Shuttle Orbiter High Resolution Accelerometer Package Experiment: Preliminary Flight Results

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A description of the HiRAP experiment designed to measure rarefied flow aerodynamic accelerations is given. The ground test calibration factors as well as post-flight data processing techniques to extract aerodynamic accelerations are discussed and applied to the recorded reentry data of the recent STS-6 Shuttle Orbiter flight. The ratio of the measured normal-to-axis aerodynamic accelerations during reentry is used to obtain the first flight measurement of the L/D of a winged entry vehicle in the rarefied flow flight regime. The initial flight results on L/D are compared with current predictions which are based upon theoretical and empirical considerations. The measured free-molecule flow L/D value (0.10 ± 0.3) is higher than that predicted by a factor of about 2.5, indicating either that surface reflection is not completely diffuse as is currently assumed, or that the vehicle does not reside fully in the free molecule flow regime. In the rarefied flow transition regime, the Shuttle data book bridging formula fits the flight data adequately. Upper altitude density profiles are also deduced from the measurements and presented. The density profile show a wave phenomenon with amplitude of about 60% relative to a standard model.

Nomenclature

A_x, A_y, A_z	= acceleration in the x, y, and z channels
A_m	= measured acceleration
C	= aerodynamic coefficient
C_A	= axial force coefficient
C_c	= continuum flow aerodynamic coefficient
C_D	= drag coefficient
$C_{\rm FMF}$	= free-molecule flow aerodynamic coefficient
C_L	= lift coefficient
C_N	= normal force coefficient
Cr	= Chapman-Rubesin proportionality factor
C_{tr}	= transitional flow aerodynamic coefficient
Kn	= Knudsen number for $\ell = 12.0609$ m (39.57 ft)
L/D	= lift-to-drag ratio
M	= Mach number
p,q,r	= angular rates about the principal axis
$\dot{p},\dot{q},\dot{r}$	= angular accelerations about the principal axis
R	= A_z/A_x ratio of measured acceleration
Re	= Reynolds number
S/M	= spacecraft area to mass ratio
Si, Sr	= incident and reemitted speed ratios
v	= spacecraft velocity
α	= angle of attack
α_2	= partial energy accommodation coefficient
$\Delta A_x, \Delta A_y, \Delta A_z$	= induced accelerations into the x, y, and z channels
μg	= micro-g (9.8×10^{-6} m/s^2)
ρ	= mass density
ρ_{62}	= mass density from the 1962 standard atmosphere
Ω	= rotational matrix

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Introduction

An experiment using an orthogonal triaxial set of sensitive linear accelerometers is being conducted on the Shuttle Orbiter. This experiment, called High Resolution Accelerometer Package (HiRAP), provides accurate measurements of low-level (down to 1.0 μg) aerodynamic accelerations along the Shuttle Orbiter's principal axes during initial reentry into the atmosphere, i.e., in the rarefield-flow regime. There are two identical experiment packages, one currently installed on the Orbiter Vehicle (OV)-099 (the "Challenger") which on April 9, 1983, successfully completed its maiden flight, and the other recently installed on OV-102 (the "Columbia").

The aerodynamic acceleration data from the HiRAP experiment are being used to calculate rarefied aerodynamic performance parameters and/or atmospheric properties over several flights starting with the recent STS-6 mission. These flight data support advances in the prediction of aerodynamic behavior of winged entry vehicles in the high-speed, low-density flight regime, including free molecular flow and the transition into the hypersonic continuum. Aerodynamic performance under these conditions cannot be simulated in ground facilties; consequently, current predictions rely solely upon computational techniques.[1] For improvement or advances, these techniques depend upon actual flight data to serve as "benchmarks," particularly in the transition regime between free molecule flow and continuum flow where two distinct computational techniques are used, namely the discrete (e.g., Monte Carlo) and continuum (e.g., Navier-Stokes) computation techniques.

Advancements in rarefied aerodynamics of winged entry vehicles may also prove useful in the design of future advanced orbit transfer vehicles (OTVs).[2] Such OTVs may use aerodynamic braking and/or maneuvering to dissipate excess orbital energy into the upper atmosphere upon return to low-orbit rendezvous with a Space Transportion System or Space Station. A key aerodynamic parameter in the design of an OTV is the lift-to-drag ratio (L/D) which is measured directly in this experiment. Further, an OTV may require a flight-proven sensitive onboard accelerometer system to overcome uncertainties in the upper atmosphere. The experience gained from the planned multiple flights of HiRAP equipment may provide valuable test data toward future navigation system development. In addition, the experiment provides data on key atmosphere properties (e.g., density) in a region of flight which is not readily accessible to orbital vehicles, nor regularly assessed by meteorological soundings.

