Analysis of Spacelab 3 Residual Acceleration Data

Melissa J. B. Rogers* and J. Iwan D. Alexander†
University of Alabama in Huntsville, Huntsville, Alabama 35899

A data reduction plan is being developed to efficiently process residual acceleration data, making such data more accessible to principal investigators of low-gravity experiments. Accelerometer data collected during the Spacelab 3 mission is being processed using a prototype version of this plan. The plan addresses various aspects of acceleration data analysis: the identification of disturbances that are intolerable to experiments, the investigation of acceleration orientations, the definition and characterization of the background acceleration corresponding to a given experiment time line, the isolation and examination of particular significant disturbances, and the identification of disturbance sources. Acceleration magnitude, frequency, and orientation are discussed: transient accelerations can have magnitudes as large as $10^{-2}g$ with frequency components (from 4.5×10^{-3} to 150 Hz) no greater than $10^{-3}g$. These accelerations fluctuate rapidly in orientation. The occurrence of disturbance sources in an orbiter is tentatively identified as a random process, whereas the response of the orbiter to given accelerations is considered deterministic. The need to continue monitoring of residual accelerations in orbiting space laboratories is stressed: future measurements are needed to establish acceleration characterizations of specific orbiters and to establish appropriate acceleration tolerance limits for specific experiment classes in low-gravity conditions.

Nomenclature

A_i = amplitude spectra of three components of a_i, g
a = magnitude of residual acceleration vector
a_i = residual acceleration vector, g
$f_{\min}$ = minimum frequency investigated, $1/T_w$
g = gravitational acceleration at the earth's surface, 9.81 ms^{-2}
R_{ij} = transformation matrix
T_w = window length, s (or number of points)

Introduction

THE low-gravity environment of space has been a subject of interest since the early days of manned spaceflight. Early references to zero gravity were based on the fact that at the center of mass of a freely orbiting spacecraft the gravitational force is balanced by the centrifugal force. This ideal situation cannot be realized in an actual spacecraft because of a variety of internal and external disturbing forces causing low-amplitude residual accelerations in orbiters over a broad range of frequencies. Sources of residual accelerations are classified as quasisteady, having magnitudes in the $10^{-6}g$ range and frequencies on the order of the orbital frequency (the Earth's gravity gradient, spacecraft attitude motions, atmospheric drag), and transient or oscillatory, having high magnitudes (up to $10^{-2}g$) and frequencies up to 100 Hz (machinery vibrations and rotations, spacecraft vibrations, thruster firings, crew activity).[1,2]

The gravitational environment of an orbiter is continuously changing because of these residual accelerations. Investigators are interested in the effects of such an environment on man, spacecraft, and the variety of experiments being run under low-g conditions. To analyze the effects and evaluate the experiments, a complete description of the environment is required. To define the environment quantitatively, various accelerometer systems designed to measure residual accelerations in the $10^{-6}g$ range at frequencies from 10^{-4} to 150 Hz have been flown on several different spacecraft. These projects have resulted in a plethora of accelerometer data that has been subjected to only limited analysis. Discussions of various accelerometer measurements and low-gravity experiments since the mid-1970s can be found in the literature.[1,3-9]

We are developing a data reduction plan to efficiently process residual acceleration data, making such data more accessible to principal investigators. Using a prototype version of this plan, we have begun to process accelerometer data collected during the Space Transportation System (STS) 51-B Spacelab 3 (SL3) mission in April–May 1985. Some typical disturbances have been identified and cataloged and a general description of background accelerations has been made. This work complements previous descriptive studies of the low-g environment of the orbiter.[1,7,8]

In the Data and Data Processing sections, we give some details about the collection of the SL3 accelerometer data and introduce the data reduction plan used to process the data. In the Results section, we present some examples of typical disturbances that are seen in the SL3 data, compare these accelerations to ones discussed in other references,[4,8] and discuss the magnitude and orientation of certain disturbances measured by the accelerometer system. In the Discussion section, we consider the question of whether the data are random or deterministic and comment on the need to monitor residual accelerations in orbiting space laboratories to aid in the planning and development of future low-gravity experiments.

