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ROBERT C. BLANCHARD

KEVIN T. LARMAN

CHRISTINA D. MOATS

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National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23681-0001

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Robert C. Blanchard
NASA Langley Research Center
Hampton, Virginia 23681-0001

Kevin T. Larman and Christina D. Moats
Lockheed Engineering & Sciences Company
Hampton, Virginia 23666-1339

Abstract

A rarefied-flow shuttle aerodynamic model spanning the hypersonic continuum to the free molecule-flow regime has been formulated. The model development has evolved from the High Resolution Accelerometer Package (HiRAP) experiment conducted on the Orbiter since 1983. The complete model is described in detail. The model includes normal and axial hypersonic continuum coefficient equations as functions of angle-of-attack, body flap deflection, and elevon deflection. Normal and axial free molecule flow coefficient equations as a function of angle-of-attack are presented, along with flight derived rarefied-flow transition bridging formulae. Comparisons are made with data from the Operational Aerodynamic Design Data Book (OADDB), applicable wind-tunnel data, and recent flight data from STS-35 and STS-40. The flight-derived model aerodynamic force coefficient ratio is in good agreement with the wind-tunnel data and predicts the flight measured force coefficient ratios on STS-35 and STS-40. The model is not, however, in good agreement with the OADDB. But, the current OADDB does not predict the flight data force coefficient ratios of either STS-35 or STS-40 as accurately as the flight-derived model. Also, the OADDB differs with the wind-tunnel force coefficient ratio data.

Nomenclature

a	=acceleration measurements
C	=aerodynamic force coefficient

$\overline{C}$	=normalized aerodynamic coefficient
Kn	=Knudsen number: mean-free path/12.058 m
M	=Mach number
v	=velocity
Vbar	=viscous parameter
δ	=deflection angle
α	=angle-of-attack

Acronyms

HiRAP	=High Resolution Accelerometer Package
IMU	=Inertial Measurement Unit
OADDB	=Operational Aerodynamic Design Data Book
STS	=Space Transportation System

Subscripts

A	=axial force
bf	=body flap
c	=continuum
EL	=elevon
f	=free molecular flow
N	=normal force
α	=angle-of-attack
x,y,z	=body axes

Introduction

Prediction of vehicle aerodynamic coefficients come from several sources, e.g., wind-tunnel testing, computational simulations, and aerodynamic models. Historically, starting with the Wright brothers, when appropriate scaling parameter(s) are identified, wind-tunnel data have successfully been applied to predicting aerodynamic flight behavior. But, with the advent of space flight, and the interest in hypersonic rarefied-flow phenomena, current tunnel capabilities are being pushed to the technology limits for providing flight predictions. Over the last decade or so, a parallel effort for providing wind-tunnel like information has been developed using computer simulations of the flow-field. These computational methods are becoming more potent with continued computer innovations and the theoretical bounds appear limitless. However, there are technical problems which are more economically served by a simpler approach, for instance, preflight design studies. In these cases, a simple aerodynamic model is adequate. This report provides an aerodynamic force model for applications on winged entry vehicles in the hypersonic rarefied-flow flight regime.

In the recent past, the Shuttle was especially instrumented with a variety of experiments to measure aerodynamic and aerothermodynamic parameters.[1] This capability provided an opportunity to make repeated in-situ measurements in the rarefied-flow regime so that the predictive models could be developed with flight data. A rarefied-flow aerodynamic model has been formulated from the High Resolution Accelerometer Package (HiRAP) experiment.[2] By examining the force coefficient ratio on multiple flights, the rarefied-flow transition aerodynamic functional behavior has been extracted. This provided the keystone to a simple model which can be used to predict rarefied-flow aerodynamics of a winged reentry vehicle, e.g., the Shuttle. The model incorporates aerodynamic coefficient derivative data from the Operational Aerodynamic Design Data Book (OADDB)[3] at the rarefied-flow transition boundaries, that is in the hypersonic continuum and in the free molecule-flow regime. In the hypersonic continuum regime, the absolute value of the individual force coefficients in the model have been adjusted to values determined on STS-61C, when hypersonic continuum pressure measurements first became available. The Orbiter control surface aerodynamic contributions, i.e., the body-flap and elevon coefficients, are generated from curve fits to the OADDB data. At the other end of the rarefied-flow transition boundary, the free-molecule flow force coefficient values are also generated from curve fits to the OADDB data.

The purpose of this report is to provide a complete description of the flight model and to show its usefulness to predict the aerodynamic force coefficients of the Orbiter in the rarefied-flow regime. To demonstrate this, the model is used to predict the force coefficient ratios of two recent flights, STS-35 and STS-40. For these flights, a similar comparison is made using the OADDB. Also, both the flight model and the OADDB are compared with rarefied-flow wind-tunnel data taken early in the Shuttle vehicle development.

Model Description

The sign convention used for the model is the standard used in the Orbiter program documentation and is presented in Fig. 1.

The OADDB data come from the "change 3" update which reflect the most recent normal and axial coefficient Shuttle flight information. A subset of OADDB data were chosen which includes parameters appropriate to the comparisons discussed later. These parameters include: angle of attack with range of 0^{o} to 60^{o} for the payload bay doors closed (corresponding to free molecule-flow conditions), angle of attack with range of 35^{o} to 45^{o} for the entry region, elevon deflection with range of -15^{o} to 22.5^{o}, body flap deflection with range of -11.7^{o} to 22.5^{o}; viscous parameter with range of 0.001 to 0.05, and Mach number with range of 15 to 30. The entry coefficients were obtained by summing contributions from the basic, high altitude, real gas, viscous interaction, body flap, elevator/aileron (elevon), and vehicle components.

The rarefied-flow Shuttle aerodynamics flight model discussed in this report is a simple model. It contains three segments: the hypersonic continuum, the free molecule flow, and the transition bridging formulae. Each segment is described in detail.

Hypersonic Continuum

The formulae for the hypersonic continuum normal and axial coefficients as a function of α are:

$$C_{N_{c,\alpha}} = -9.25704 \times 10^{-5}\alpha^2 + 5.23808 \times 10^{-2}\alpha - .839782$$

$$C_{A_{c,\alpha}} = 5.86689 \times 10^{-7}\alpha^3 - 6.72027 \times 10^{-5}\alpha^2 + 3.32044 \times 10^{-3}\alpha - .0086314$$

These equations are for the Shuttle vehicle at an angle-of-attack envelope of $35^{o} < \alpha < 45^{o}$. The above coefficient functions are resulting curve fits to the basic data in the OADDB with adjustments resulting from an earlier analysis using flight data from mission 61C.[2] Unlike the more sophisticated OADDB, the flight model basic coefficients previously given do not separate physical phenomena such as, real gas and viscous effects . In effect, each equation results in one combined coefficient allowing for computation ease and, as discussed later, not introducing significant errors. Figure 2 shows the calculations using the above equations for angle-of-attack between 35^0 and 45^0. Also included on the graphs are a comparison of the flight model force coefficients angle-of-attack behavior with the OADDB data. The conditions for the OADDB data are M=15, Vbar=0.005, and $\delta_{bf}=\delta_{EL}=0^0$. These conditions corresponds to an altitude of approximately 58 km. Two OADDB data sets are shown; one is the OADDB basic coefficients (the circles), while the other (the squares) has the real gas, viscous and vehicle effects included, i.e., a composite coefficient, comparable to the above equations. The primary difference between the individual OADDB basic coefficients and the points labeled, "OADDB (total)" is real gas effects for C_N and viscous effects for C_A. Comparing these OADDB composite coefficients with the flight model, it is seen that the flight model C_N coefficient is consistently lower by about 7 percent than the OADDB, while the C_A coefficient is slightly higher (about 2 percent) for all angles-of-attack. These differences will produce noticeable differences (about 9 percent) in the coefficient ratio, to be discused later.

The Shuttle control surfaces modeled are the hypersonic continuum body flap and elevons at $\alpha = 40^0$ and M = 20. The normal and axial contributions for each are:

BODY FLAP

for $-11.7^0 \le \delta_{bf} \le 22.5^0$,

$$C_{N_{c,bf}} = 4.46278\times10^{-4} + 1.92931\times10^{-3}\delta_{bf} + 3.6029\times10^{-5}\delta_{bf}^2$$

$$C_{A_{c,bf}} = 2.39178\times10^{-4} + 4.81862\times10^{-4}\delta_{bf} + 3.03937\times10^{-5}\delta_{bf}^2 - 3.500869\times10^{-7}\delta_{bf}^3$$

ELEVONS

for $-15^0 \le \delta_{EL} \le 15^0$,

$$C_{N_{c,EL}} = 1.00333 \times 10^{-3} + 5.76021 \times 10^{-3} \delta_{EL} + 1.18538 \times 10^{-4} \delta_{EL}^2$$

$$C_{A_{c,EL}} = -1.3981 \times 10^{-3} + 1.55864 \times 10^{-3} \delta_{EL} + 8.6081 \times 10^{-5} \delta_{EL}^2$$

Figures 3 and 4 show the above functions compared with the data from the OADDB for the body flap and elevons, respectively.

Then, the total hypersonic continuum coefficients are:

$$C_{N_c} = C_{N_{c,\alpha}} + C_{N_{c,bf}} + C_{N_{c,EL}}$$

$$C_{A_c} = C_{A_{c,\alpha}} + C_{A_{c,bf}} + C_{A_{c,EL}}$$

Free Molecule Flow

The formulae for the free molecule flow normal and axial coefficients as a function of α are:

$$C_{N_{f,\alpha}} = -7.16528 \times 10^{-6} \alpha^3 + 9.66197 \times 10^{-4} \alpha^2 + 9.18422 \times 10^{-3} \alpha + 1.58739 \times 10^{-3}$$

$$C_{A_{f,\alpha}} = -1.17117 \times 10^{-5} \alpha^3 + 5.92205 \times 10^{-4} \alpha^2 + .0164864 \alpha + .751105$$

The above free molecule flow normal and axial coefficient equations are for the Shuttle (payload doors closed) at $0^{\circ} < \alpha < 60^{\circ}$. A comparison of these functions with the data from the OADDB is shown in Fig. 5. The body flap and elevons contributions, that is,

$$C_{N_{f,bf}}, C_{A_{f,bf}}, C_{N_{f,EL}}, C_{A_{f,EL}}$$

in the free molecule flow regime are undetermined and are currently set to zero.