This paper presents a discussion of the objectives and goals of the experiment, a description of the experiment equipment, including installation on the Shuttle Orbiter, a discussion of the flight data reduction schemes, and a presentation of the flight data. It also presents the preliminary flight results from the recent STS-6 mission on the L/D in the rarefied flow regime and the density profile at the base of the thermosphere.

Experiment Objective and Goals

The objective of the HiRAP experiment is measurement of low-level aerodynamic accelerations, principally in the rarefied-flow flight regime. The measurement of low-level aerodynamic accelerations during flight requires technical advances in system design as well as post-flight data reduction schemes. The major technical issues addressed by the HiRAP experiment are: 1) can the reentry aerodynamic signal be extracted from the flight measurements in the presence of all acceleration inputs, e.g., vehicle thrusts, vibration, etc., and 2) can a flight instrument be designed, manufactured, calibrated, and flown such that μg levels of absolute accuracy are achieved? The initial phase of the experiment consists of addressing these, and other, technical issues through demonstration by multiple flights on the Shuttle Orbiter. In addition, during the initial flights, the first flight measurement of the L/D of a winged entry vehicle in the free molecule flow and transition flow flight regime will be obtained. This is possible since determination of L/D does not require atmospheric measurements. In addition, some preliminary calculations on upper altitude atmospheric properties are also possible with the HiRAP data. Currently, these calculations depend upon prior knowledge of aerodynamic force components, for example, normal force coefficient.

The final phase for the HiRAP experiment will combine the HiRAP system with an atmospheric density measurement instrument, the Shuttle Upper Atmosphere Mass Spectrometer (SUMS),[3] planned for OV-102. HiRAP and SUMS will provide for the direct measurement of the in-situ rarefied flow aerodynamic coefficients during reentry.

Figure 1 shows the approximate anticipated measurement range of the HiRAP in terms of a modified viscous parameter and altitude for a typical simulated Shuttle Orbiter reentry. The modified viscous parameter is defined as:

$$M\sqrt{Cr}/Re$$

Also on the figure are the HiRAP measurement range in relation to that of existing force measurement equipment, the Aerodynamic Coefficient Identification Package (ACIP) used for lower altitude aerodynamic acceleration measurement, and the Inertial Measurement Unit (IMU) used for Orbiter navigation. Also shown are the ranges of corresponding instrument systems for obtaining atmospheric information. For example, at low altitudes an existing development flight pressure transducer is used as a companion atmospheric measurement for either the IMU or ACIP to obtain aerodynamic coefficients. At high altitudes in the rarefied flow regime, the SUMS system provides the atmospheric measurements to accompany the HiRAP measurements. However, the SUMS system was not available for the STS-6.

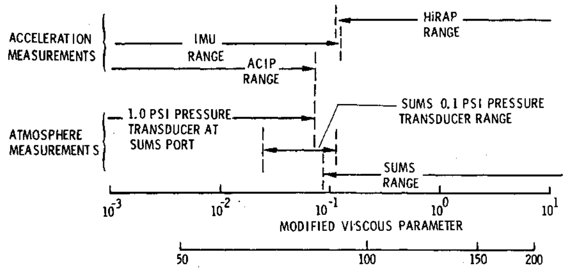

Fig. 1 Measurement range of flight sensors for investigations of the Shuttle Orbiter's rarefied flow aerodynamic.

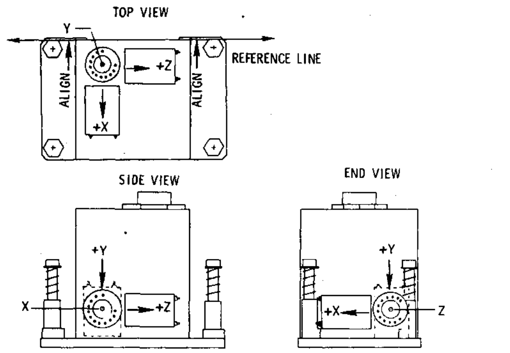

Fig. 2 Location of accelerometer triad within HiRAP.

Equipment Description

Specifications

The HiRAP linear accelerometers are the pendulous type (gas damped) and are not compensated for thermal variations. The location of the miniature accelerometer sensor within the package is shown in Fig. 2. A temperature transducer is included inside each accelerometer and is designed to provide fine and coarse temperature monitor output. These outputs are used to compensate the accelerometer output thermally in the post-flight processing described later. Table 1 lists some of the general design specifications of the HiRAP system and its three identical sensors.