Data

The residual acceleration data from Spacelab 3 were collected with a Bell Aerospace Miniature Electrostatic Accelerometer (MESA) package. The data were recorded at 300 samples/s with a bandwidth of 50 Hz. The system was a part of the Fluids Experiment System, which was mounted on a double rack in the Spacelab module. The accelerometer's x and z axes were rotated 112.5 deg clockwise about the orbiter y axis (orbiter structural coordinate system). The origin of the accelerometer coordinate system was a little more than 1 m radially off from the orbiter center of gravity.[3]

We obtained the SL3 data from the Marshall Space Flight Center (MSFC) in the form shown in Table 1. Experiment x-, y-, and z-axis data are given for each time mark in units of $10^{-6}g$. The total amount of acceleration data expected from the experiment was approximately 1.5×10^8 data points per

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*Research Associate, Center for Microgravity and Materials Research.

†Associate Director, Center for Microgravity and Materials Research.

Table 1 Data as received from the Marshall Space Flight Center

Time, h:min:s.ms	L20Q6002A[a] μg	L20Q6005A[a] μg	L20Q6008A[a] μg
123:10:00.000	−0.760000E+02	0.110000E+04	0.480000E+03
123:10:00.003	−0.200000E+03	0.120000E+04	−0.510000E+03
123:10:00.007	0.960000E+03	0.800000E+03	−0.200000E+04
123:10:00.010	0.120000E+04	0.620000E+03	−0.120000E+04
123:10:00.013	0.100000E+04	0.360000E+03	−0.130000E+04
123:10:00.017	0.560000E+03	0.220000E+03	0.200000E+04
123:20:00:020	−0.690000E+02	−0.680000E+02	0.760000E+03
⋮	⋮	⋮	⋮

[a] Accelerometer axes x, y, and z correspond to L20Q6002A, L20Q6005A, and L20Q6008A, respectively; acceleration is in $10^{-6}g$.

axis, which represents 140 h and would comprise about 9 Gbytes of data as stored at MSFC.[3] Because of telemetry and instrument problems, however, blocks of data up to 1 h in length are missing. For the SL3 data base, this makes the task of data processing time intensive because windows of missing data must be identified and avoided.

Data Processing

We are developing a multistep data reduction plan for the analysis of residual acceleration data. The plan addresses various aspects of acceleration data analysis: the identification of disturbances which are potentially disruptive to experiments, the investigation of acceleration orientations, the definition and characterization of the background acceleration corresponding to a given experiment time line, the isolation and examination of particular significant disturbances, and the identification of disturbance sources. All of these aspects are important for the analysis of experimental results. Standard digital signal processing techniques were used[10-12]; specifics of the application of these techniques to residual acceleration data are discussed elsewhere.[13] The first two topics mentioned above are specifically addressed in this section.

Identification of Intolerable Accelerations

The initial concern of the plan is the identification of potentially disruptive disturbances. A disturbance is deemed potentially disruptive when certain acceleration limits are surpassed. Ideally, these limits should be specified by investigators who know what levels of acceleration, in reference to both time and frequency, their experiments can tolerate. However, for most experiments, such tolerance limits have not yet been established. Nonetheless, it can be expected that as we obtain a better knowledge of the low-g environment of specific orbiters and the sensitivity levels of experiments run in space, the a priori establishment of realistic disturbance limits will be easier to achieve. In working with the SL3 data, test limits were chosen based on our current understanding of the sensitivity of crystal growth from solution.[14] These limits were used because such an experiment was flown on SL3 in conjunction with the accelerometer system.

The identification of potentially disruptive disturbances consists of two equally important parts: a peak detection routine applied in the time domain to identify accelerations exceeding designated limits and a spectral analysis technique to identify significant frequency components and to test these components against frequency limits. The importance of both time and frequency domain analyses for the identification of potentially disruptive accelerations will be discussed later in this section.

Segments of the SL3 accelerometer data were processed as follows. The data from all three axes were used to calculate the magnitude of the residual acceleration vector a_i for each sample time:

$$a = \sqrt{a_1^2 + a_2^2 + a_3^2} \tag{1}$$

The resulting total acceleration array was used as input to a peak detection routine that identifies times when test limits are exceeded in the time domain. From the list of times produced by the detection routine, windows containing occurrences of high acceleration values were identified and plotted. Windows of length $T_w = 6.8$ s (2048 points) were used for further analysis; this window length provides good detail and is long enough to include most types of transient disturbances. Unfortunately, this window length imposes a 0.15-Hz lower limit on frequencies that can be studied using spectral analysis because $f_{\min} = 1/T_w$.[13] To test the lower frequency limits (<0.15 Hz), windows of length $T_w = 3.6$ min (65,536 points) containing several disturbances were chosen and processed as mentioned earlier. This length window contains information on frequencies as low as 4.5×10^{-3} Hz.

