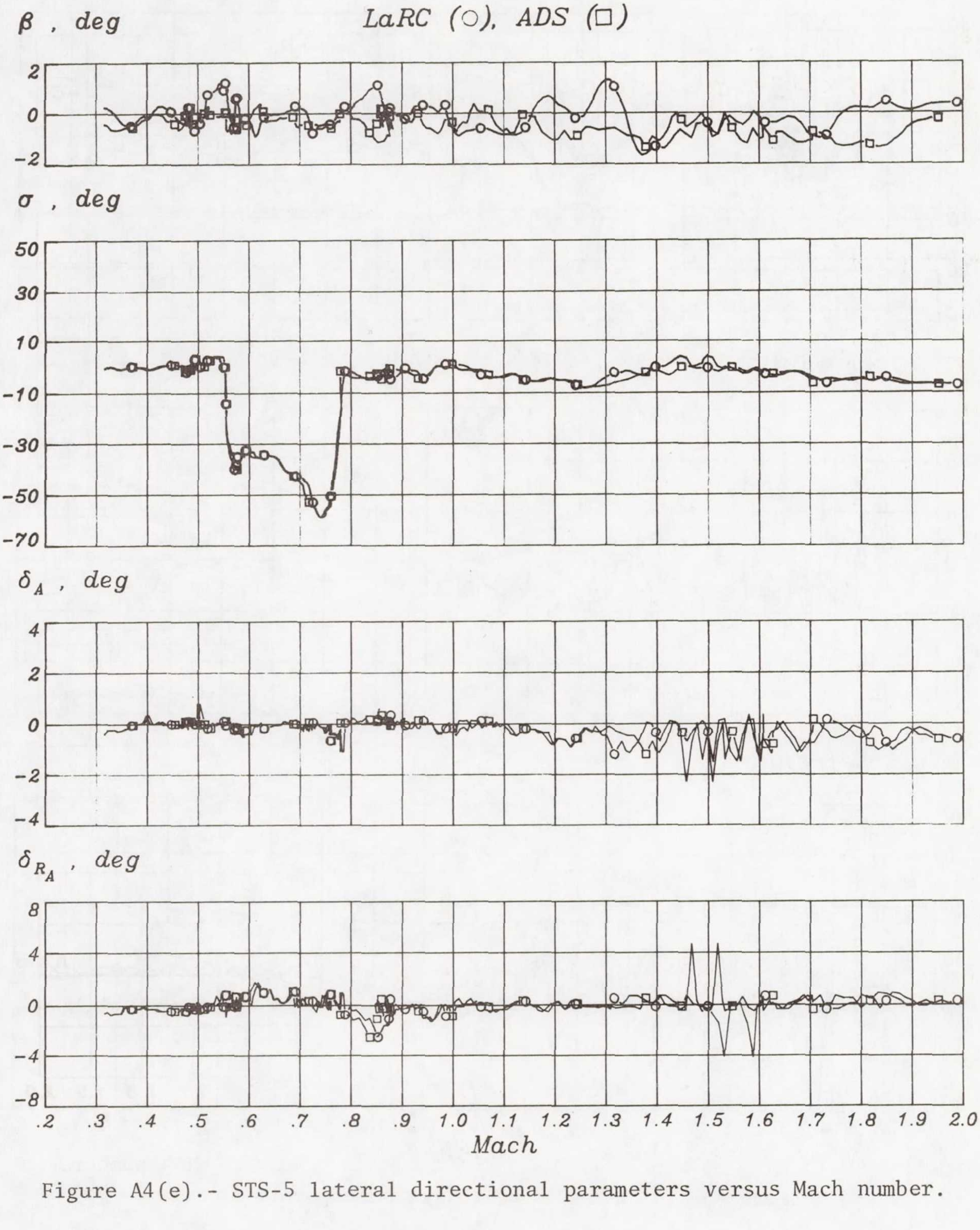

Figure A4(e).- STS-5 lateral directional parameters versus Mach number.