Instrument Calibration

Rarefied aerodynamics determination from flight data requires accurate measurements of acceleration, down to μg levels. Achieving this accuracy requires special attention to calibration testing, careful application of calibration factors to the flight data, and unique modeling of the sensors and physical parameters. Several series of tests were performed on the two HiRAP units during manufacture to determine bias and scale factors at various constant temperatures accurately, including the range anticipated during flight. In general, a good description of the behavior of the instrument was obtained during laboratory tests to achieve a level of accuracy less than 10 μg depending upon the actual temperature variations that occur during the flight. The flight temperatures obtained from the transducers within each sensor are necessary factors in obtaining this high level of accuracy as described later.

System Installation

The location of the HiRAP on the Shuttle Orbiter is shown in Fig. 3. The HiRAP is colocated with ACIP and shares data handling electronics as well as the data recording device (magnetic tape recorder) which is remotely located. The input axes of each sensor are accurately aligned with the Shuttle Orbiter's principal body axis system to an angular accuracy of less than three minutes of arc.

Flight Data Reduction

Flight Data Display

The extraction of the aerodynamic signal from HiRAP flight data starts with the display of the flight data from each sensor. For the Shuttle Orbiter STS-6 mission, the "raw" flight data time history from each HiRAP sensor is shown on Figs. 4, 5, and 6. The data are given in terms of digital counts where 1 count is equivalent to 0.9765 μg. The data of each figure cover the entire time period from the deorbit burn maneuver (between 64,500 to 64,545 s GMT) to touchdown which occurs at 68,071 s GMT on day 99. As anticipated, all sensors saturate during reentry beyond the entry interface which is defined as an altitude of about 400,000 ft. However, the Y sensor saturates at a lower altitude than the X and Z sensors and returns on scale after landing.

Several features are seen in the raw flight data. First, the many spikes are due to components of thrust from the reaction control system (RCS). The unusual "square wave" at 65,125 s is the forward RCS fuel dump which lasts about 30 s for this flight. This procedure terminates the usage of the forward jets to control the vehicle attitude, and the jets on the aft pods are used thereafter. Also evident on the figures is a bias on each of the three channels where the zero reference is 8,192 counts. This bias has two principal components. The largest component is correctable with ground calibration temperature data. The remaining bias is small, about 3%, but variable, and referred to as the "turn on" bias. This unpredictable bias is removed each flight through an in-flight calibration procedure during the phase of flight when the accelerations are typically less than the resolution of the instrument.

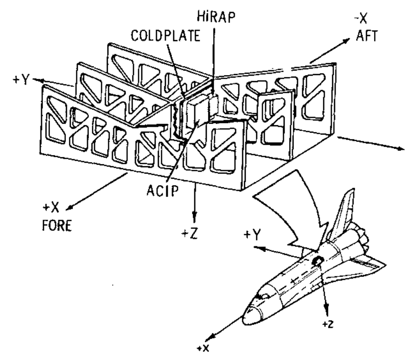

Fig. 3 Location of HiRAP within the Shuttle Orbiter and coordinate system definition.

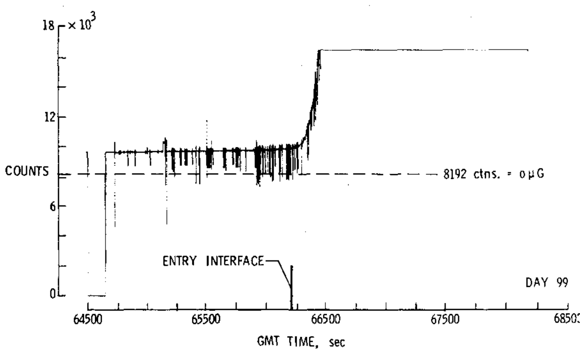

Fig. 4 HiRAP x-axis raw flight data (STS-6).

Separate Orbiter instrument data are used to obtain Orbiter altitude for the HiRAP measurement interval. The altitude is calculated from navigation state data (i.e., position and velocity vectors) recorded during entry and transformed to a coordinate system compatible with the NASA Langley Best Estimate Trajectory (BET) process reported earlier.[4] Figure 7 gives the corresponding altitude time history for STS-6 based upon the data from the onboard navigation system and referenced to the Fisher ellipsoid. Indicated on the figure are the altitudes at which the X and Z sensors saturate.