Table 2 Maximum tolerable acceleration levels for given frequencies, determined from numerical modeling of crystal growth from solution[14]

Frequency, Hz	Magnitude of component, g
$<10^{-2}$	10^{-4}
10^{-2}–1.0	10^{-3}
>1.0	10^{-2}

The second part of the identification process involves the spectral analysis of the data windows. The frequency domain tolerance limits used with the SL3 data are shown in Table 2. To test these for a given window, the three axes of residual acceleration data are individually transformed into the frequency domain using a fast Fourier transform algorithm ($a_1 \leftrightarrow A_1$, $a_2 \leftrightarrow A_2$, $a_3 \leftrightarrow A_3$). The three resulting amplitude spectra (A_1, A_2, A_3) are used to form a combined amplitude spectrum array: $A = (A_1^2 + A_2^2 + A_3^2)^{1/2}$. The values of this combined spectrum are tested against the frequency limits. If any of the limits are exceeded, the window is identified as potentially intolerable.

As stated earlier, the time and frequency domain analyses of residual acceleration data are equally important. The effect of an acceleration on a given experiment depends on the response of that experiment to the amplitude, frequency, and orientation of the acceleration.[2,14,15] It is, therefore, necessary to establish both time and frequency tolerance limits for different classes of experiments. The two domains provide different perspectives on the data from which it is possible to obtain important information. The time history gives an indication of the instantaneous acceleration experienced at the sensor location for each time sample and is especially important in the analysis of experiments sensitive to transient disturbances. The representation of data in the frequency domain gives an indication of the frequency components that sum together to produce the time domain record. Because of this, the amplitude at any given frequency can only be a fraction of the highest magnitude represented in the time window. The use of amplitude spectra, as opposed to power spectral densities, gives the magnitude of a particular frequency component over the time period considered in the same units as the original time series.[10-13] This frequency domain representation is the most practical when comparing acceleration components to thresh-

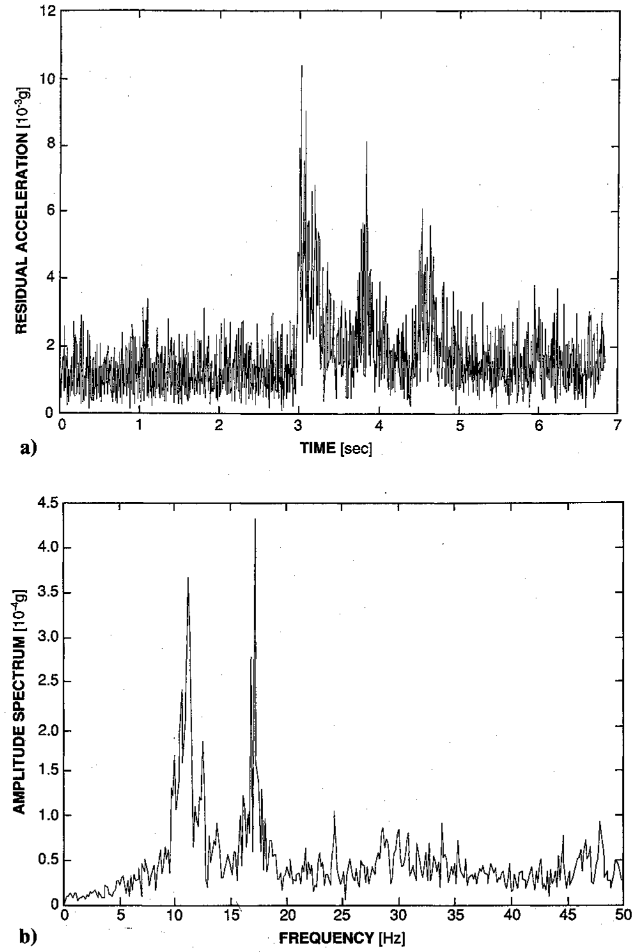

Fig. 1 Window containing three large magnitude pulses surrounded by quiet data: a) total acceleration array, maximum magnitude $\sim 1 \times 10^{-2} g$; b) combined amplitude spectrum, dominant frequency components 11 and 17 Hz.

old limits typically stated as units of g at a particular frequency.

