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Enhanced Reduction of Velocity Data Obtained During CETA Flight Experiment

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Summary

The Johnson Space Center performed a preliminary reduction of the data taken by a Langley-designed velocity-measuring system using a Hall-effect device during the Crew and Equipment Translation Aid (CETA) experiment on the STS-37 Shuttle flight in April 1991. The data reduction provided average velocity profiles. This paper describes a new enhanced data reduction technique based on a least-squares method that allows instantaneous velocity profiles to be obtained. Sample velocity profiles of several CETA carts tested in this experiment were obtained using this technique. The results show that the technique dramatically enhances the velocity measurement, especially at the beginning and end of the runs.

Introduction

A means of moving personnel and equipment on the Space Station was investigated on the Crew and Equipment Translation Aid (CETA) experiment on the STS-37 Shuttle flight in April 1991. Two types of instrumentation were used to sense the velocity of a cart moving along a specially constructed track. One sensor was a Langley-designed special system using a Hall-effect device as the basis for a noncontacting motion monitor (ref. 1). This system provided the exact times that the cart passed small magnets placed along the track. A reliable average velocity profile could also be determined with a minimum amount of data manipulation, but with a limited ability to sense rapidly changing velocities. Therefore, the velocity profiles did not closely follow the true cart velocity, especially during cart acceleration and deceleration.

The other sensor was a three-axis accelerometer package installed on the cart. In theory, accelerometer data can be integrated to provide instantaneous velocity profiles at the data system sampling rate. The time resolution is limited only by the data system sampling rate and thus can be much higher than that obtained from the Hall-effect sensor data (can be as high as 300 to 1). However, this method requires accurate accelerometers and data acquisition systems. Information on the initial conditions (velocity and displacement) and the accelerometer calibration constants (bias and sensitivity) also need to be carefully determined.

This technique can also be applied in other measurement areas. For instance, a similar technique can be used to verify the performance of the accelerometers currently being used for critical microgravity measurements. Also, the technique can enhance the measurements by verifying the calibration constants of the instrument *in situ*.

Background and Requirement

The CETA experiment involves accelerating and decelerating a cart and its payload along a 50-ft track (fig. 1) to various speeds by different propulsion methods. The velocity of the cart must be measured to evaluate the different propulsion methods as well as the effectiveness of the brakes. Because the cart does not remain in continuous contact with the track in the low-gravity environment in orbit, a noncontacting type of sensor was required to avoid causing drag on the cart, thus contaminating the experiment.

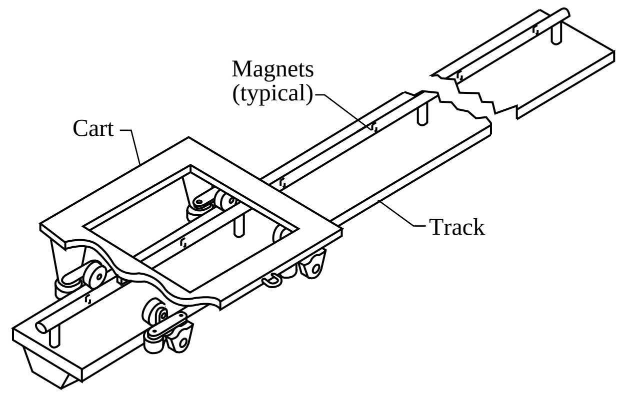

Figure 1. Cart and track on CETA experiment.

The sensing system had to be small and battery operated (5 V at 50 mA). Another obvious requirement was that the measuring system must be safe and not interfere with other subsystems on the Shuttle. Accuracy requirements were that the system would provide velocity information up to 6 ft/sec within 5 percent of full scale. The output of the system had to be compatible with the battery-operated Portable Data Acquisition Package (PDAP) that logged all the data on the cart. A means of determining the direction of motion was also required (ref. 1). The system had to sense the cart motion without being affected by the off-axis motion.