Calibration Application

Flight accelerometer readings are changed from digital counts to millivolts and then scaled by application of calibration factors determined during preflight testing. In another process, the temperature monitor output on each sensor is interpreted, giving the temperature of each sensor during flight as a function of time. The resultant temperatures for reentry of STS-6 are shown on Fig. 8. The temperature during the acceleration measurement period is fairly linear as shown on Fig. 8. These flight temperature data are interpolated with respect to time at each accelerometer measurement point in order to remove the major bias as seen in the raw data previously discussed.

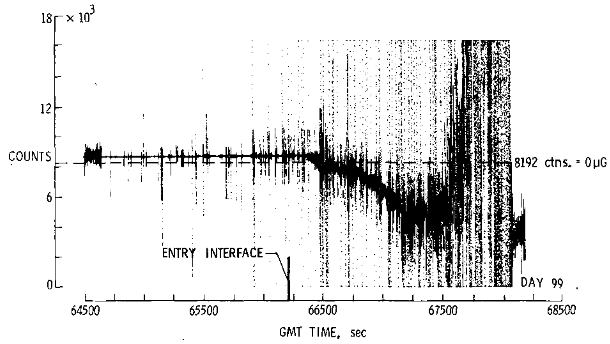

Fig. 5 HiRAP y-axis raw flight data (STS-6).

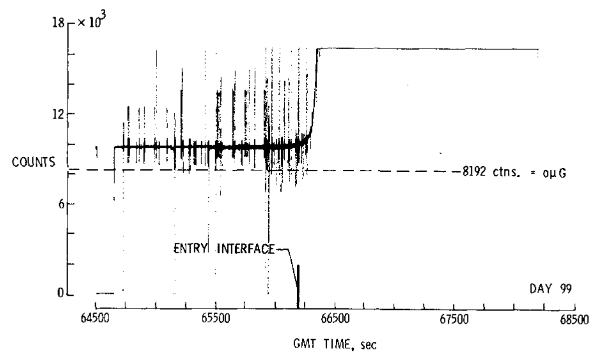

Fig. 6 HiRAP z-axis raw flight data (STS-6).

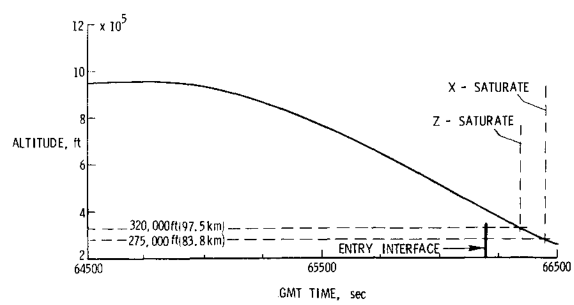

Fig. 7 Altitude profile derived from the Orbiter's navigation data.

The "turn on" bias is determined during a brief period just after deorbit burn and subsequently removed from the data. The net results after all calibration applications for each accelerometer channel are shown in Figs. 9, 10, and 11.

Thrust Removal

The accurate determination of aerodynamic induced accelerations requires an accounting for the thrusting during recording of the data. Either the thrust can be modeled and the total signal corrected, or the data intervals during thrusting can simply be deleted. The latter option has been selected since the data rate from HiRAP is very high and little is lost by simply deleting the data record when thrusters are active.

There are 38 primary thrusters and 6 verniers onboard the Shuttle Orbiter. They are physically arranged on the vehicle in three areas, forward in the nose area, aft on the left pod, and aft on the right pod. Data on each thruster chamber pressure are recorded during flight. A record of the length of time of thrust activity has been obtained after removing the pressure sensor bias and the time skew. The results are presented on Fig. 12, clearly showing the forward RCS fuel dump which terminates the activity of the thrusters in the forward area. Also, as time increases the thruster activity increases, indicated by the density of the data on the figure. The application of these data to the calibrated accelerometer data shown previously produces accelerometer records without the thrust spikes seen on the previous figures.

Rotational Motion Considerations

The location of the HiRAP with respect to the Orbiter's center of gravity causes an induced acceleration input whenever rotational motion of the vehicle occurs. The rotational motion about the principal axes are measured by the navigation gyro systems onboard the Orbiter. The level of acceleration in each sensor produced by rotational motion of the HiRAP about the center of gravity is given by

$$\begin{bmatrix} \Delta A_x \\ \Delta A_y \\ \Delta A_z \end{bmatrix} = \Omega \begin{bmatrix} -29.8 \\ -1.96 \\ 19.3 \end{bmatrix} 10^4$$

Table 1: HiRAP design specifications

Range, μg	± 8000
Resolution, μg	1.0
Accuracy, μg (after calibration)	3-10
Sample rate/s	174
Size, cm (in.)	$8.89 \times 12.7 \times 10.16$ ($3.5 \times 5 \times 4$ in.)
Weight, kg (lb)	1.34 (2.5)
Power, W	5