Then, the total free molecule flow coefficients are:

$$C_{N_f} = C_{N_{f,\alpha}} + C_{N_{f,bf}} + C_{N_{f,EL}}$$
$$C_{A_f} = C_{A_{f,\alpha}} + C_{A_{f,bf}} + C_{A_{f,EL}}$$

Bridging Formulae

The method to bridge between the hypersonic continuum to the free molecule flow regime includes the following "bridging" formulae[4]

$$\overline{C}_N = \exp\left[-0.2998\left(1.3849 - \log_{10} Kn\right)^{1.7128}\right] \quad \textit{if} \quad \log_{10} Kn < 1.3849$$

otherwise $\overline{C}_N = 1.0$

$$\overline{C}_A = \exp\left[-0.2262\left(1.2042 - \log_{10} Kn\right)^{1.8410}\right] \quad \textit{if} \quad \log_{10} Kn < 1.2042$$

otherwise $\overline{C}_A = 1.0$

where the normalized normal and axial coefficients use Knudsen number, Kn, as the independent parameter. The normalized aerodynamic coefficients are used to generate the actual cofficients by the following:

$$C_N = C_{N_c} + (C_{N_f} - C_{N_c})\overline{C}_N$$
$$C_A = C_{A_c} + (C_{A_f} - C_{A_c})\overline{C}_A$$

Flight Data

The flight data for STS-35 and STS-40 is summarized in this section. The Orbiter position, velocity, and orientation information is obtained from a "best estimate trajectory" process.[5,6] This process includes using flight measurements from the IMU and is the source of the IMU acceleration ratios shown later. Figure 6 shows the Orbiter velocity and corresponding Kn as a function of altitude for STS-35 and STS-40. The Kn is computed using the 1976 U.S. standard atmosphere7 and a reference length of 12.058 m, the Orbiter's mean aerodynamic chord. The Kn parameter serves as a guide for the vehicle flow regime. Namely, large Kn (roughly > 10) indicate free molecule flow behavior with few intermolecular interactions, while small Kn (roughly $< 10^{-3}$) indicate near continuum flow where intermolecular collisions are an important consideration to the flow physics. Clearly, most of the altitudes included in Fig. 6 are for the rarefied-flow transition regime, where the vehicle environment is "transitioning" from free molecule flow to continuum flow. In addition to a flow indicator, Kn is also the independent parameter for the bridging formulae presented earlier.

Figure 7 gives the angle-of-attack profile of the Orbiter vehicle for STS-35 and STS-40. Throughout the entire rarefied-flow transition into the hypersonic continuum region, about 170 km to 60 km, the angle-of-attack is close to 40^{0}. The corresponding control surface settings for these flights are shown in Fig. 8 and Fig. 9. Both body flap and elevon are held constant in their stored positions until shortly below 90 km, when they are activated, mostly in the pitch direction, in order to establish longitudinal control.

An application of the STS-35 and STS-40 flight data with the rarefied-flow aerodynamics flight model described in the preceding section produces the results shown in Fig. 10. These results show angle-of-attack effects which influence both the C_A and C_N coefficients. The angle-of-attack variations are easily seen in C_N at both low and high altitudes (see Fig. 7 for comparisons). Due to scale selection, the C_A angle-of-attack variations are not easily seen at low altitudes, but are discernable at high altitudes.

Model Comparisons

With Flight Data

A method of examining aerodynamic models with flight data is to compare the model coefficient ratio with the corresponding acceleration measurement ratio since,

$$\frac{C_N}{C_A} = \frac{a_Z}{a_X}$$

The use of these ratios alleviates the need to determine dynamic pressure and thus, density which is a widely varying quantity.[2] Figure 11 shows 2 graphs, both of which contain measurements of the ratio of acceleration from the IMU and HiRAP on STS-35 (the IMU data are below 97 km). Figure 11(a) shows the results of application of the aerodynamic coefficients using the OADDB. Clearly, there are differences of the coefficient ratio throughout the rarefied-flow regime with the most notable deviations, about 10 percent, in the hypersonic continuum. Figure 11(b) includes a comparison with the aerodynamics generated with the flight model and is labeled "flight model." The difference between this model and the flight data is very small, less than 1 percent throughout the entire regime. Fig. 12 is a similar set of comparisons using data from STS-40. Figure 12(a) shows again the comparison of the flight data with the OADDB, while Fig. 12(b) shows a comparison with the flight model. The results further confirm STS-35 comparisons, namely, the OADDB continuum aerodynamics do not satisfactorily match the flight data.

With Wind-Tunnel Data

Wind-tunnel data were collected by the Orbiter Project on a 1.0 percent scale model in a hypersonic shock tunnel facility[8] in order to examine viscous interaction effects. The test conditions were Mach numbers up to 16 and viscous interaction parameters values up to 0.06. Shown in Fig. 13 are the C_N and C_A test results, in terms of a ratio, for $\alpha = 40^0$ and $\delta_{bf} = \delta_{EL} = 0^0$, as a function of Kn. Also shown in the figure are the OADDB data and the flight model. As seen, the ratio of wind-tunnel force coefficient data is in excellent agreement with the flight model. This is somewhat fortunate, since clearly combinations of viscous and real gas effects must cancel in the ratio for these coefficients. Also shown in the figure are the ratio data from OADDB which show differences with the wind-tunnel data. (Note, at $Kn=10^{-3}$, corresponding to about 86.868 km (300,000 ft), there is a small discontinuity in the OADDB.) The differences between the OADDB data and the wind-tunnel data are small, but appear statistically significant insofar as the functional behavior of the transition into the hypersonic continuum flow is not being followed. This is not true for the flight model which shows good agreement with the tunnel data. This fact, coupled with the good agreement with the STS-35 and STS-40 flight data, provides an argument that the flight model has good predictive capabilities throughout the entire rarefied-flow regimes. Further, its application is relatively simple.

Summary

A rarefied-flow Shuttle aerodynamics model with data from the OADDB and HiRAP flight measurements has been formulated. This model is compared with flight data from STS-35 and STS-40, wind tunnel data, and the current OADDB. The method of comparison uses the force coefficient ratio in order to eliminate the dependency on density. There is excellent agreement between the flight aerodynamic model and the flight data(~1 percent) and the wind-tunnel data when expressed as a ratio. Similar comparisons with the OADDB exhibit a problem as the hypersonic continuum is approached. Namely, the OADDB hypersonic continuum coefficient ratio values show a consistent significant difference with the flight data (about 10 percent) and the wind-tunnel data.

References

[1]Throckmorton, D. A., "Shuttle Entry Aerothermodynamic Flight Research: The Orbiter Experiments (OEX) Program," AIAA Paper 92-3987, 17th Aerospace Ground Testing Conference, July 1992.

[2]Blanchard, R. C., Hinson, E. W., and Nicholson, J. Y., "Shuttle High Resolution Accelerometer Package Experiment Results: Atmospheric Density Measurements Between 60-160 km," AIAA Paper 88-0492, 26th Aerospace Sciences Meeting, Jan. 1988.

[3]Operational Aerodynamic Design Data Book, STS 85-0118 CHG 3, September 1991.

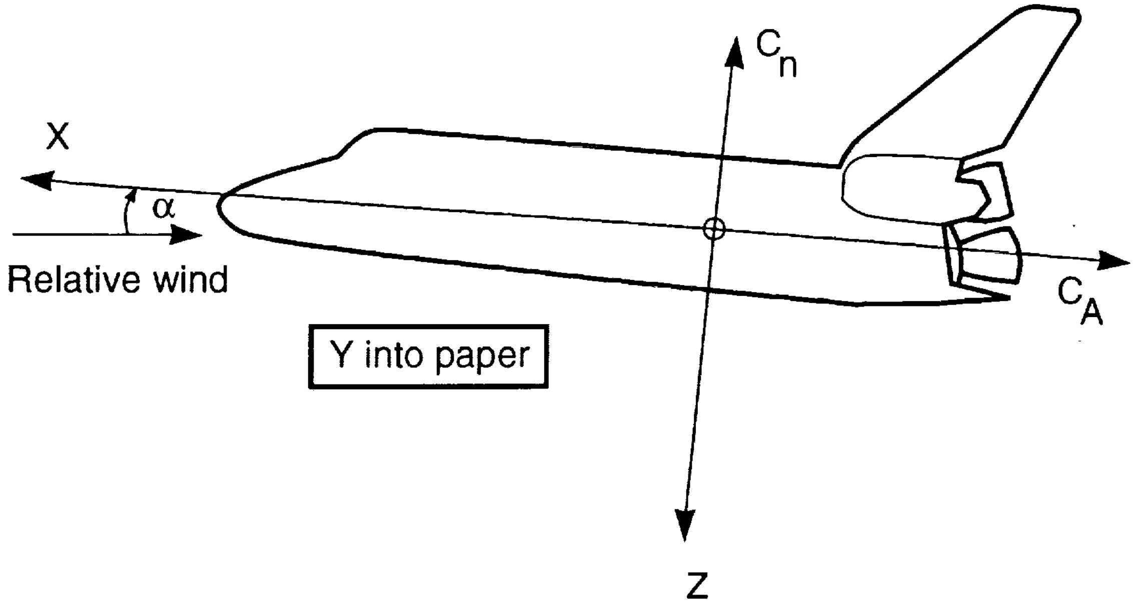
[4]Blanchard, R. C., "Rarefied Flow Lift-to-Drag Measurements of the Shuttle Orbiter. ICAS Proceedings 1986-15th Congress of the International Council of the Aeronautical Sciences, Vol. 2, P. Santini and R. Stauenbiel, eds., 1986, pp. 1421-1430. (Available as ICAS-86-2.10.2.)

[5]Oakes, K. F., Findlay, J. T., Jasinski, R. A., and Wood, J. S., "Final STS-35 'Columbia' Descent BET Products and Results for LaRC OEX Investigations", NASA CR-189569, Nov. 1991.

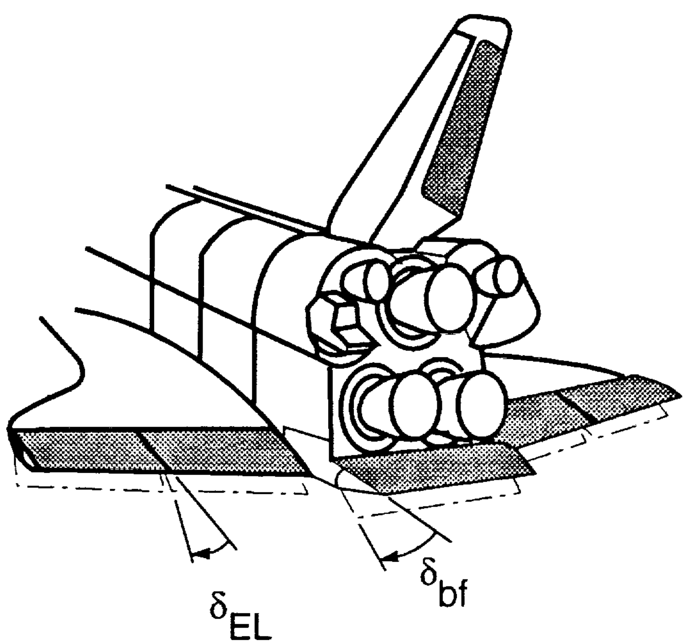
[6]Oakes, K. F., Wood, J. S., and Findlay, J. T., "Final Report: STS-40 Descent BET Products -Development and Results," NASA CR-189570, Nov. 1991.

[7]U.S. Standard Atmosphere, 1976 NOAA, NASA, USAF, Oct. 1976.

[8]"Aerodynamic Design Substantiation Report-Vol. I: Orbiter Vehicle", Rockwell International Space Div., SD74-SH-0206-1H, Jan. 1975.