Instrumentation

The first measurement technique provided used a Hall-effect sensor (a solid-state device that senses magnetic fields) mounted on the cart to sense magnets that are mounted in evenly spaced (1-ft) locations along the track (fig. 2). Position information was recorded directly, and the average velocity was determined by measuring the time between encounters with consecutive magnets. The Hall-effect sensor and the magnets were commercially available. The system required no external circuitry and needed no adjustments. A second Hall-effect sensor was used

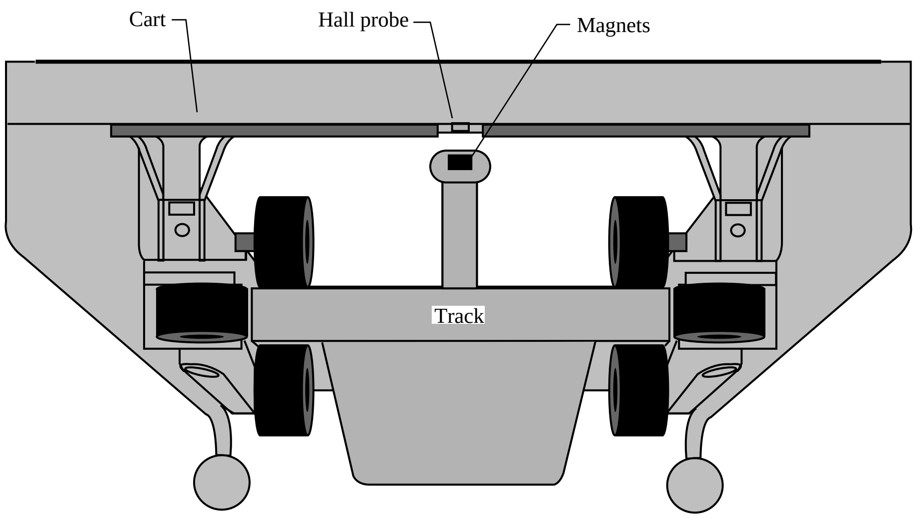

Figure 2. Magnet and Hall-probe locations on CETA assembly.

in tandem to sense the direction of the cart motion. This was not essential to the CETA experiment but facilitated the data reduction without having to correlate the acquired data with the video images on tape. It also provided a redundant measurement that enhanced the system reliability. The second measurement technique employed three commercially available accelerometers to sense the instantaneous acceleration levels of the cart in three axes (longitudinal, lateral, and vertical).

Flight Summary

The CETA experiment was successfully conducted on April 8, 1991. Three carts, each using a different propulsion method, were successfully operated at speeds up to 4 ft/sec. Data were successfully acquired on the two Hall sensors and the three accelerometers. One cart was propelled by manually pulling it along the handrail. This method produced jerky acceleration but excellent coasting because the cart was not in continuous contact with the rail. The other carts (mechanical and electrical) had a somewhat jerky motion and limited coasting because the pumping action used a wheel pressed against the track. The deceleration in each case was generated by a caliper brake controlled by the astronaut. In all cases, the maximum acceleration was generated during the braking phase of the run. Maximum deceleration rates were approximately 4 ft/sec/sec.

Data Acquisition

The raw data of the CETA experiment were recorded by the PDAP, which recorded 31 analog data channels. The data were sampled 150 times per second, digitized to a 12-bit resolution, and time tagged. A 40-Hz low-pass filter was used to reduce the noise and prevent aliasing. A detailed description of the data acquisition procedure can be found in reference 2.

Preliminary Data Reduction

The data of the experiment were initially reduced into two formats: the quick-look and the close-up. The quick-look format contains data in 1800-sec durations over the entire course of the experiment (ref. 2) and provides quick overviews of the events that happened during the experiment. The time resolution is therefore limited. The close-up format contains data in 45-sec durations and provides enlarged views of the experiment, thus allowing more detailed inspections of the data. The close-up data are available from the Johnson Space Center (JSC) upon request. Figures 3 to 5 (taken from ref. 3), which are examples of the close-up data, contain both Hall-effect sensor data and accelerometer data obtained during the manual cart, mechanical cart, and electrical cart evaluations. The average velocity profiles reduced from these data are also included in these figures.