Investigation of Acceleration Orientation

In the process of identifying potentially disruptive accelerations, we are not concerned with the orientation of the disturbing acceleration, only the magnitude and frequency. Information on the orientation of disturbing forces can aid in the analysis of experiment results, and so two options are included in the processing plan involving the orientation of the data: 1) data can be transformed into coordinate axes other than those in which they were recorded, and 2) the direction cosines of the three axes of acceleration can be computed, giving an indication of the continuously changing orientation of the recorded accelerations. Such manipulation of data will be useful in the postflight analysis of experimental results for cases when the orientation of accelerations, as well as magnitude and frequency, is important to experiment sensitivity.[2,14,15]

The orientation of experiments flown on orbiters varies greatly. Transformation of accelerometer data into other experiment axes will aid in the analysis of results of experiments sensitive to impulses in specific directions. The transformation of data is obtained by the application of a transition matrix to the original data

$$a_i' = R_{ij} a_j \tag{2}$$

where a_i' denotes the acceleration components in the transformed coordinates, and a repeated index indicates a summation.[13] The transformation matrix R_{ij} is constructed from the direction cosines of the primed axes with respect to the unprimed axes. This procedure has been used to transform the SL3 accelerometer data into the orbiter structural coordinate axes so that data plots may be compared more directly to results from other papers.

An additional processing technique in the data reduction plan provides an indication of the orientation of the recorded accelerations. As with the ability to transform data into different coordinate axes, a knowledge of the direction of measured accelerations will aid in the analysis of experimental results. Direction cosines are used to determine the orientation of measured accelerations with respect to the recording axes. Tests have been run on the SL3 data using this method to determine whether certain transient disturbances act in characteristic directions or whether acceleration orientations vary with time.

Results

Residual acceleration data collected during the SL3 mission were processed using the prototype data reduction plan discussed earlier. Acceleration events were declared potentially intolerable when the time domain tolerance limit of $4 \times 10^{-3} g$ and/or the frequency domain limits given in Table 2 were exceeded. In addition to events identified as intolerable, windows with no apparent high-magnitude disturbances were also studied in an attempt to definitively characterize the background acceleration level. This is important because the steady accelerations contained in the background have just as great a potential to adversely affect some experiments as high-magnitude transient disturbances have to affect other experiments.[2,14,15] It must be emphasized that the measurement of steady accelerations is currently restricted in part by instru-