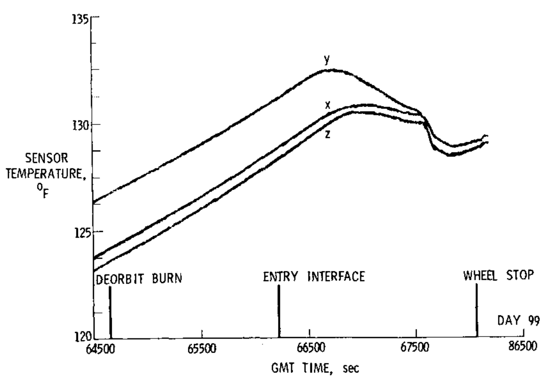

Fig. 8 Temperature monitor flight data (fine scale) for each HiRAP sensor.

where

$$\Omega = \begin{bmatrix} q^2+r^2 & -(pq-\dot{r}) & -(pr+\dot{q}) \\ -(pq+\dot{r}) & p^2+r^2 & (qr-\dot{p}) \\ -(pr-\dot{q}) & -(qr+\dot{p}) & q^2+p^2 \end{bmatrix}$$

Using the gyros from the IMU and assuming zero rotational accelerations produces the resulting acceleration shown on Fig. 13 for STS-6. For the most part, the induced accelerations into each channel are negligible except for occasions which are readily identifiable with vehicle maneuvers to obtain the proper attitude prior to reentry. These data are added algebraically to the measured values to eliminate this rotational effect, thereby isolating the desired aerodynamic acceleration.

Smoothing Process

The statistical averaging procedure used for the flight data consists of a moving median process, or digital median smoother. This process consists of arranging $(2N+1)$ data (the window) in increasing order and selecting the $(N+1)$ point, the median value, which is taken as representative of the sample window. The window in each data channel is moved, point by point, through the data set. This process smooths expected in-flight oscillations and removes spurious

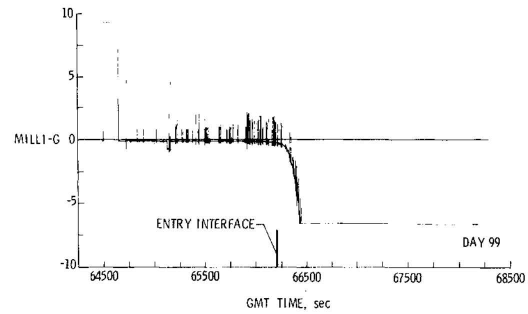

Fig. 9 HiRAP x-axis calibrated flight data.

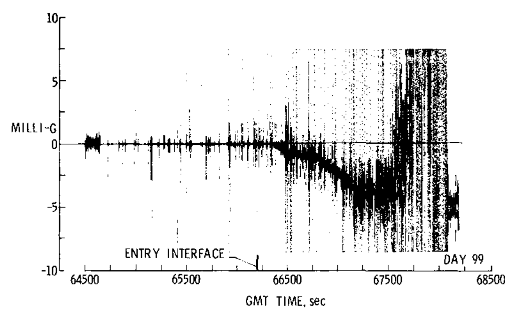

Fig. 10 HiRAP y-axis calibrated flight data.

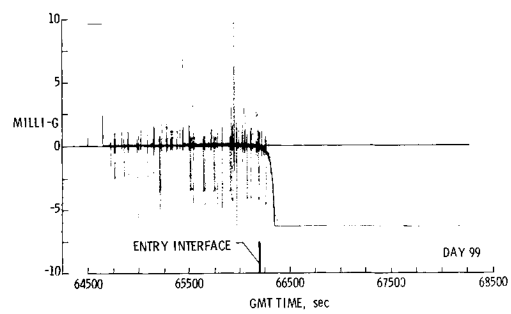

Fig. 11 HiRAP z-axis calibrated flight data.

data points. Application of this technique to the STS-6 flight data after thrust removal and corrected for motion about the center of gravity produces the final product of the flight data reduction process, namely the accelerations due to aerodynamics only.