The average cart velocity is determined by dividing the distance between magnets by the time between the Hall-effect sensor transitions. The accelerometer data can be integrated to produce velocity profiles. Errors in the data system and the accelerometer are two factors affecting the accuracy of the results. The 12-bit data system causes a quantization error of about 0.024 percent. Because the longitudinal acceleration range of the experiment is about $0.5g$ (where $1g \approx 32.174$ ft/sec^2), the corresponding error is thus $0.00012g$. This

(a) Raw data.

(b) Reduced backward velocity data.

Figure 3. Typical Hall-probe and velocity close-up data of channel 28. Data are taken from reference 3.

(a) Raw data.

(b) Reduced forward velocity data.

Figure 4. Typical Hall-probe and velocity close-up data of channel 29. Data are taken from reference 3.

Figure 5. Typical close-up data of accelerometers. Data are taken from reference 3.

error can cause a velocity error of 0.08 ft/sec (i.e., $0.00012g \times 32.2 \text{ ft/sec}^2 \times 20$ sec) by the end of a typical 20-sec run. The estimated accelerometer error is $0.01g$, which can cause a 6.4-ft/sec error by the end of a similar run. The maximum root-mean-square velocity error due to the data system and accelerometer is thus 6.4 ft/sec by the end of a 20-sec run.

Enhanced Data Reduction Technique

This paper presents an enhanced data reduction technique that combines the advantages of both methods mentioned previously. The data used for this technique include the time data, the Hall-effect sensor data (channel 29), the velocity data calculated from the Hall-effect sensors, and the longitudinal acceleration data (channel 30). The basic idea is to use a least-squares method to fit the displacements indicated by the Hall-effect sensor data to the corresponding displacements obtained from the double-integrated acceleration data. This method provides a better estimate of the velocity and displacement profiles. The resulting estimated parameters include the initial conditions of the velocity and displacement, and also the accelerometer sensitivity and bias. A detailed derivation of the equations involved in this method is provided in the appendix. A description of the procedure for this enhanced data reduction technique is given in the following six steps:

1. Locate the time window from the close-up data.

The time window desired is first located in graphs designated by "channel 28 aft speed" and "channel 29 forward speed" of the close-up data (similar to those in figs. 3 and 4). These graphs contain the velocity profiles obtained from reducing the two sets of Hall-effect sensor data. Because the starting point of each test is not obvious from the data, the desired starting point of the time window is assumed to be approximately 1 sec before the beginning of each velocity profile. Data in the opposite direction from

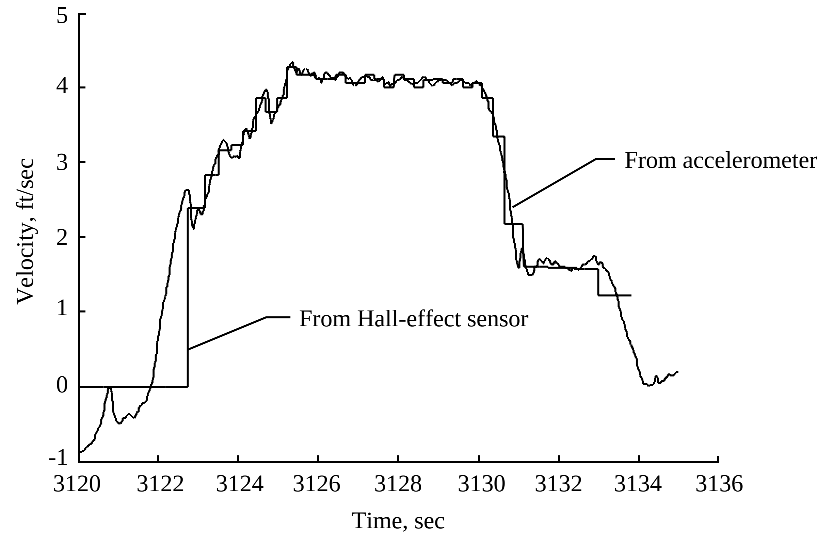

Figure 6. Forward velocity profile of manual cart. Constants at $t_0 = 3120$ sec: $s_0 = -0.56$ ft; $v_0 = -0.87$ ft/sec; $b = 0.27$ ft/sec^2; $m = -30.82$ ft/sec^2/g units.