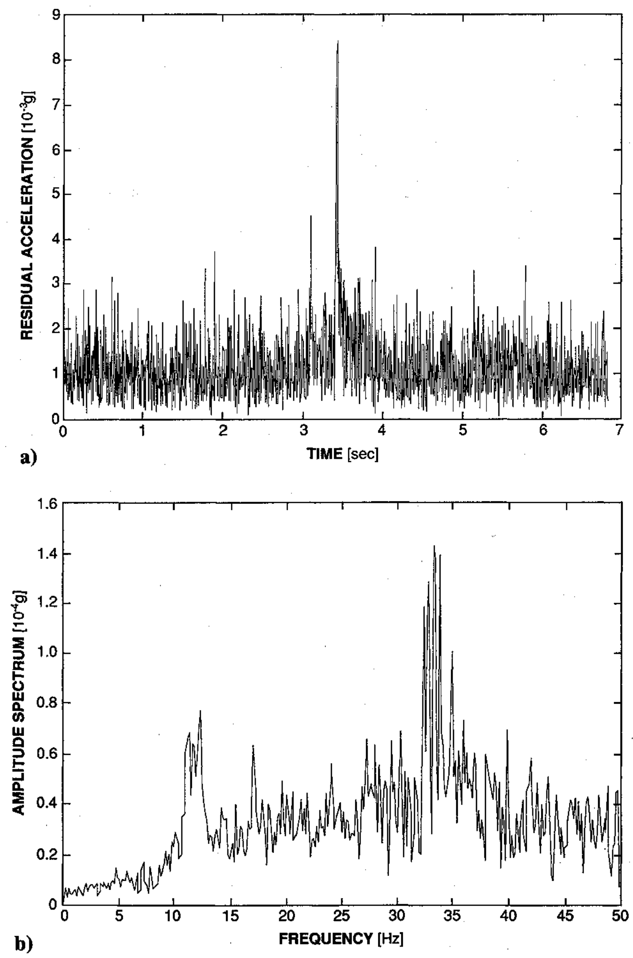

Fig. 2 Window containing crew induced disturbance: a) total acceleration array, maximum magnitude $\sim 8.5 \times 10^{-3} g$; b) combined amplitude spectrum, dominant frequency component 33 Hz.

ment limitations, but also largely by the presence of low-magnitude background accelerations and instrument noise. However, steady accelerations can be predicted to some extent from a knowledge of the orbiter altitude and attitude and solar activity during a mission.

On the order of 4×10^6 samples of SL3 residual acceleration data have been processed to date, representing approximately 3 noncontinuous hours of data. Windows of interest ($T_w = 6.8$ s) from the SL3 data identified as intolerable or background have been cataloged. Cataloging consists of the notation of identification codes and occurrence times and the plotting of time histories and amplitude spectra for each window (Figs. 1 and 2). Although we have no way of correlating these disturbances with specific sources, we are comparing them to signals with known sources presented in other papers.[1,4,7,8] As a result of these comparisons, the sources of the cataloged signals have been tentatively identified and the signals are considered to be representative of certain classes of disturbances: those caused by thruster firings; those stemming from mechanical sources such as motors, fans, etc.; those induced by crew activity; and those of unknown origin, but nonetheless interesting. Comparisons of windows of quiet data ($a \le 4\times10^{-3}g$) reveal that a characteristic background acceleration level does not exist for the SL3 data. Amplitude spectra vary among windows, indicating the presence of low-magnitude accelerations and instrument noise, which masks any information on quasi-steady accelerations we might wish to gain directly from the data.

Despite the fact that the $4\times10^{-3}g$ time domain tolerance limit was often exceeded, the frequency domain limits (obtained from the same modeling) were never surpassed. This indicates that the power contained in the windows studied is spread out enough over the frequencies investigated (4.5×10^{-3}–150 Hz) so that, although a time domain limit may be exceeded, frequency limits are not. This stresses the importance of defining sensitivity limits for different classes of experiments in both the time and frequency domains. Continued flights of potentially sensitive experiments will help define how sensitive various types of experiments are and to what types of disturbances, allowing the establishment of better limits.

Figures 1 and 2 show cataloged windows from the SL3 residual acceleration data. Figures 1 have been tentatively identified as part of a sequence of thruster firings or crew activity in the vicinity of the accelerometer sensors. A dominant frequency component of this data is 11 Hz. This frequency probably reflects the excitation of orbiter structural modes as well as localized modes within the Spacelab.[16] Although no designated frequency limits are exceeded, the acceleration levels are quite high ($10^{-2}g$) and may affect other classes of sensitive experiments being run in the Spacelab.

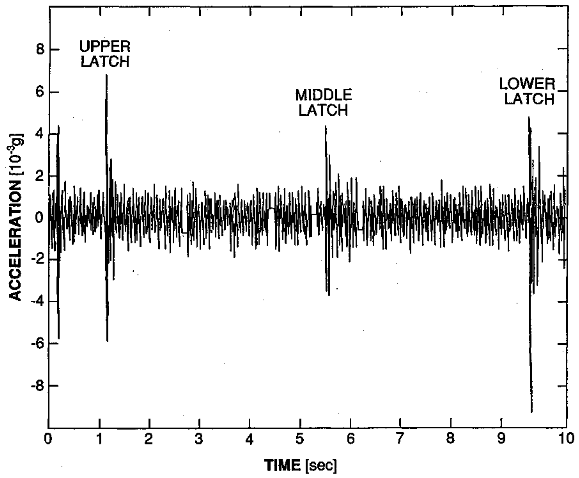

Fig. 3 Crew induced disturbances related to FES latch openings during Spacelab 3, experiment *x* axis, after Chassay and Schwaniger.[4]