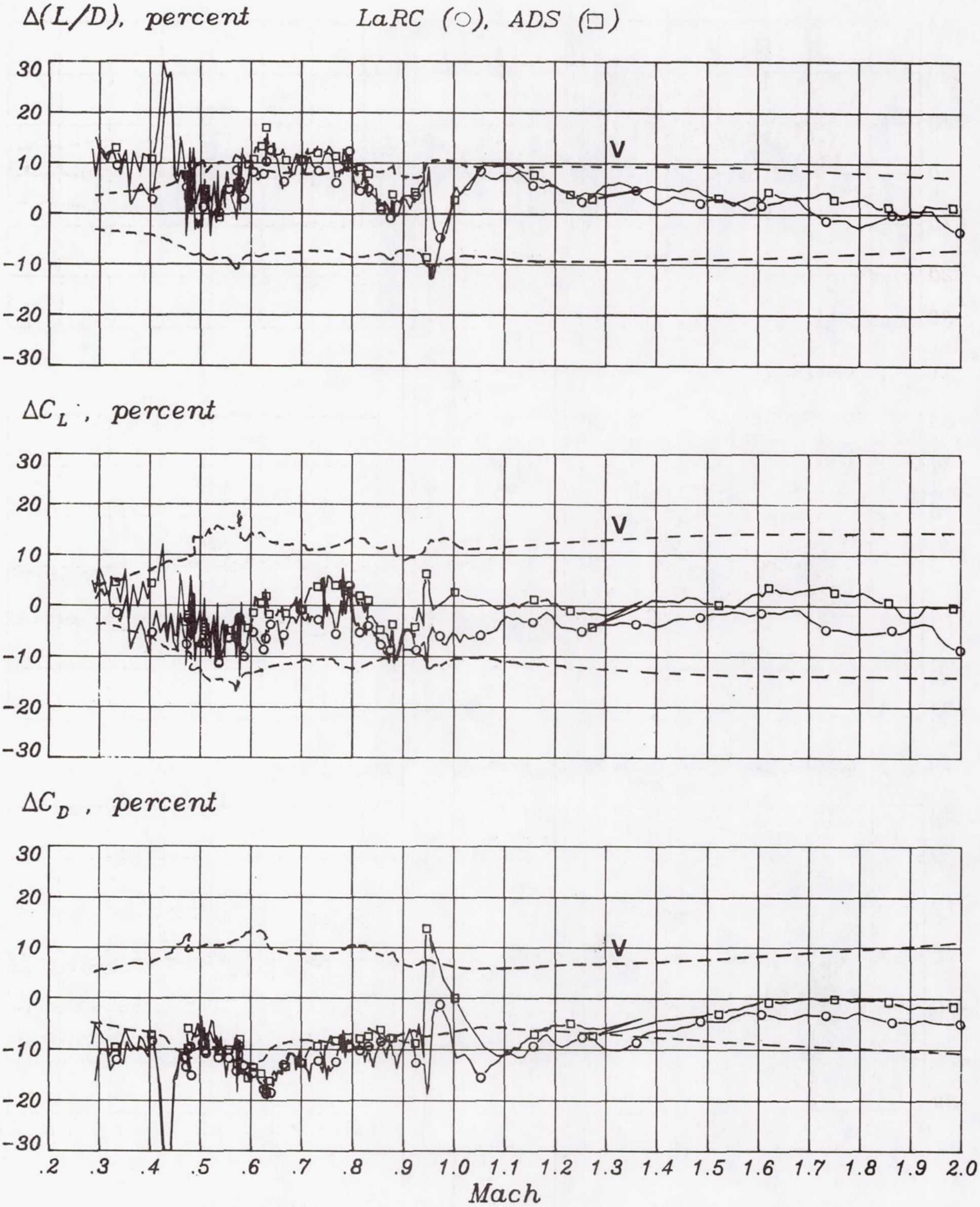

Figure A5(a).- STS-1 flight/data base comparisons.