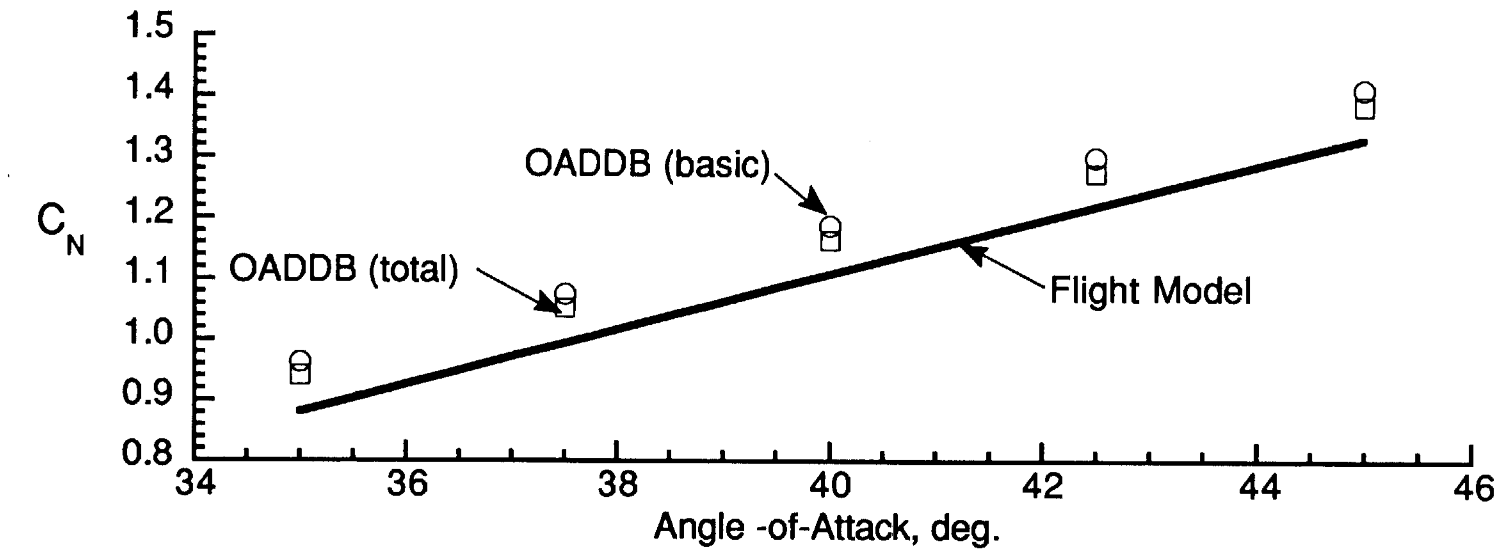


(a) for aerodynamic coefficients.

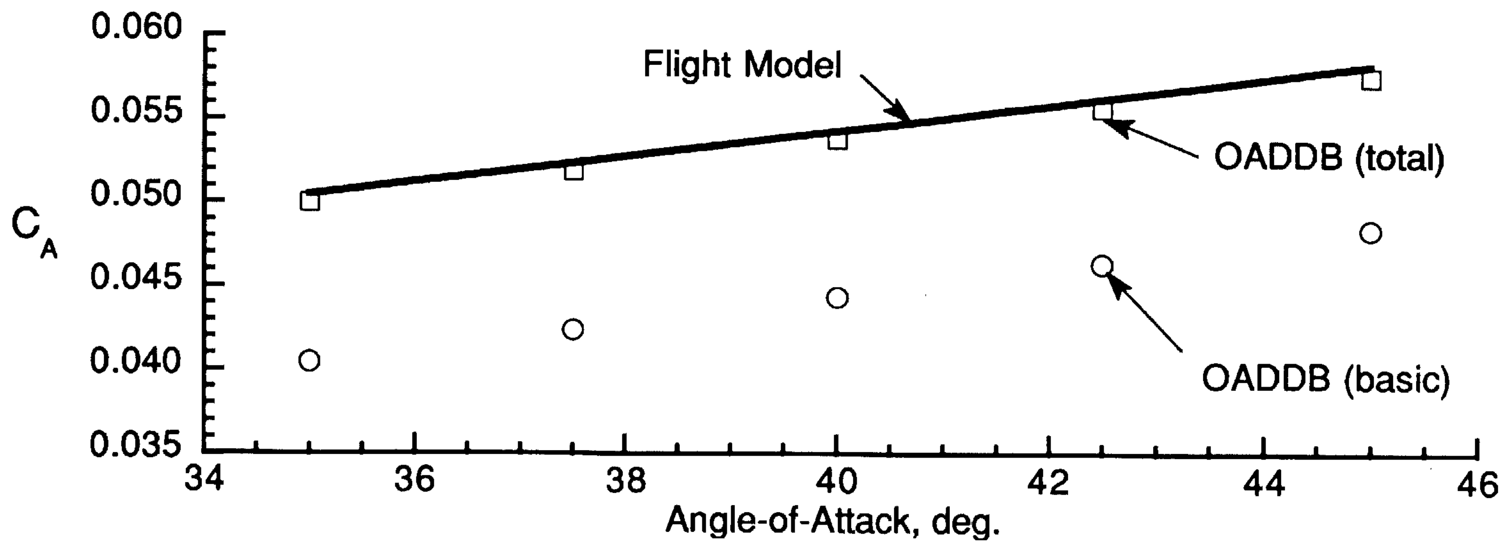


(b) for aerodynamic control surfaces.

Fig. 1 Sign conventions.

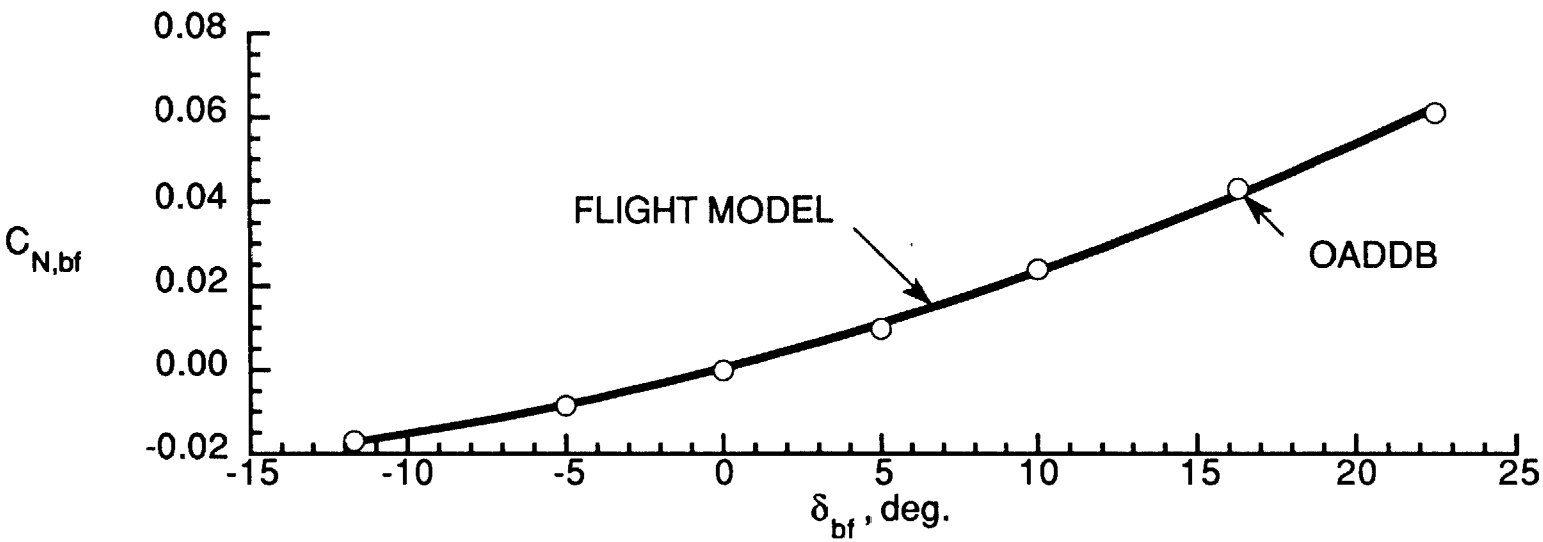


(a) Normal axis coefficient.

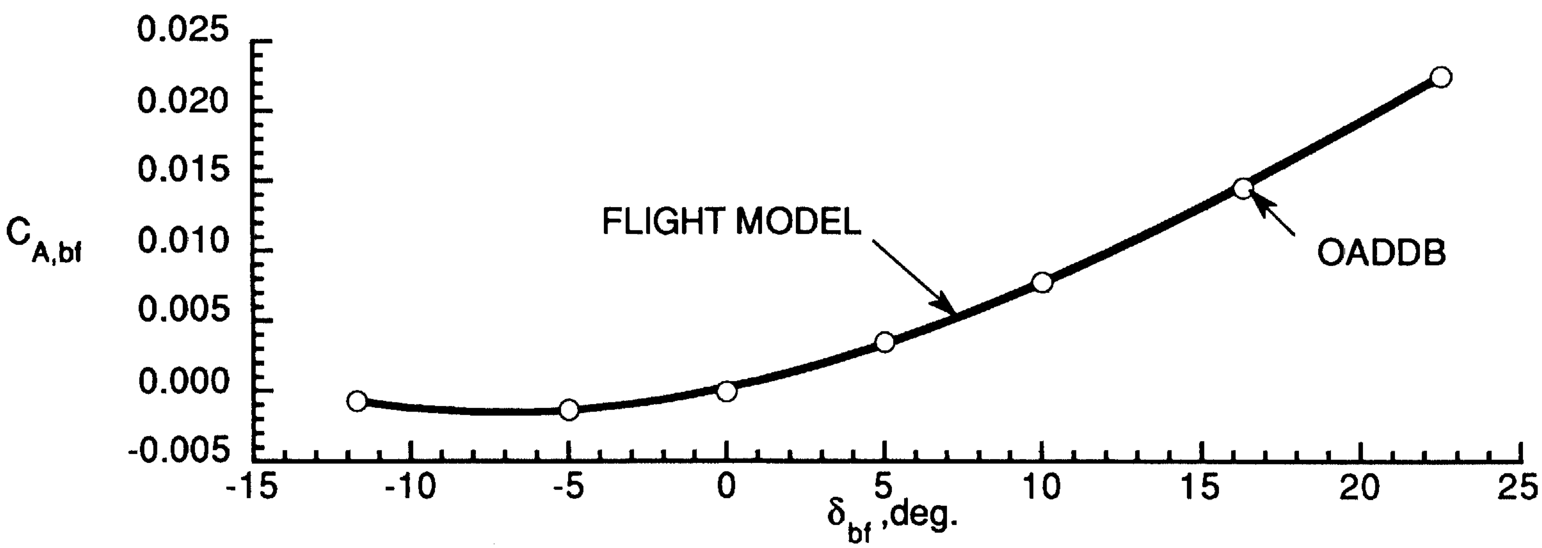


(b) Axial axis coefficient.

Fig. 2 Body axes coefficients comparison - *hypersonic continuum*.