Aerodynamics Results

L/D Measurements

Measurements of force coefficients depend not only on accelerations, but also on measurements of the freestream atmospheric state. The present measurements on STS-6 were obtained without the accompanying atmosphere data. Hence, an accurately determined aerodynamic parameter is L/D since the local dynamic pressure cancels. The L/D is calculated by:

$$\frac{L}{D} = \frac{R - \tan\alpha}{1 + R\tan\alpha}$$

where α is obtained from the onboard navigation gyro data. The time history of the angle of attack for STS-6 covering the HiRAP measurement period is given on Fig. 14. The maneuvering of the Orbiter after deorbit is done to achieve a 40 deg angle of attack prior to the entry interface. The initial calculations of L/D for STS-6 are confined to the time after which the Orbiter achieves a 40 deg attitude. This corresponds to about 66,000 s GMT on the figure. The results of the calculations of L/D with the flight data are given on Fig. 15 with respect to altitude. At an altitude of about 160 km, the L/D is about 0.10 as seen on the figure. An estimate of the Knudsen number based upon the 1962 standard atmosphere is about 6.2, which indicates the Orbiter to be in, or near, the free molecule flow regime. As altitude decreases, density increases, and the L/D increases due to the diminishing contribution of viscous effects. As HiRAP sensors saturate, the IMU accelerometers begin to achieve acceptable signal to noise, allowing the data from the sensors to supply the remaining portion of the curve from transitional flow into the hypersonic continuum where the L/D is about 1.03. The merging of data between these two independent acceleration systems, physically located at opposite ends of the Orbiter, indicates that the HiRAP system is performing as desired.

L/D Comparisons

Some comparisons between the preliminary STS-6 HiRAP results and various theoretical predictions have been made. The comparisons are separated into two areas; first, in the free molecule flow regime, and second, in the transitional flow regime.

Free Molecule Flow Regime

The measured HiRAP flight value for L/D and an accompanying error bar, which reflects the preliminary nature of the calculations, is shown on Fig. 16. Also shown is a curve of the values contained in the Shuttle Aerodynamic design Data Book. The computational technique used to generate the data book points assumed an energy accommodation coefficient of 1.0 (i.e., completely diffuse reflection conditions) for the Orbiter geometry. Clearly, the flight data from STS-6 does not substantiate a diffuse reflection condition. Also shown on the figure are the calculations for a flat plate using the Hulbut and Sherman[5] theory for diffuse reflection conditions. Comparing this with the design book establishes the fact that a flat plate is a reasonable geometry model, as might be expected. Using this flat plate model and varying key surface reflection parameters produces the results shown on Fig. 17. The curves show the variation in L/D for two parameters which specify the surface reflection conditions, namely partial energy accommodation coefficient α_2 and reemitted speed ratio S_r. The reemitted speed ratio is normalized with respect to the incident speed ratio S_i, which has a value of about 16.0 for the Shuttle Orbiter entry conditions.

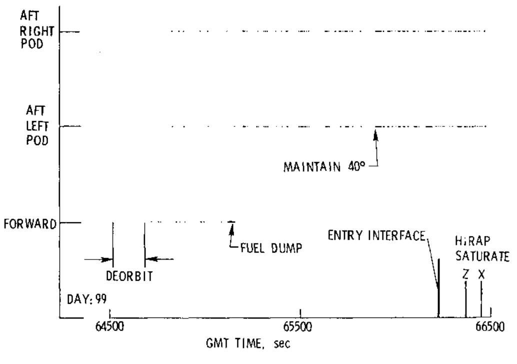

Fig. 12 Times during reaction control system thrust activity.

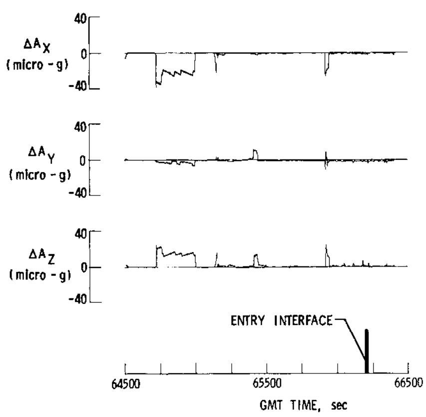

Fig. 13 Components of acceleration due to HiRAP rotational motion about the center of gravity.

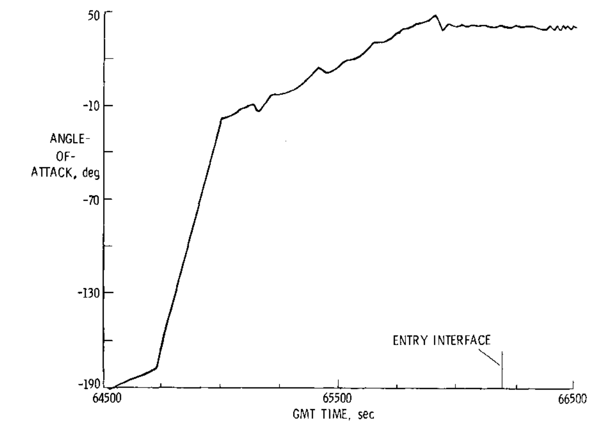

Fig. 14 Angle of attack profile derived from the Orbiter's navigation data.