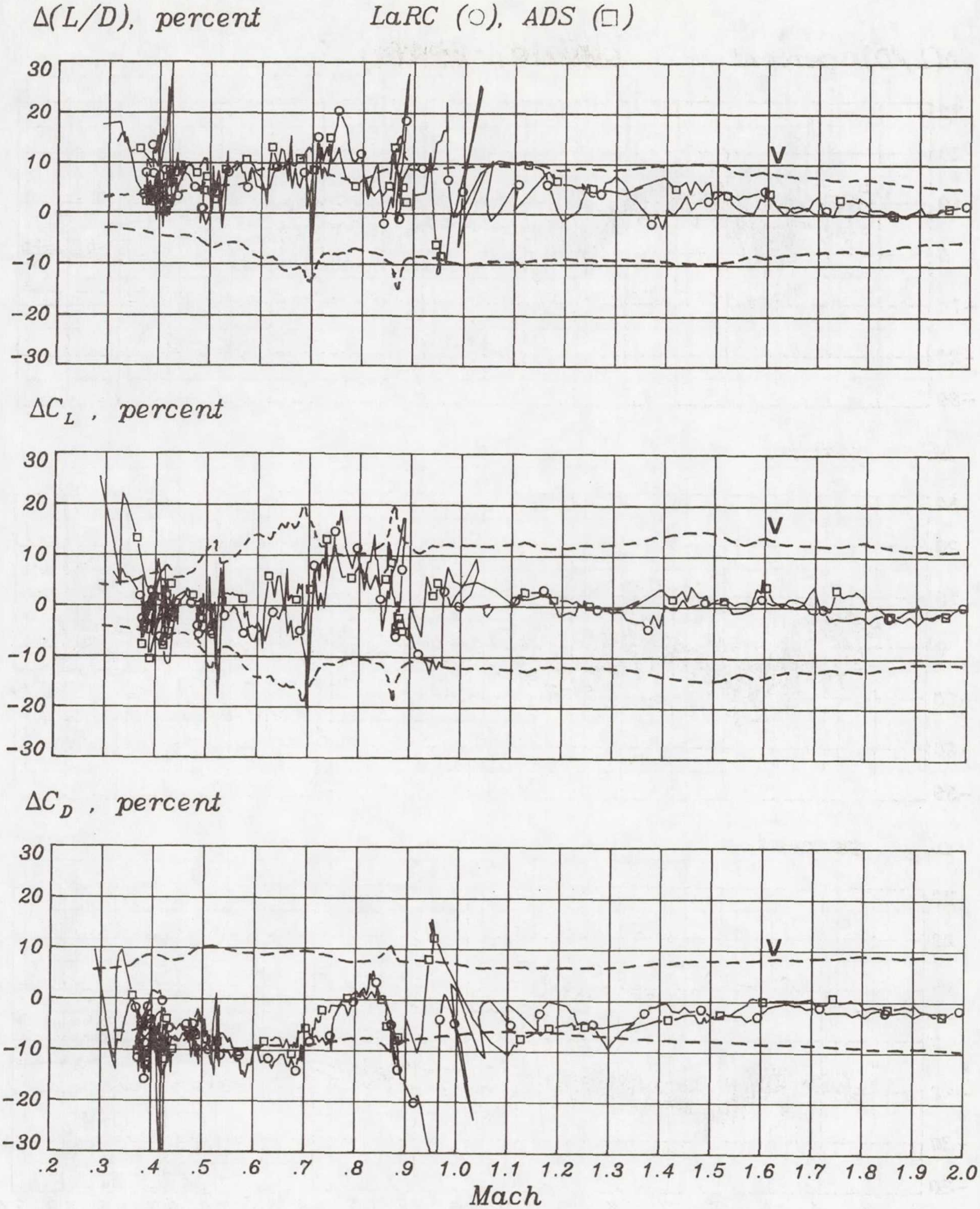

Figure A5(b).- STS-2 flight/data base comparisons.