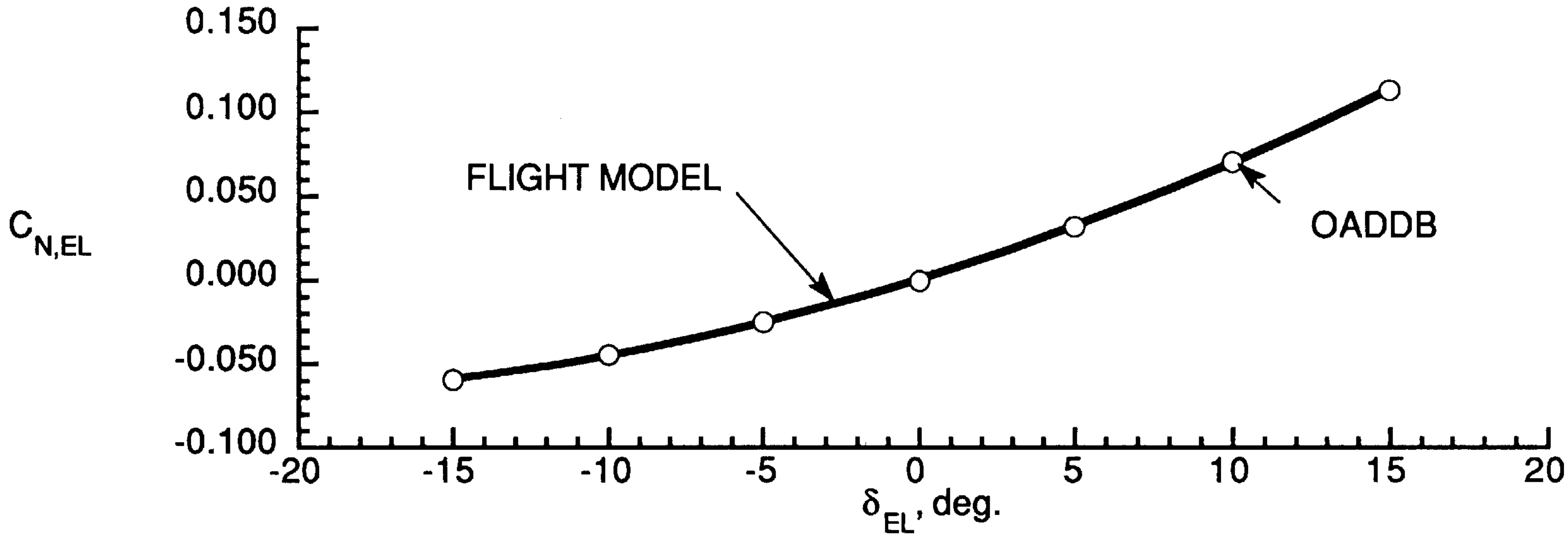


(a) Normal axis coefficient increment.

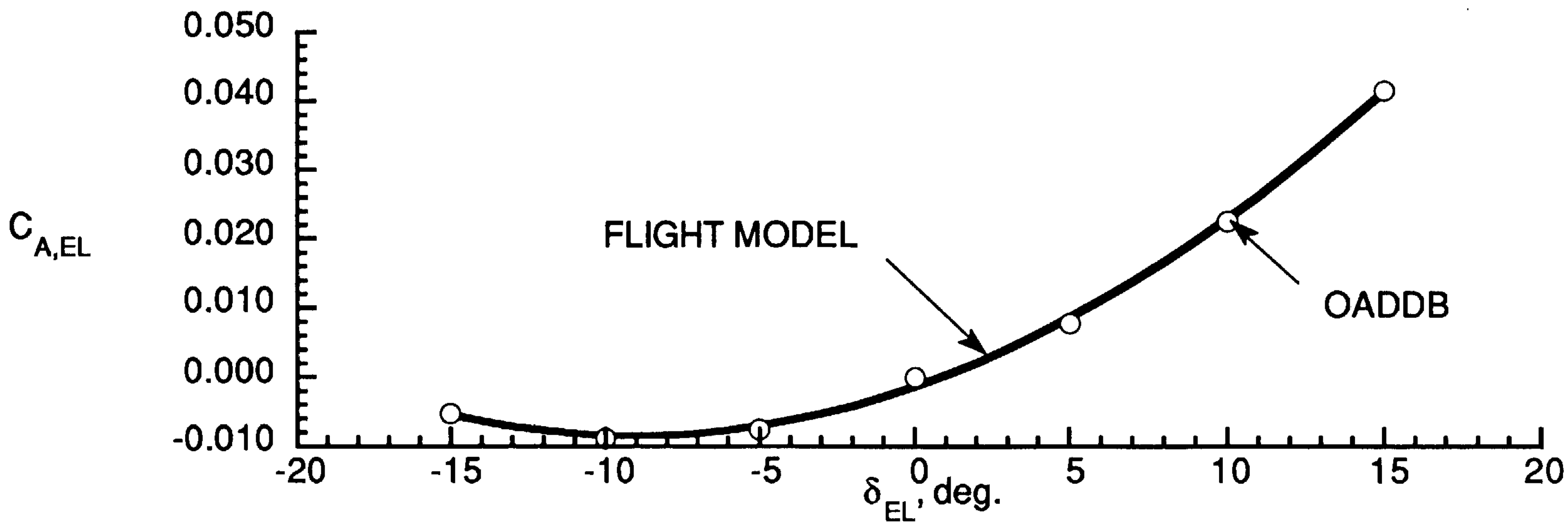


(b) Axial axis coefficient increment.

Fig. 3 Body flap coefficients comparison ($\alpha = 40^{o}$).

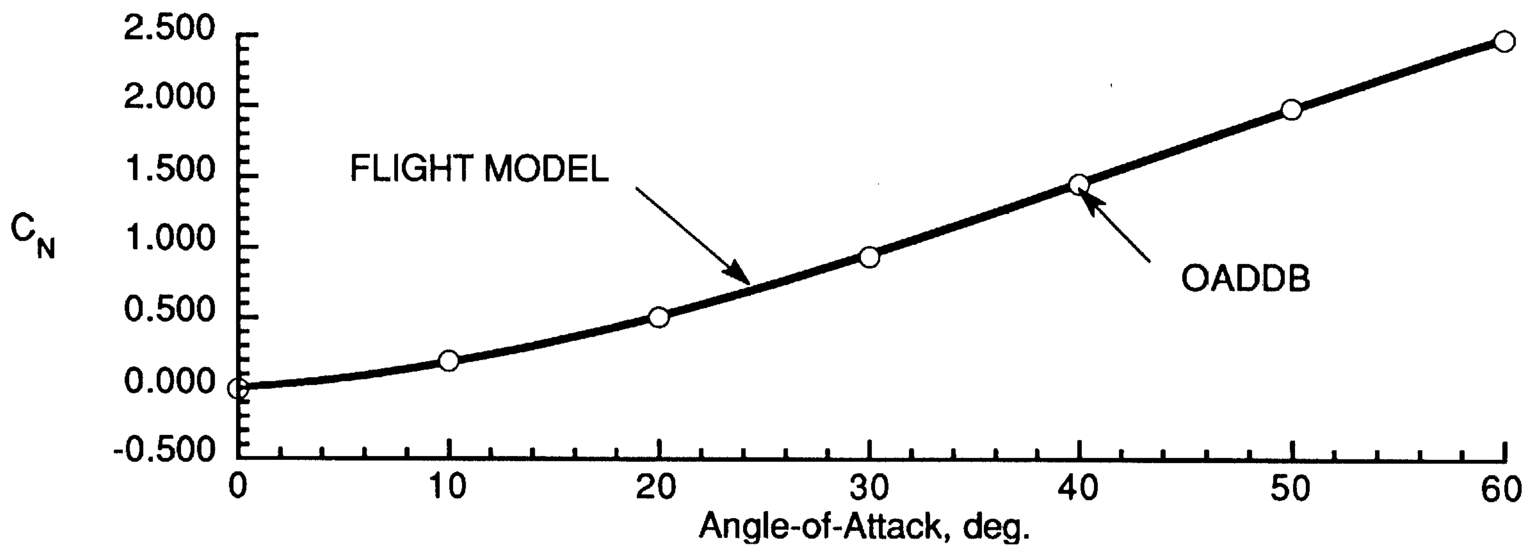


(a) Normal axis coefficient increment.

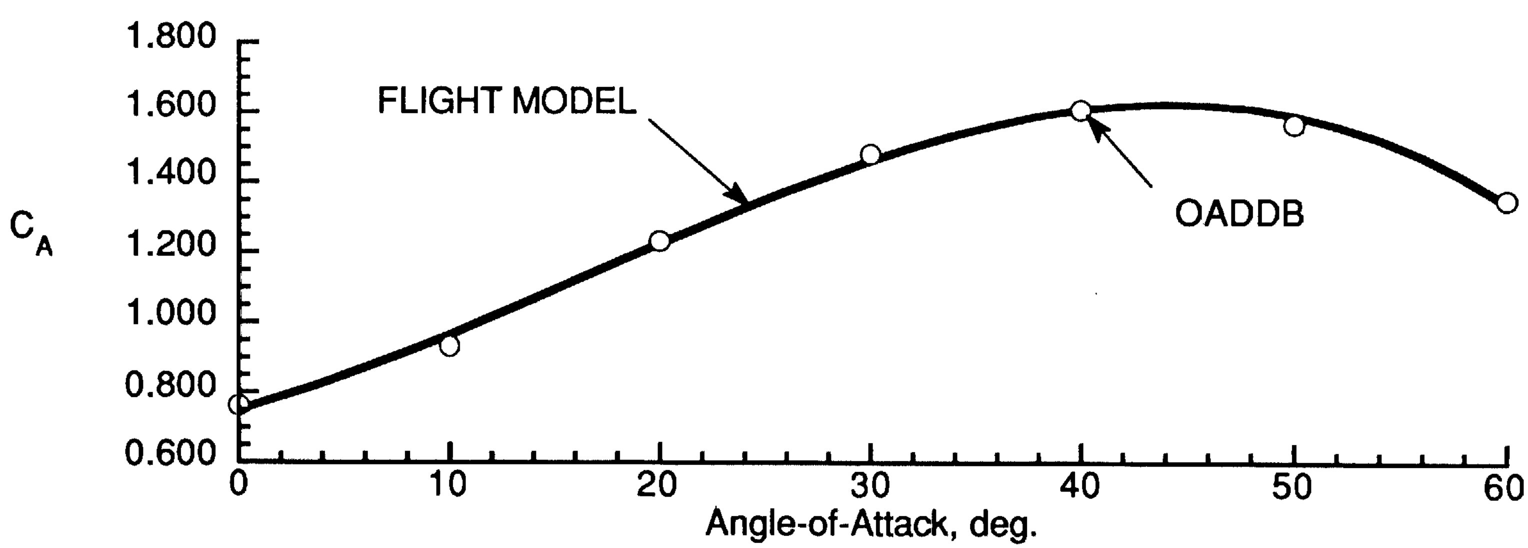


(b) Axial axis coefficient increment.

Fig. 4 Elevon coefficients comparison ($\alpha = 40^{o}$).