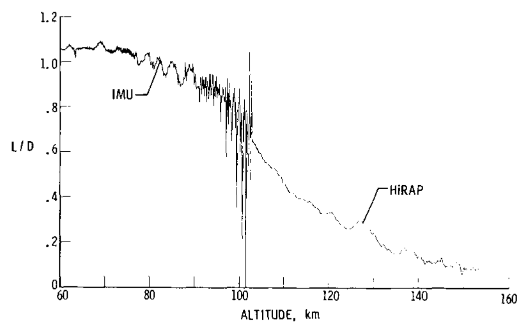

Fig. 15 Lift-to-drag flight measurements in the rarefied flight regime.

For the L/D value obtained from flight, the partial energy accommodation ranges from 0.84 to very nearly 1.0 depending upon the average reemitted speed of the reflected molecules. However, the theory shows that the reemitted speed ratio is sensitive to L/D. Further investigations and perhaps other data will be required to substantiate these intiial findings.

Transition Flow Regime

The transitional flow regime aerodynamics for the Shuttle Orbiter are predicted using an empirical relationship with the rarefaction parameter, Knudsen number. This relationship provides the "bridge" between free molecule flow and the hypersonic continuum regimes and, hence, is referred to as the bridging formula. The transitional flow regime flight data are compared with the Shuttle Orbiter data book bridging formula. After adjustment for truncation errors in the data book, the bridging formula used for the comparison is:

$$C_{tr} = C_c + (C_{FMF} - C_c)\sin^2\omega$$

where

$$\omega = \frac{\pi(2.55 + \log_{10}Kn)}{7.10}$$

The values of Knudsen number are restricted by the two coefficients in the ω equation. Those shown correspond to Knudsen numbers of $2.8 \times 10^{-3} \leq Kn \leq 10$. The value of C_c is either the continuum coefficient C_D or C_L, and C_{FMF} is the corresponding free molecule flow coefficient C_D or C_L. For the C_{FMF} coefficients, HiRAP results at $\alpha = 40$ deg are used. That is, for $L/D = 0.10$, the flat plate estimates for the free molecule force coefficients are $C_D = 2.185$ and $C_L = 0.2186$.

The results of the computation using the 1962 Standard Atmosphere[6] are shown on Fig. 18. The comparison shows good agreement with the general features of the flight data indicating the adequacy of the bridging formula. In addition, it has been necessary here to assume a standard atmosphere to be calculated Kn. Apparently, the actual atmosphere encountered in flight must have been close to the standard.

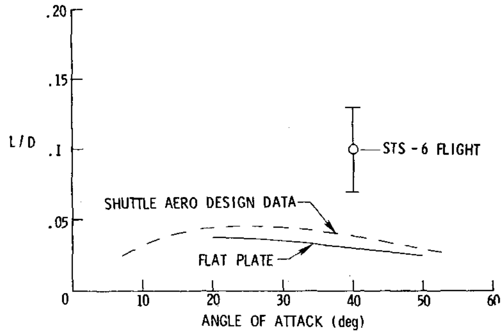

Fig. 16 Comparison of flight and predicted L/D for the Shuttle Orbiter.

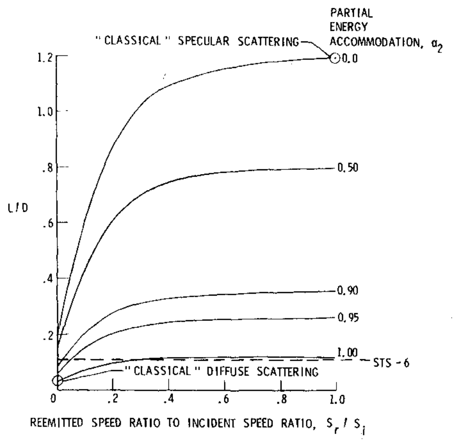

Fig. 17 Comparison of flight measured L/D with free molecule kinetic theory.