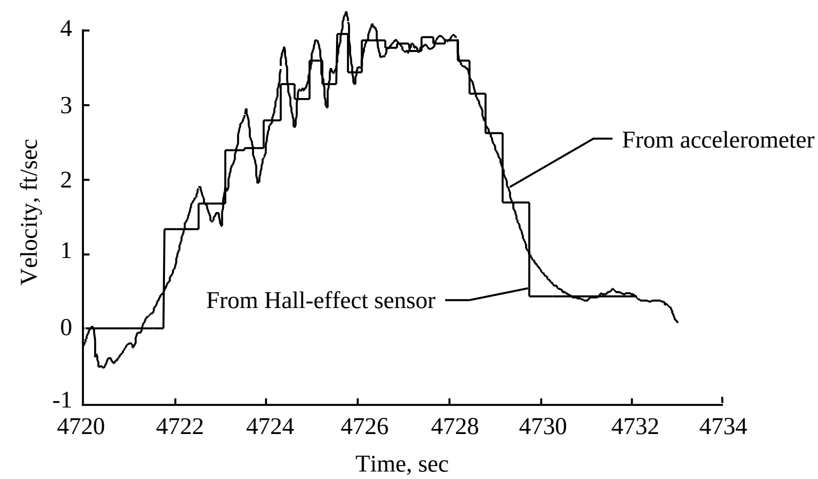

Figure 7. Forward velocity profile of mechanical cart. Constants at $t_0 = 4720$ sec: $s_0 = 0.33$ ft; $v_0 = -0.25$ ft/sec; $b = 0.30$ ft/sec^2; $m = -31.18$ ft/sec^2/g units.

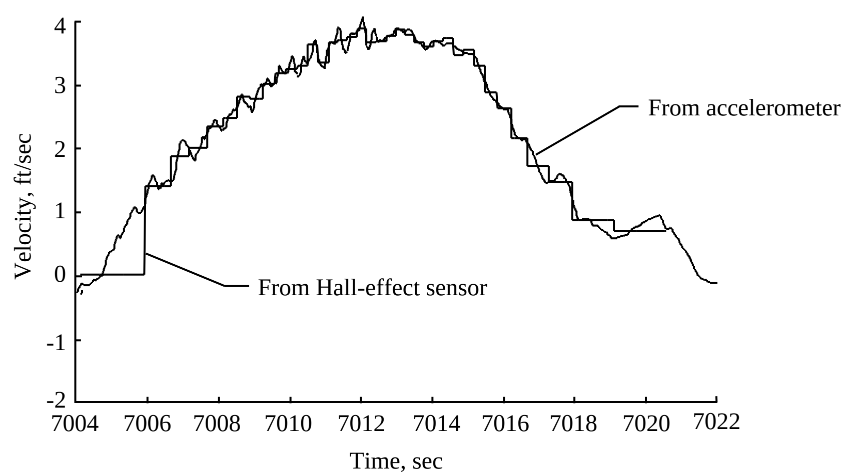

Figure 8. Forward velocity profile of electrical cart. Constants at $t_0 = 7004$ sec: $s_0 = -0.73$ ft; $v_0 = -0.29$ ft/sec; $b = 0.28$ ft/sec^2; $m = -29.00$ ft/sec^2/g units.

the previous run should never be included because these data produce anomalous results.

2. Extract the time data, Hall-effect sensor data, and acceleration data.

The time data, the Hall-effect sensor data recorded from channel 28, and the longitudinal acceleration data of the corresponding time window are extracted from the standard data file (SDF) and stored as a single data file. The SDF is the principal processed file that contains the CETA experiment data. (See ref. 3.)