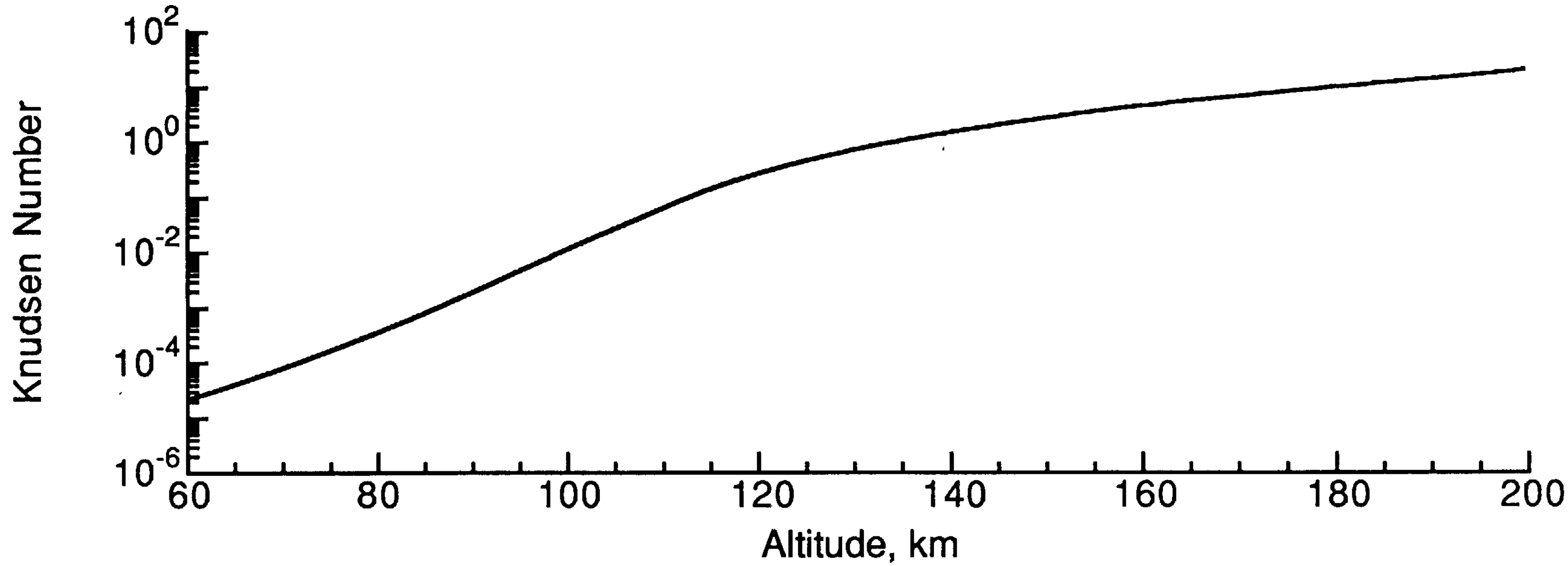


(a) Normal axis coefficient.

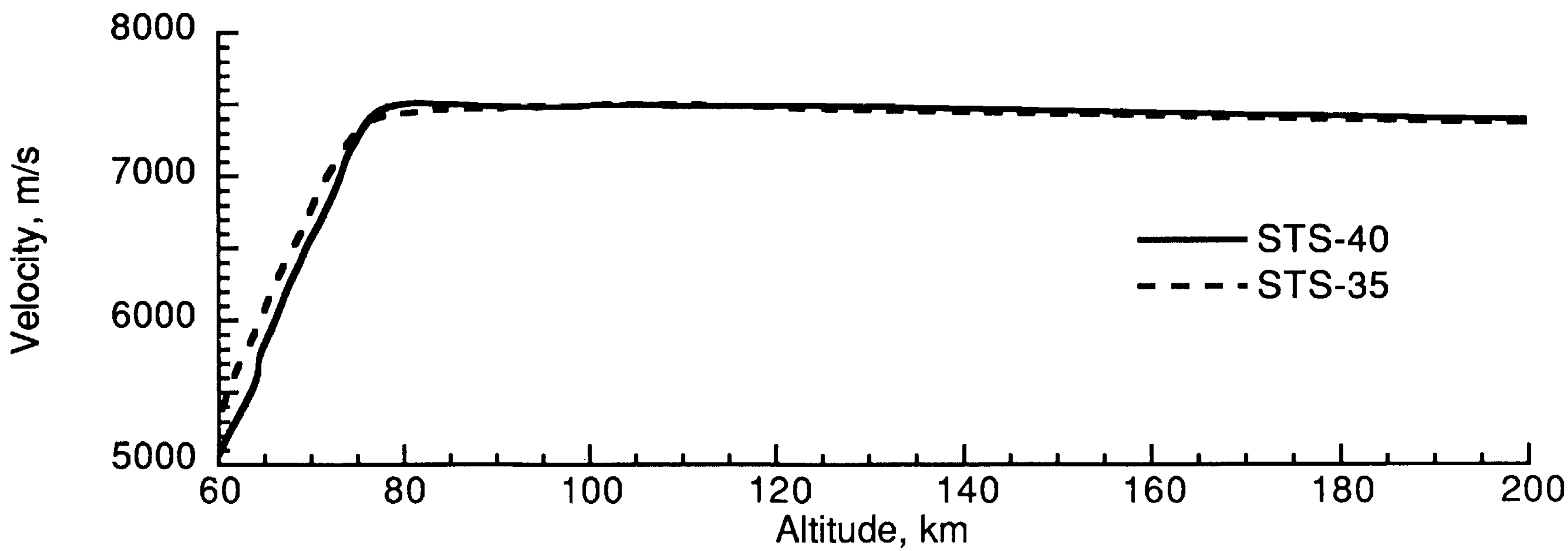


(b) Axial axis coefficient.

Fig. 5 Body axes coefficient comparison - *free molecular flow.*

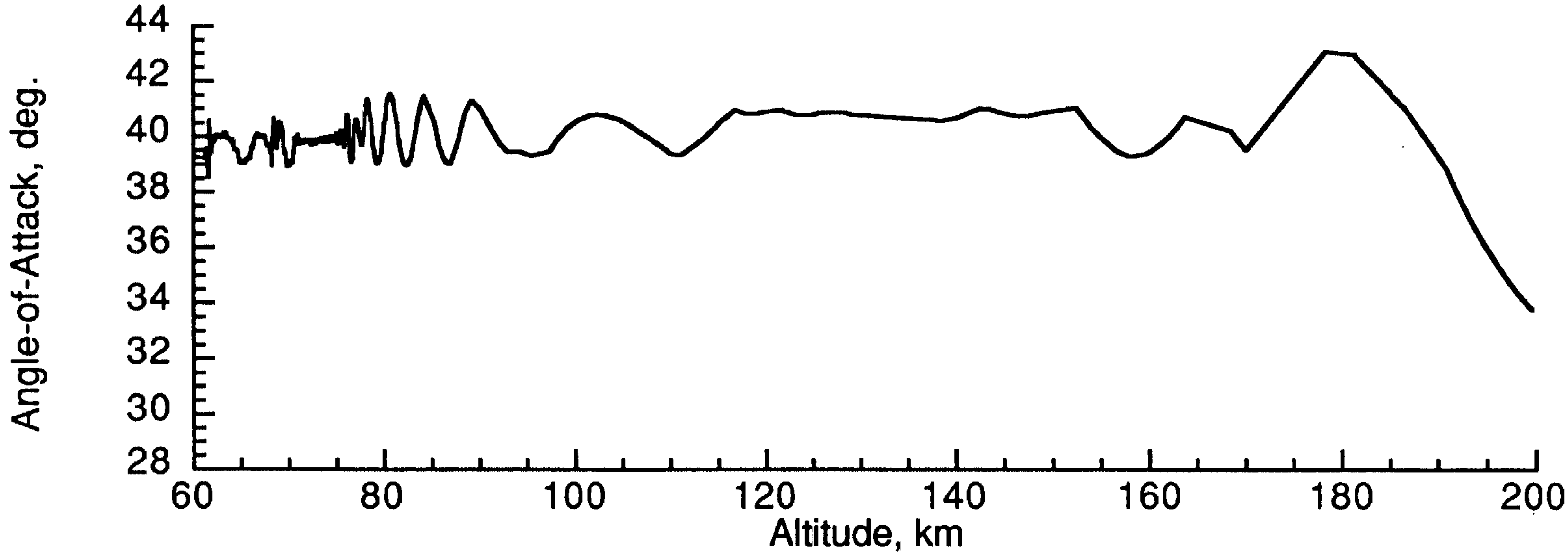


(a) Knudsen number profile (1976 U.S. Standard).

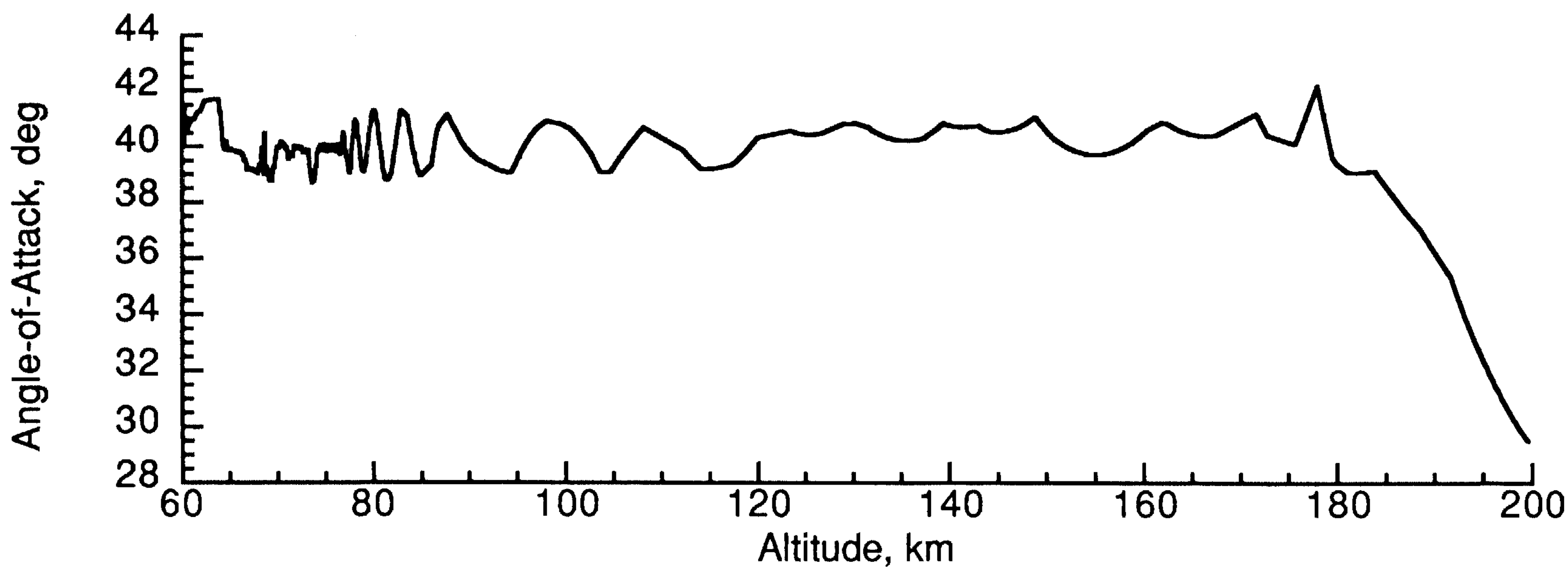


(b) Velocity profiles.