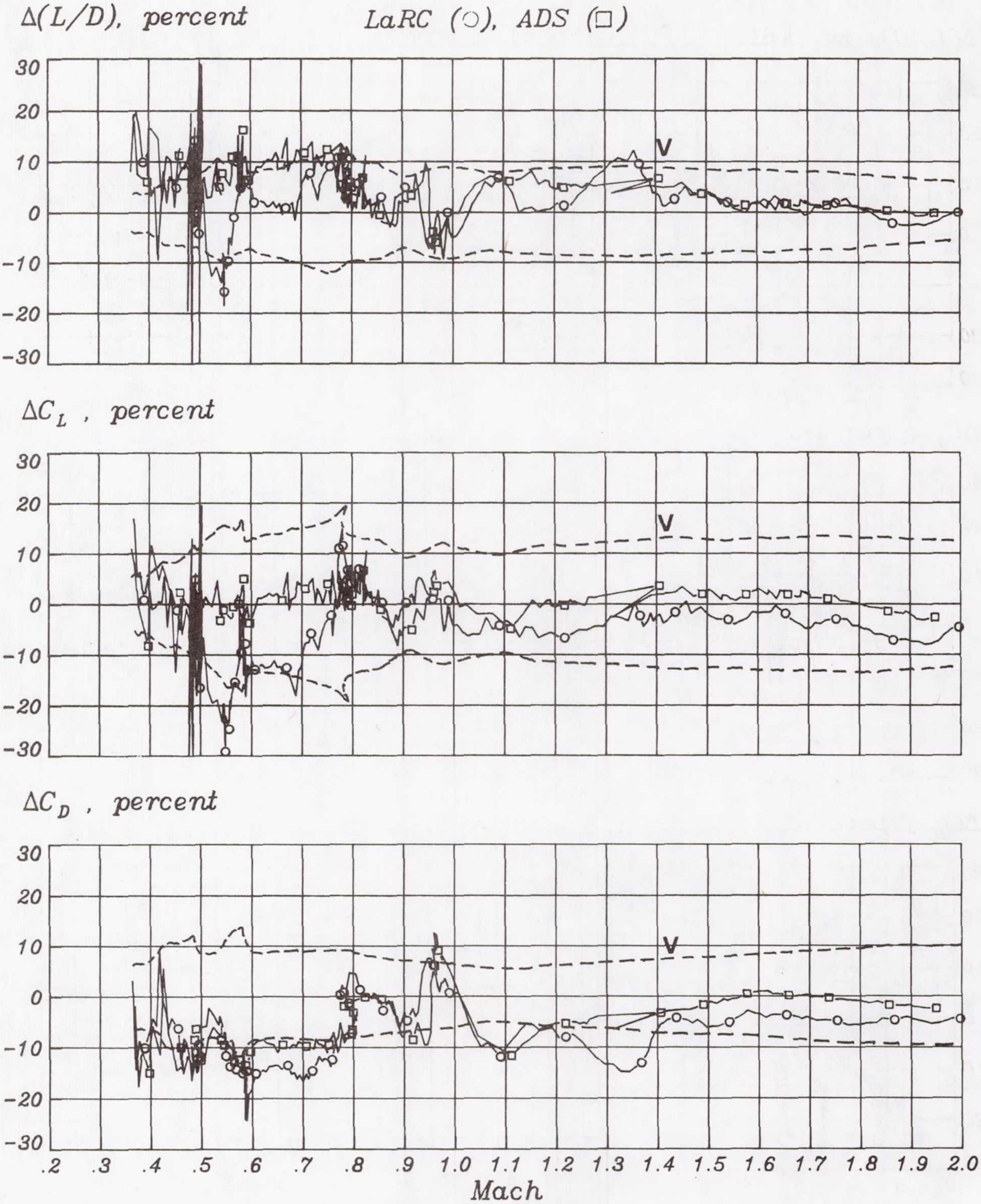

Figure A5(c).- STS-3 flight/data base comparisons.