3. Import the data file into spreadsheet software.

4. Execute the macro within the spreadsheet.

The spreadsheet contains a macro (a set of commands that can be executed with a single command) that integrates and then extracts the displacements from the acceleration data. The macro first numerically integrates the acceleration data to obtain the velocity and displacement profiles (zero initial conditions). The gradients of the Hall-effect sensor data are also calculated. The gradients of the data are then sorted for magnitudes over 100 V/sec. This magnitude is chosen as a criterion to detect the transition periods in the data. (Transition periods are the time intervals during which the Hall-effect sensor changes state as it passes over a magnet.) The macro then looks for sign changes in the computed gradients. Whenever a sign change occurs, the macro extracts the corresponding time and displacements from the integrated acceleration data.

5. Calculate the matrix elements and the curve-fitting constants.

The data extracted in step 4 are then used to least-squares fit the displacements indicated by the Hall-effect sensor, which are relative to the first transition. The distance between two consecutive transitions is 1 ft. The least-squares fit is done by first calculating the matrix elements in equation (A16) shown in the appendix. Equation (A17) is then evaluated to obtain the initial parameters s_0, v_0, b, and m, where s_0 is the initial displacement relative to the first magnet encountered by the vehicle, v_0 is the initial velocity of the time window, and b and m are the accelerometer bias and sensitivity correction factors, respectively.

6. Reintegrate the acceleration data to obtain the instantaneous velocity and displacement profiles.

The acceleration data are reintegrated using equations (A6) and (A7) in the appendix with the parameters obtained in step 5 to correct the velocity and displacement profiles.

Results

Figures 6, 7, and 8 illustrate the velocity profiles obtained by using the enhanced data reduction technique for the manual, mechanical, and electrical carts, respectively, tested in the CETA experiment. Shown in each figure is the corrected velocity profile using the enhanced data reduction technique compared with the velocity profile obtained from the Hall-effect sensor data. The parameters (s_0, v_0, b, and m) estimated by this least-squares method are also listed. Because the acceleration data are used, the instantaneous velocities are now available instead of the average velocities. Also, the enhanced resolution due to using the acceleration data provides more detailed velocity information in the beginning, end, and between magnets. The error contributed by this technique is primarily from the numerical integrations of the discrete acceleration data.

Concluding Remarks

The newly developed enhanced data reduction technique provides an improved procedure that allows least-squares minimization to become possible between data sets with an unequal number of data points. This technique was applied in the Crew and Equipment Translation Aid (CETA) experiment on the STS-37 Shuttle flight in April 1991 to obtain the velocity profile from the acceleration data. This new technique uses a least-squares method to estimate the initial conditions and calibration constants. These initial conditions are estimated by least-squares fitting the displacements indicated by the Hall-effect sensor data to the corresponding displacements obtained from integrating the acceleration data. The velocity and displacement profiles can then be recalculated from the corresponding acceleration data using the estimated parameters. The technique enables instantaneous velocities to be obtained from the test data instead of only average velocities at varying discrete times. Therefore, more detailed velocity information is offered, particularly during periods of large acceleration or deceleration.

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Appendix

Derivation of the Least-Squares-Fit Matrix Equation

The new enhanced data reduction technique is designed to obtain least-squares estimates of the correction factors and initial conditions of the acceleration calibration by fitting the integrated acceleration data to the Hall-effect sensor displacement data.

Let $x(t)$ denote the uncorrected acceleration data obtained as a function of time during a CETA run. If the calibration factors (the sensitivity m and the bias b) are in error, the corrected acceleration data ($a(t)$) may be obtained from $x(t)$ by correction factors as shown in the equation

$$a(t) = m\ x(t) + b \tag{A1}$$

The corrected velocity data ($v(t)$) are obtained by integrating the corrected acceleration data to give

$$v(t) = v_0 + \int_{t_0}^{t} a(t)\ dt \tag{A2}$$

where v_0 and t_0 denote the initial velocity and time, respectively.