Fig. 6 Orbiter flight conditions.

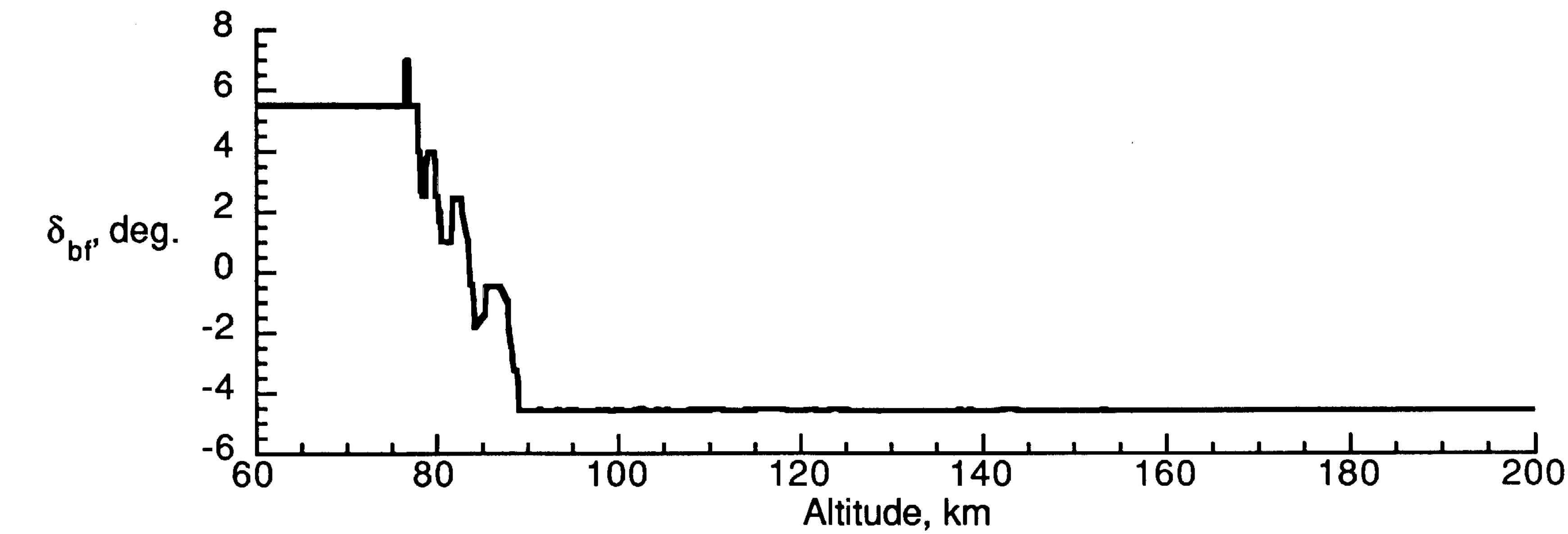


(a) STS-35.

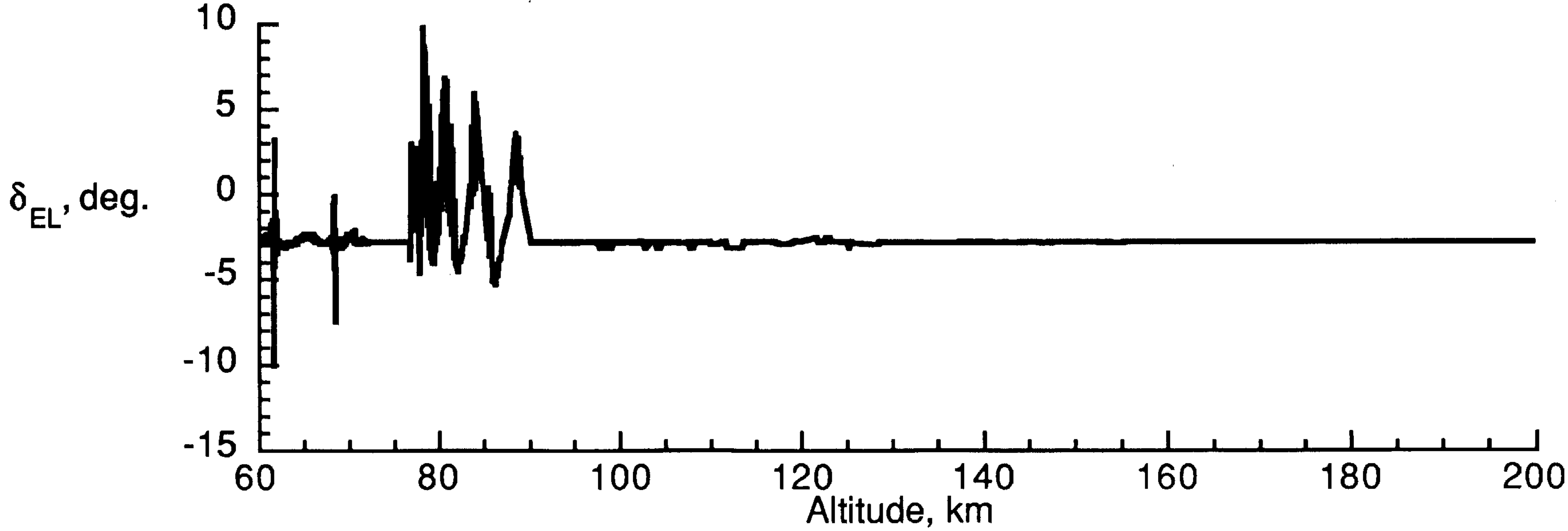


(b) STS-40.

Fig. 7 Orbiter angle-of-attack flight profiles.

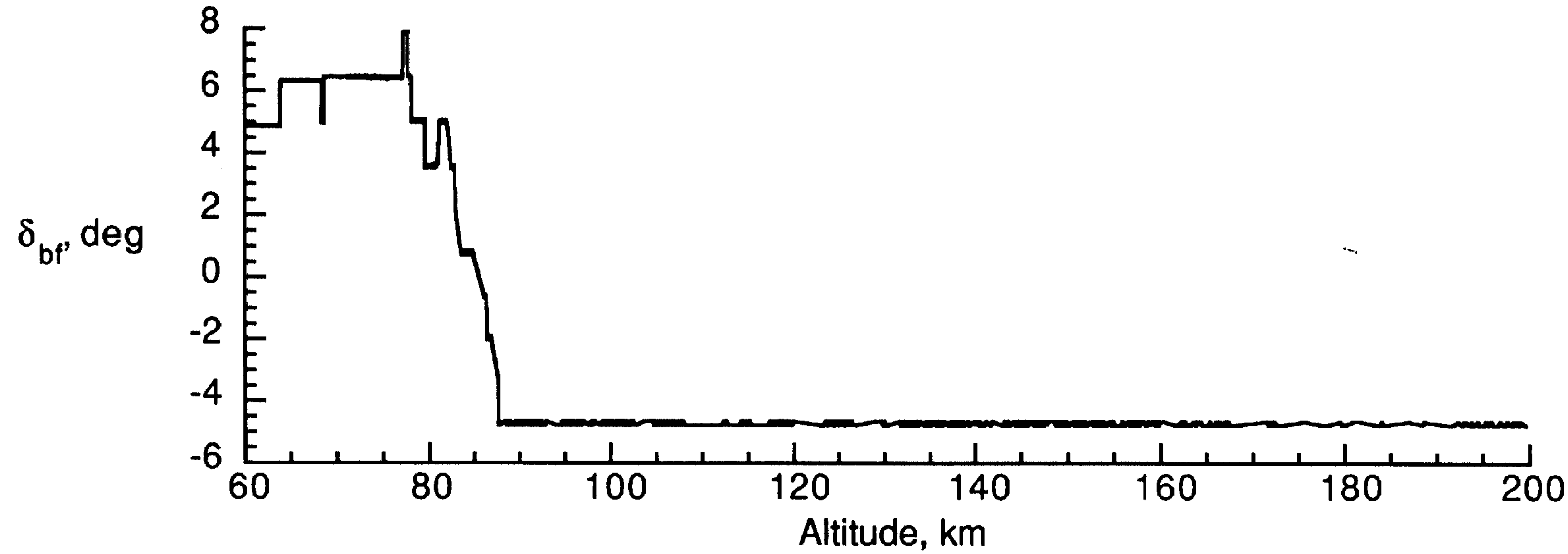


(a) Body flap.

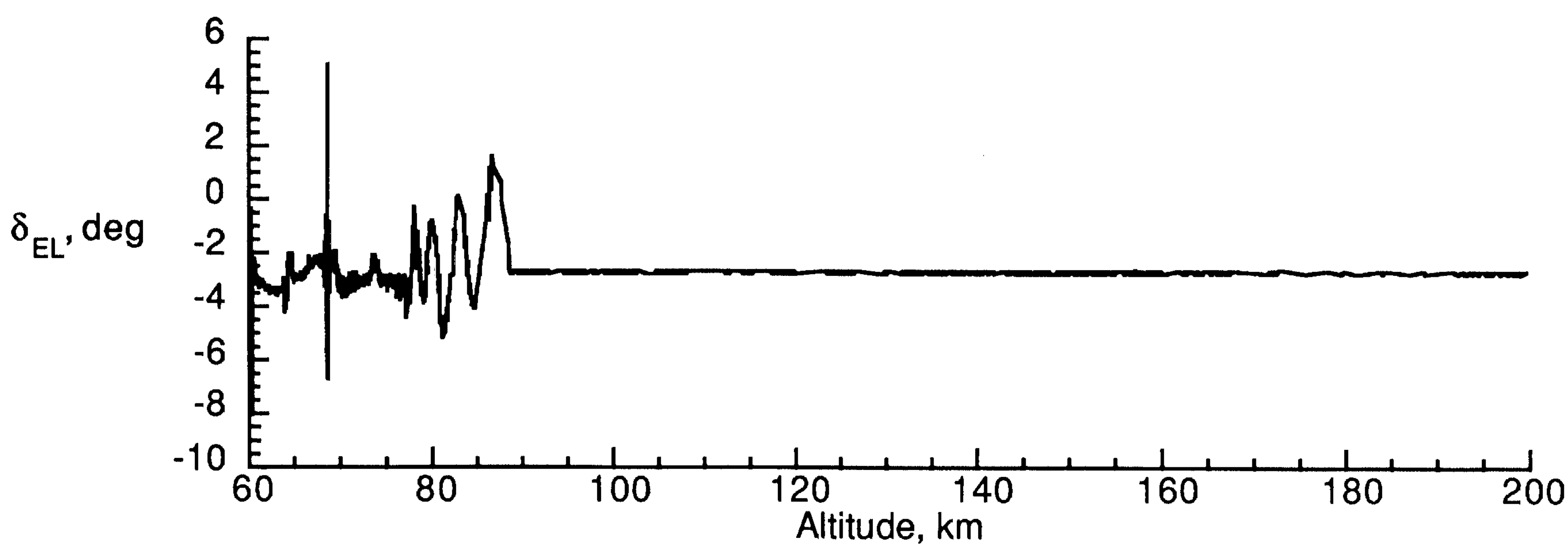


(b) Elevon.