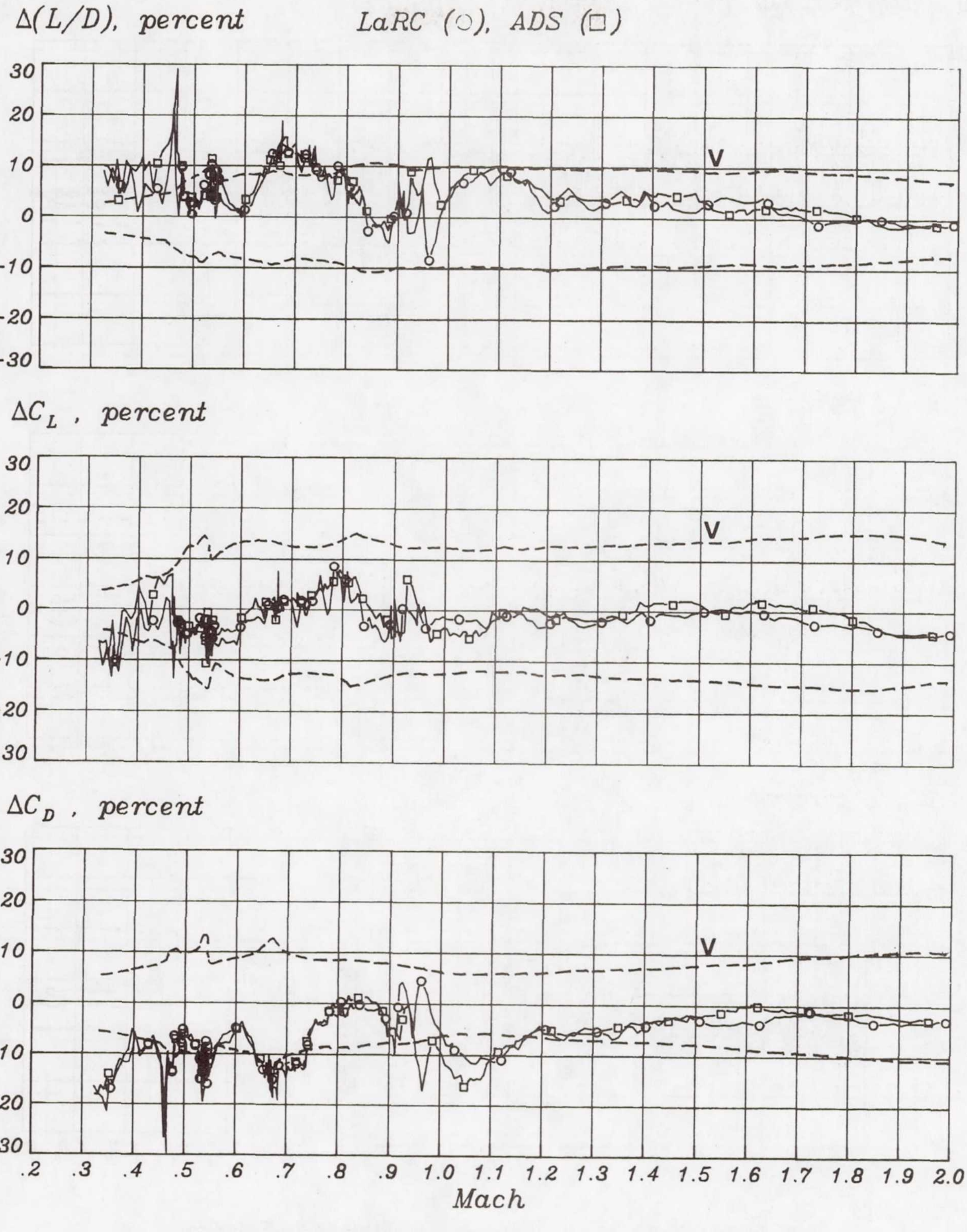

Figure A5(d).- STS-4 flight/data base comparisons.