Substituting equation (A1) into equation (A2) gives

$$v(t) = v_0 + \int_{t_0}^{t} [m\ x(t) + b] dt \tag{A3}$$

The result of the integration is the equation

$$v(t) = v_0 + b(t - t_0) + m\ I'(t) \tag{A4}$$

where

$$I\prime(t) = \int_{t_0}^{t} x(t)\ dt$$

Equation (A4) can be further integrated to obtain the corrected displacement data ($s(t)$). That is,

$$\begin{aligned} s(t) &= s_0 + \int_{t_0}^{t} v(t)\ dt \\ &= s_0 + \int_{t_0}^{t} [v_0 + b(t - t_0)] dt + m \int_{t_0}^{t} I'(t)\ dt \\ &= s_0 + v_0(t - t_0) + \frac{1}{2} b(t - t_0)^2 + m\ I(t) \end{aligned} \tag{A5}$$

where s_0 denotes the initial displacement and

$$I(t) = \int_{t_0}^{t} I'(t)\ dt$$

For discrete data, equations (A4) and (A5) can be evaluated at sampling time (t_n) as, respectively,

$$v(t_n) = v_0 + b(t_n - t_0) + m\ I'(t_n) \tag{A6}$$

and

$$s(t_n) = s_0 + v_0(t_n + t_0) + \frac{1}{2} b(t_n + t_0)^2 + m\ I(t_n) \tag{A7}$$

where

$$t_n = nT \qquad (n = 0, 1, ..., N)$$

T denotes the sampling period of the data system, and N denotes the number of data points. The terms $I'(t_n)$ and $I(t_n)$ are obtained by numerical integration. In this paper, rectangular integration is used. The inner integral ($I'(t)$) is thus approximated by

$$I'(t_k) \approx \sum_{i=1}^{k} \Delta t_i\ x(t_i) \qquad (k = 1, 2, ..., N) \tag{A8}$$

where $\Delta t_i = t_i - t_{i-1}$ and $I'(t_0) = 0$. The term $I(t_n)$ is approximated by rectangular integration as

$$I(t_k) \approx \sum_{j=1}^{k} \Delta t_j\ I'(t_j) \approx \sum_{j=1}^{k} \sum_{i=1}^{j} \Delta t_j\ \Delta t_i\ x(t_i) \tag{A9}$$

Let $s_h(\mathbf{t}_{Hj})$ denote the displacement indicated by the Hall-effect sensor when it passes a magnet at time $\mathbf{t}_{Hj}$. The set of Hall-effect sensor sampling times (i.e., $\{\mathbf{t}_{Hj}\}$ where j = 1, 2, ..., M) is a subset of the data system sampling times (i.e., $\{\mathbf{t}_i\}$ where i = 1, 2, ..., N). The sum of squares of differences between the corrected displacement data and the data from the Hall-effect sensor, summed over the Hall-effect sensor sampling times, is described by the equation

$$\varepsilon^2 = \sum_{j=1}^{M} [s(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})]^2 \qquad (M \leq N) \tag{A10}$$

where M denotes the number of Hall-effect sensor samples.

If we substitute equation (A7) into equation (A10) and let $\mathbf{t}_{Hj} - t_0$ be replaced by $\mathbf{\Delta t}_{Hj}$, the equation then becomes

$$\varepsilon^2 = \sum_{j=1}^{M} [s_0 + v_0\ \Delta\mathbf{t}_{Hj} + \frac{1}{2} b\ \Delta\mathbf{t}_{Hj}^2 + m\ I(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})]^2 \tag{A11}$$