Fig. 8 Orbiter control surface settings for STS-35.

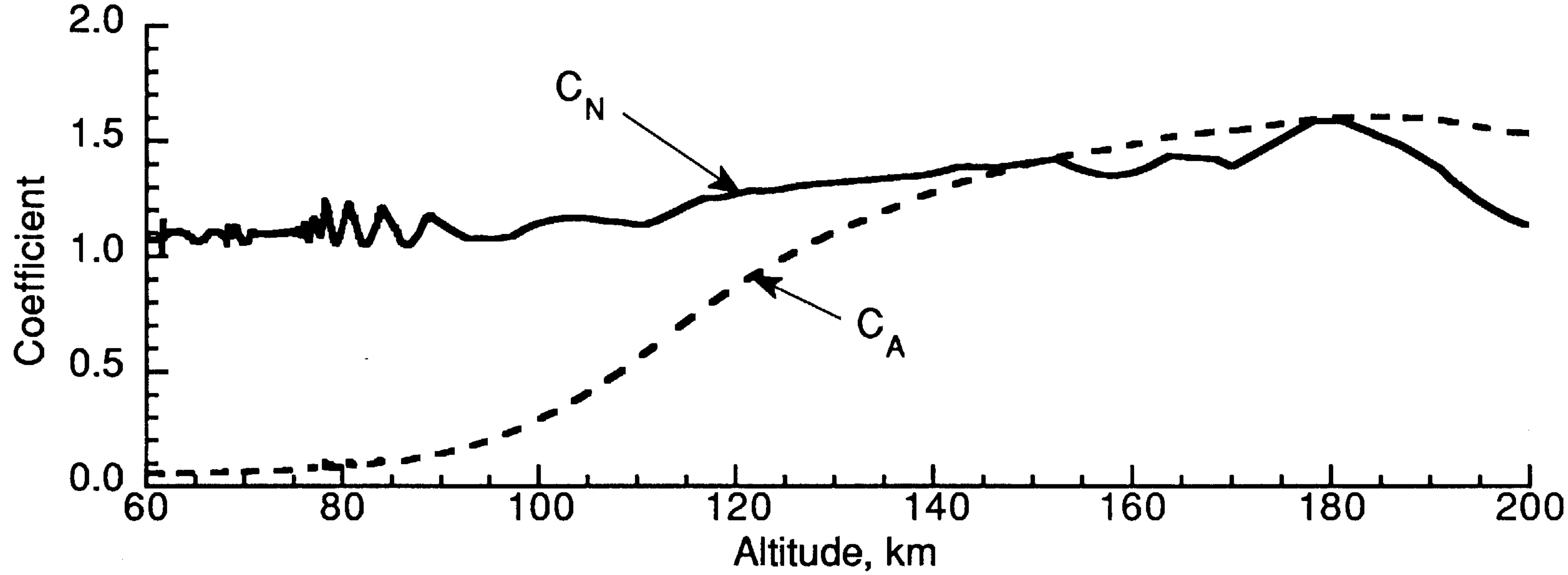


(a) Body flap.

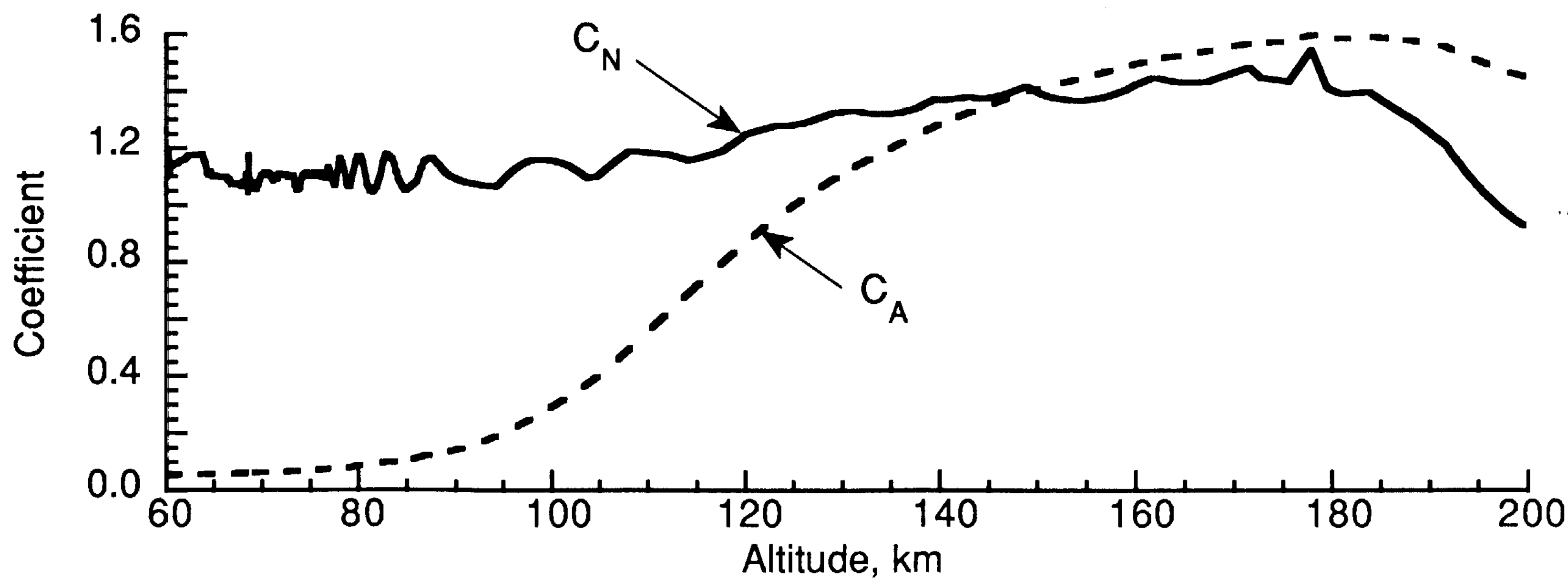


(b) Elevon.

Fig. 9 Orbiter control surface settings for STS-40.

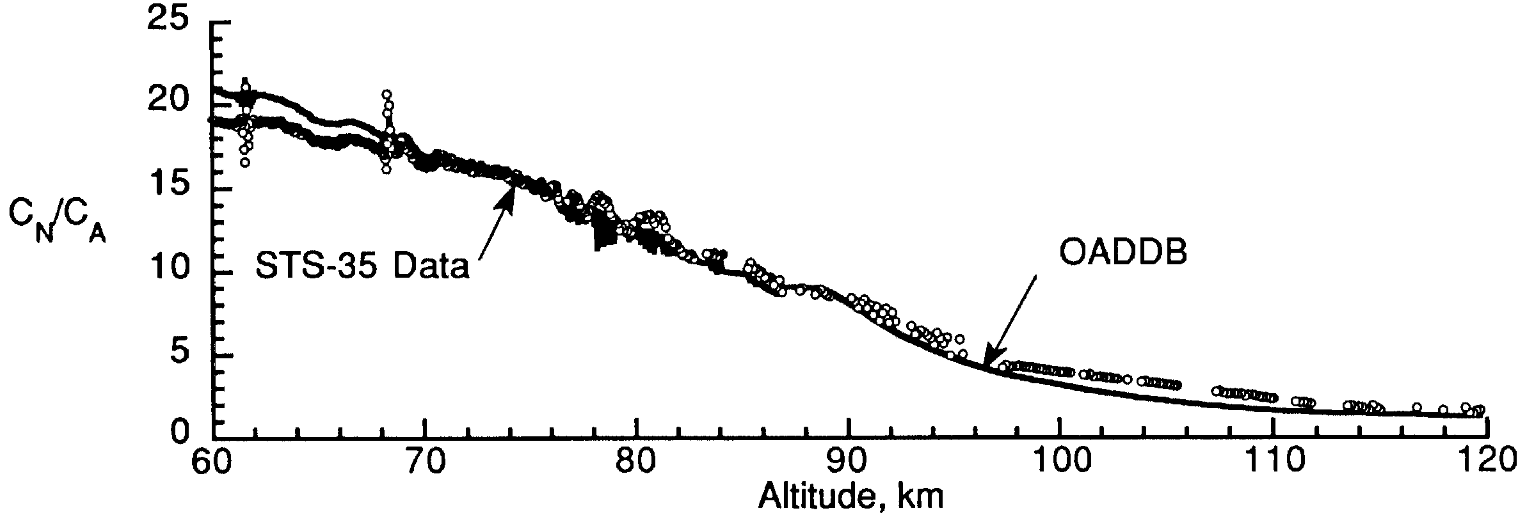


(a) STS-35.

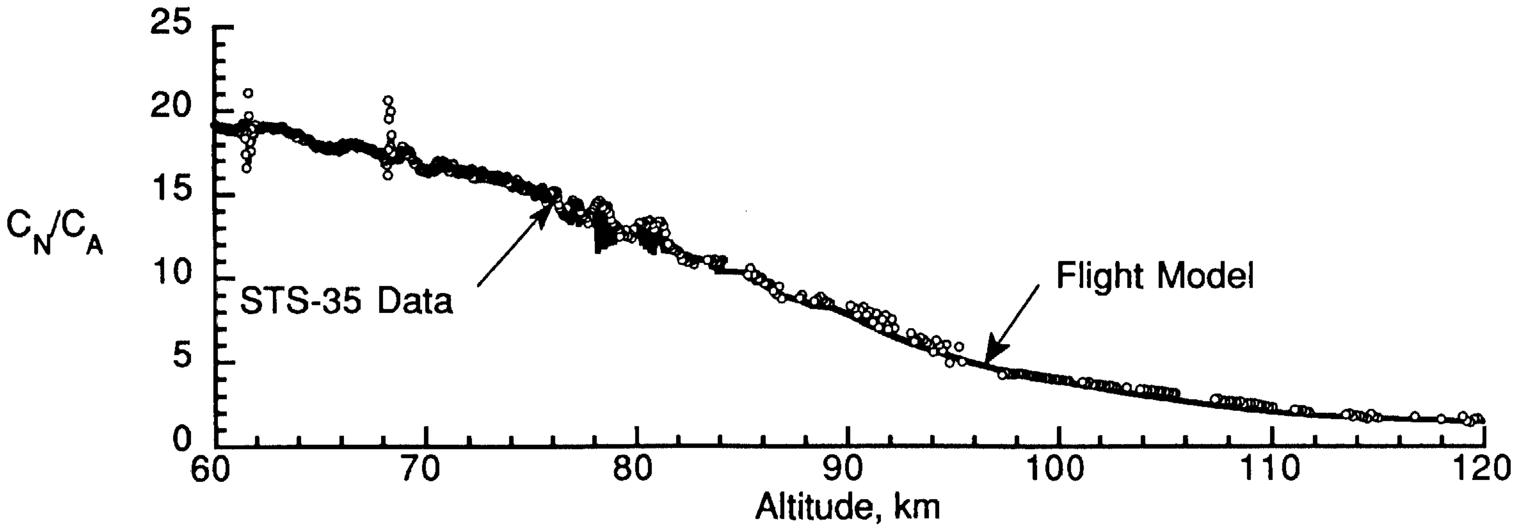


(b) STS-40.