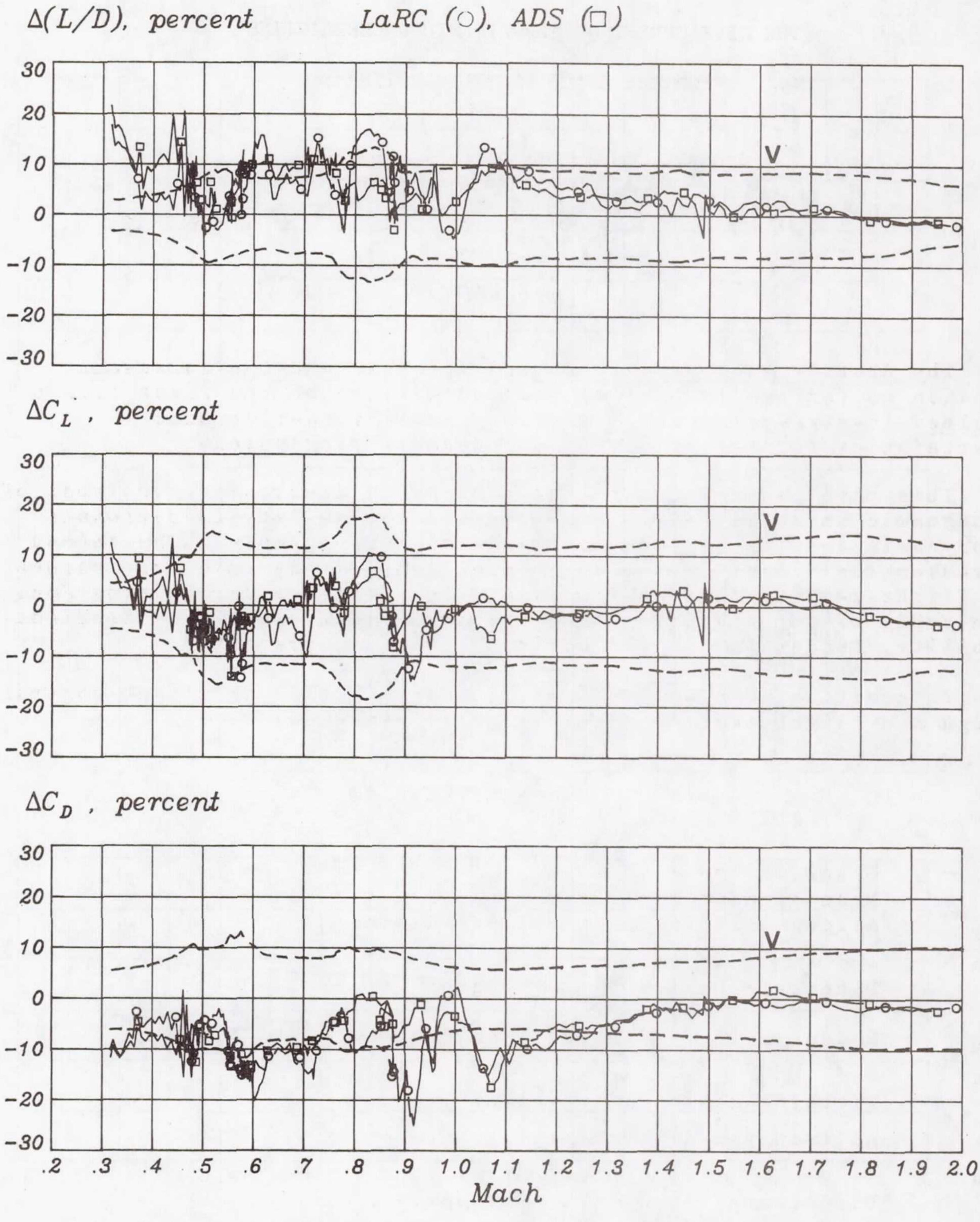

Figure A5(e).- STS-5 flight/data base comparisons.