The least-squares estimates of parameters s_0, v_0, b, and m are obtained by minimizing ε^2. That is,

$$\frac{\partial \varepsilon^2}{\partial s_0} = 0 \tag{A12}$$

$$\frac{\partial \varepsilon^2}{\partial v_0} = 0 \tag{A13}$$

$$\frac{\partial \varepsilon^2}{\partial b} = 0 \tag{A14}$$

$$\frac{\partial \varepsilon^2}{\partial m} = 0 \tag{A15}$$

If we substitute equation (A11) into equations (A12), (A13), (A14), and (A15), the corresponding partial derivatives are, respectively,

$$2\sum_{j=1}^{M} [s_0 + v_0\ \Delta\mathbf{t}_{Hj} + \frac{1}{2}b\ \Delta\mathbf{t}_{Hj}^2 + m\ I(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})]\Delta\mathbf{t}_{Hj}^2 = 0$$

$$2\sum_{j=1}^{M} [s_0 + v_0\ \Delta\mathbf{t}_{Hj} + \frac{1}{2}b\ \Delta\mathbf{t}_{Hj}^2 + m\ I(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})] = 0$$

$$2\sum_{j=1}^{M} [s_0 + v_0\ \Delta\mathbf{t}_{Hj} + \frac{1}{2}b\ \Delta\mathbf{t}_{Hj}^2 + m\ I(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})]\Delta\mathbf{t}_{Hj} = 0$$

$$2\sum_{j=1}^{M} [s_0 + v_0\ \Delta\mathbf{t}_{Hj} + \frac{1}{2}b\ \Delta\mathbf{t}_{Hj}^2 + m\ I(\mathbf{t}_{Hj}) - s_h(\mathbf{t}_{Hj})]^2 I(\mathbf{t}_{Hj}) = 0$$

The matrix form of this set of equations is given by

$$\begin{bmatrix} \mathbf{N} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^3 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\ \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^3 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^4 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\ \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\ \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2\ \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \mathbf{I}^2(\mathbf{t}_{Hj}) \end{bmatrix} \begin{bmatrix} \mathbf{s}_0 \\ \mathbf{v}_0 \\ \mathbf{b} \\ \mathbf{m} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{M} \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\ \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2\ \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj})\ \mathbf{s}_h(\mathbf{t}_{Hj}) \end{bmatrix} \tag{A16}$$

The parameters can thus be obtained by manipulating the matrix into the form

$$\begin{bmatrix} \mathbf{s}_0 \\ \mathbf{v}_0 \\ \mathbf{b} \\ \mathbf{m} \end{bmatrix} = \begin{bmatrix} \mathbf{N} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj} & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^3 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\, \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^3 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^4 & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\, \mathbf{I}(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\, \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2\, \mathbf{I}(\mathbf{t}_{Hj}) & \sum_{j=1}^{M} \mathbf{I}^2(\mathbf{t}_{Hj}) \end{bmatrix}^{-1} \begin{bmatrix} \sum_{j=1}^{M} \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}\, \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \Delta\mathbf{t}_{Hj}^2\, \mathbf{s}_h(\mathbf{t}_{Hj}) \\ \sum_{j=1}^{M} \mathbf{I}(\mathbf{t}_{Hj})\, \mathbf{s}_h(\mathbf{t}_{Hj}) \end{bmatrix} \tag{A17}$$

The parameters thus estimated can then be applied to equations (A6) and (A7) to obtain corrected velocity and displacement profiles.

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A newly developed technique for enhanced data reduction provides an improved procedure that allows least-squares minimization to become possible between data sets with an unequal number of data points. This technique was applied in the Crew and Equipment Translation Aid (CETA) experiment on the STS-37 Shuttle flight in April 1991 to obtain the velocity profile from the acceleration data. The new technique uses a least-squares method to estimate the initial conditions and calibration constants. These initial conditions are estimated by least-squares fitting the displacements indicated by the Hall-effect sensor data to the corresponding displacements obtained from integrating the acceleration data. The velocity and displacement profiles can then be recalculated from the corresponding acceleration data using the estimated parameters. This technique, which enables instantaneous velocities to be obtained from the test data instead of only average velocities at varying discrete times, offers more detailed velocity information, particularly during periods of large acceleration or deceleration.

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