Fig. 10 Flight aerodynamic model force coefficients.

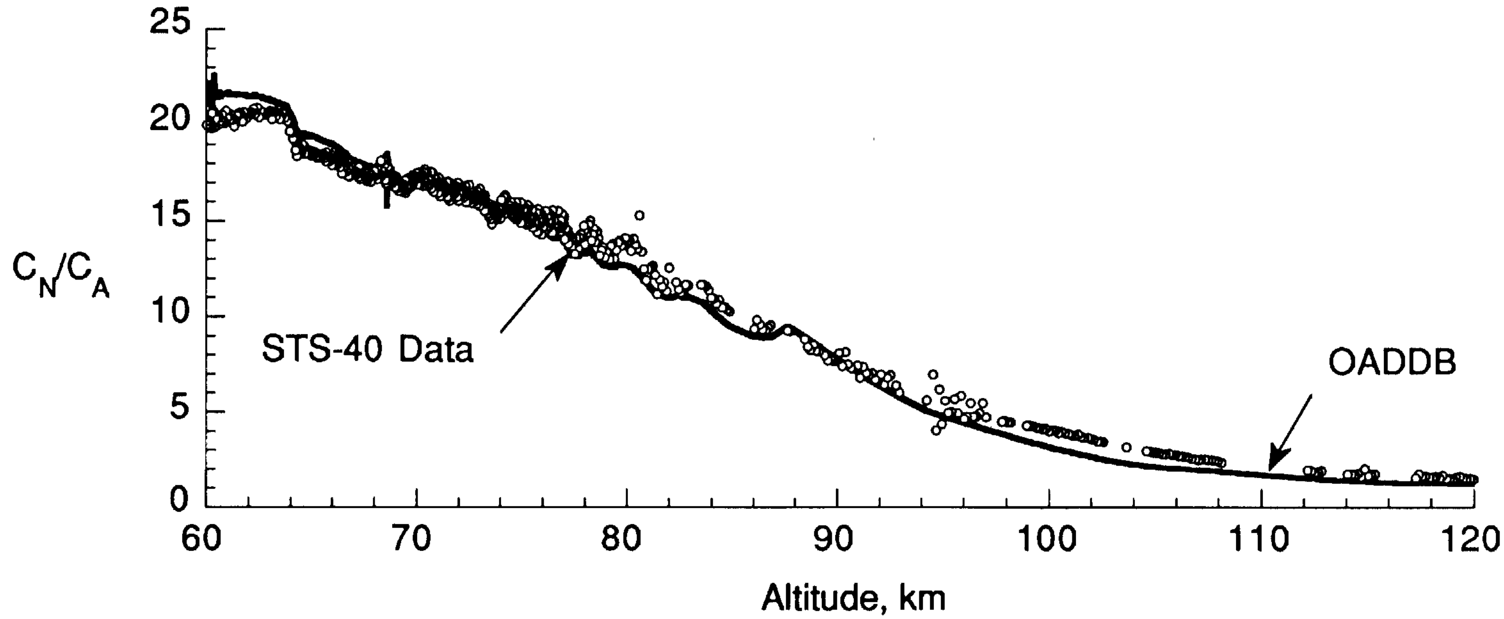


(a) OADDB predictions.

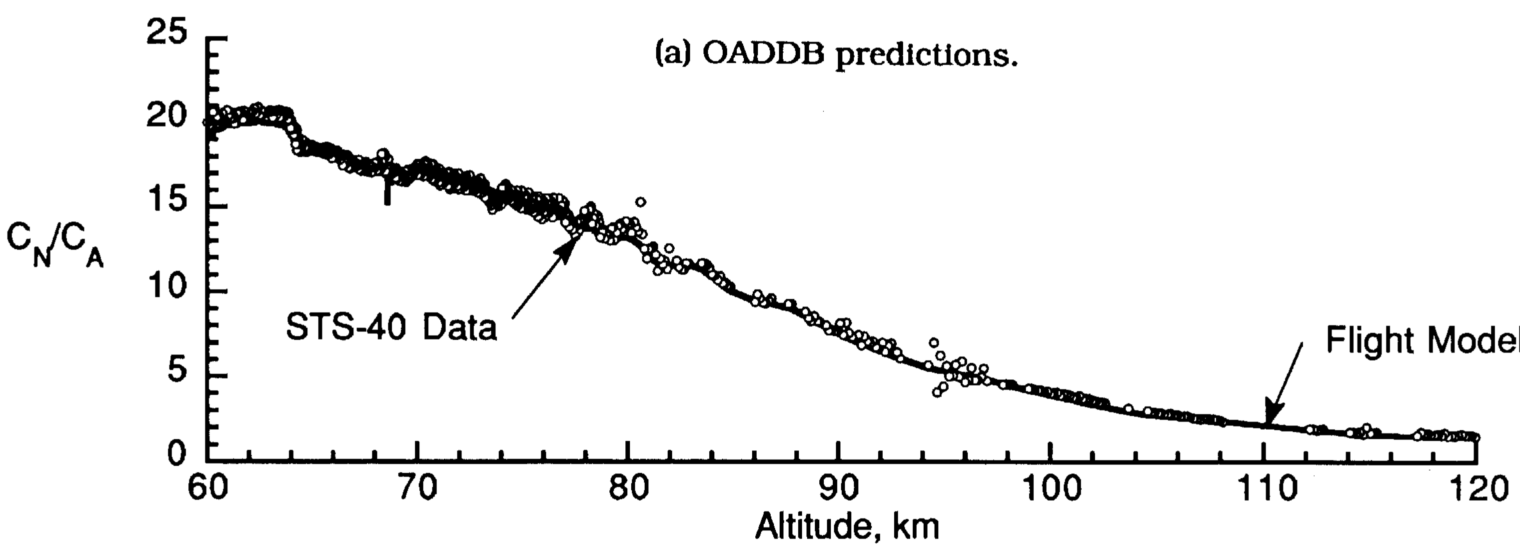


(b) Flight model predictions.

Fig. 11 Comparison of predictions with STS-35 measured acceleration ratios.



(a) OADDB predictions.



(b) Flight model predictions.

Fig. 12 Comparison of predictions with STS-40 measured acceleration ratios.

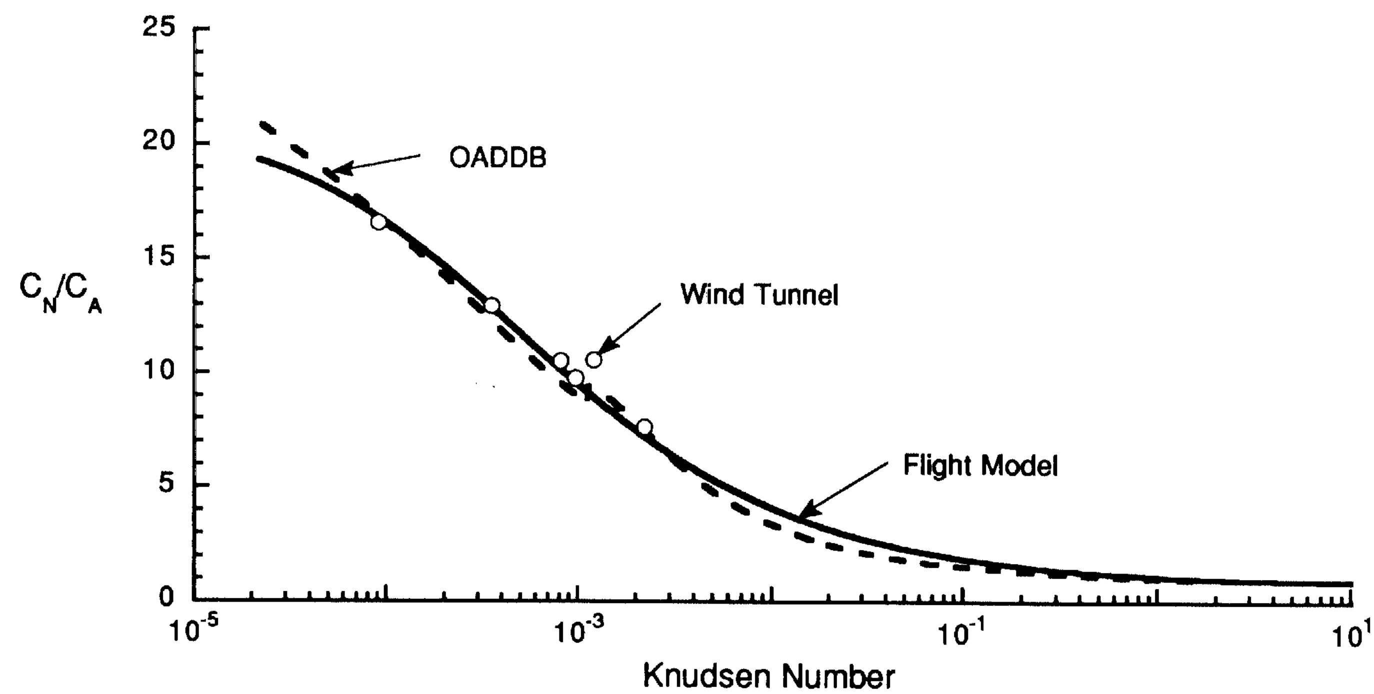


Fig. 13 Body axes force coefficient - ratio comparison ($\alpha = 40^{o}$, $\delta_{bf} = \delta_{EL} = 0^{o}$).

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Robert C. Blanchard, Kevin T. Larman
and Christina D. Moats

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

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13. ABSTRACT *(Maximum 200 words)*

An existing rarefied-flow shuttle aerodynamic model has been updated with data from the latest Operational Aerodynamic Design Data Book (OADDB). This aerodynamic model spans from the hypersonic continuum to the free molecule-flow regime. This model had been formulated from a combination of data from initial version of the OADDB and earlier flight data from the High Resolution Accelerometer Package (HiRAP) experiment. The model includes normal and axial hypersonic continuum coefficient equations as functions of angle-of-attack, body flap deflection, and elevon deflection. Normal and axial free molecule flow coefficient equations as a function of angle-of-attack are presented, along with flight derived rarefied-flow transition bridging formulae. The complete model is described and compared with data from the updated OADDB, applicable wind-tunnel data, and recent flight data from STS-35 and STS-40. The hypersonic continuum aerodynamic force coefficient ratio using the flight-derived model is in good agreement with the wind-tunnel data and the flight measured coefficient ratio on STS-35 and STS-40. However, the current data book does not predict the flight data coefficient ratio, nor is it in agreement with the wind-tunnel coefficient ratio data.

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