Atmospheric Results

Preliminary calculation of the atmospheric properties, principally density, have been performed with the HiRAP data from STS-6. These calculations depend upon assumptions on the behavior of the aerodynamics. Following work done earlier in the rarefied flow regime,[7] the transformation from acceleration to density is as follows:

$$\rho = \frac{2A_m}{V^2 C(S/M)}$$

where V is obtained from the navigation system (or the BET) discussed earlier. For the initial calculations, data from the X and Z channels are investigated. The aerodynamic coefficients (C_A and C_N) used are obtained from the bridging formula after adjusting the free molecule flow coefficients for nondiffuse reflection as discussed earlier. Figure 19 shows the HiRAP results for the two channels, labeled $HiRAP_x$ and $HiRAP_z$, with respect to altitude and normalized to the 1962 Standard Atmosphere. Similar calculations were performed with the accelerometry obtained from IMU data during this flight to complete the density curve at lower altitudes. These are labeled IMU_x and IMU_z and merge exceptionally well with the HiRAP data set. A wave form of large proportion, about 50 to 60% magnitude relative to the standard, is evident. This atmospheric phenomenon appears to be attributable to gravity waves, although the exact nature will require further analysis.

The magnitude of the density relative to the standard at 160 km indicates that the density encountered is more dense by about 50%. If this value were accepted, then the corresponding Knudsen number would be about 4.1 which is

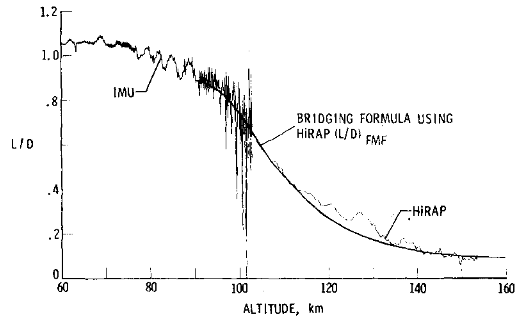

Fig. 18 Comparison of flight measured L/D flight results with bridging formula in rarefied flow transition regime.

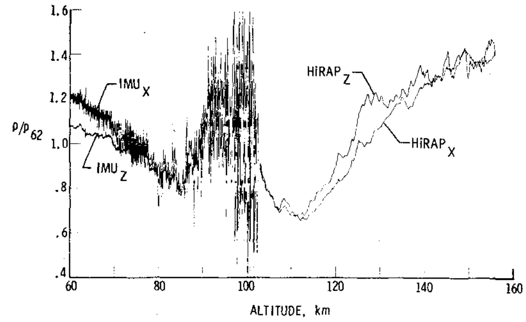

Fig. 19 Upper altitude normalized density profiles from HiRAP and IMU data (STS-6).

smaller than the value based upon the standard atmosphere. Thus, the large L/D value may be attributed to the Orbiter residing more in the transitional flow rather than the free molecule flow regime. Identifying the flow regime requires an independent measurement on atmospheric properties (such as those planned with the SUMS experiment) or possibly multiple flights of the Orbiter with the HiRAP, assuming the orbiter aerodynamic properties remain unchanged from flight to flight.

Conclusion

A sensitive experimental accelerometer system, called HiRAP, has successfully flown on the STS-6 mission. The HiRAP contains an accelerometer triad capable of resolution to less than 1.0 μg. A flight reduction process which includes application of calibration data, removal of thrust and angular accelerations, and a mid-point median smoothing technique has been applied to the flight data. This process successfully extracts the aerodynamic signals which are subsequently used to determine aerodynamic performance parameters and atmospheric density. Initial calculations on L/D have been performed with the STS-6 data. The preliminary results indicate that the free-molecule from value L/D is 0.10 ± 0.03. This measurement suggests either that surface reflection is not completely diffuse as is the currently accepted assumption used today or that the vehicle is not fully in the free molecule flow regime. Further, the bridging formula contained in the Orbiter data book adequately reflects the measured data. Although this empirical relationship provides good comparisons, it obviously does not give insight into nature of the phenomena being measured. This will require further study using computational flowfield analyses. Atmosphere density calculations have also been made with the HiRAP data. The preliminary results indicate a density wave phenomenon of large proportion, about 60% relative to a 1962 standard model. The wave appears to be confined between 70 and 140 km altitude and is initially attributed to gravity wave effects, although additional flights of the equipment will be needed to verify this. The excellent merger of the HiRAP data with the navigation IMU accelerometry provides some evidence that the HiRAP system and data processing are working satisfactorily. Data on subsequent flights will further define the accuracy limits of the system, although the experiment appears to be operating within the anticipated resolution and accuracy. It is fully expected that the repeated flights of the Shuttle Orbiter with the HiRAP will fulfill the experiment objectives and goals. In addition, the flights will generate new performance data of a winged entry vehicle in a flight regime difficult to simulate in ground facilities. It is also anticipated that data recorded on subsequent Orbiter flights will serve as benchmarks for current and future development of computational codes used to predict aerothermodynamics in this flight regime.

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