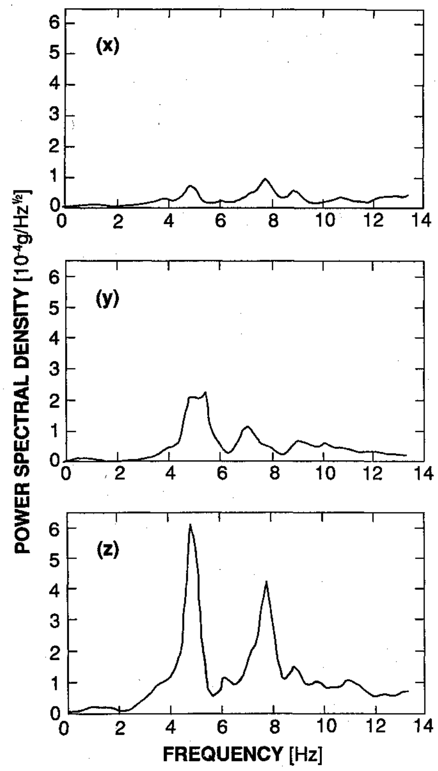

Fig. 4 Power spectral densities of crew induced disturbances within the Spacelab from the "Hop and Drop" experiment, after Hamacher et al.[8]

In addition to disturbance sources such as thruster firings, which are identified in the data by rather impulsive accelerations of high magnitude, structural modes can also be excited by mechanical sources. Accelerations caused by such sources may be no greater in magnitude than the background level and can often be identified only by the presence of related frequency components. One 30-min block of SL3 data that we analyzed was dominated by a 17-Hz component. No impulsive start for this oscillatory event could be identified in the data and the source was therefore attributed to some mechanical device. Previous study of the SL3 data has identified the driving motor of the KU band antenna as a probable source of this disturbance.[17] Although this type of disturbance has no associated high-magnitude impulses, experiments that are sensitive to oscillations in a particular frequency range could be affected by such accelerations. The 17-Hz disturbance can also be seen superimposed on transient disturbances, as in Figs. 1.

Figures 2 show one other typical high-magnitude acceleration disturbance from the SL3 data. The disturbance shown in the time window appears to be of a higher frequency than the previously discussed accelerations. This is confirmed by the amplitude spectrum, which indicates that the dominant frequency present is 33 Hz. This disturbance is very similar to accelerations caused by the opening of latches on the Fluids Experiment System (FES) optical bench doors[4] and to other accelerations originating within the Spacelab[8] (Fig. 3). Although we are not able to correlate this disturbance with any specific event, we believe it is typical of disturbances caused by general crew activity, especially within the Spacelab module.

The comparison of the signal shown in Figs. 2 to the latch opening plot of Fig. 3 was made only in the time domain. No amplitude or power spectra were provided for this identified source.[4] Previous studies have identified several common frequency components that are excited by transient sources.[4,7,8] Frequencies of approximately 5 and 7 Hz are known to be excited by activity within the Spacelab. Hamacher et al.[8] state that the 5-Hz signal represents the eigenfrequency of the suspended Spacelab module and that the 7-Hz component represents the eigenfrequency of the Spacelab rack row. In addition

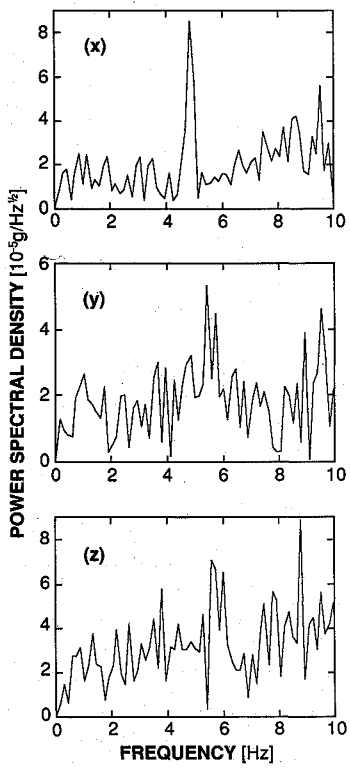

Fig. 5 Power spectral densities from the three individual accelerometer axes representing a crew induced disturbance. Data are rotated into orbiter structural axes and Butterworth filtered at 13 Hz. Note presence of components of various strengths in the 4.5–5.5 and 7–8 Hz ranges.

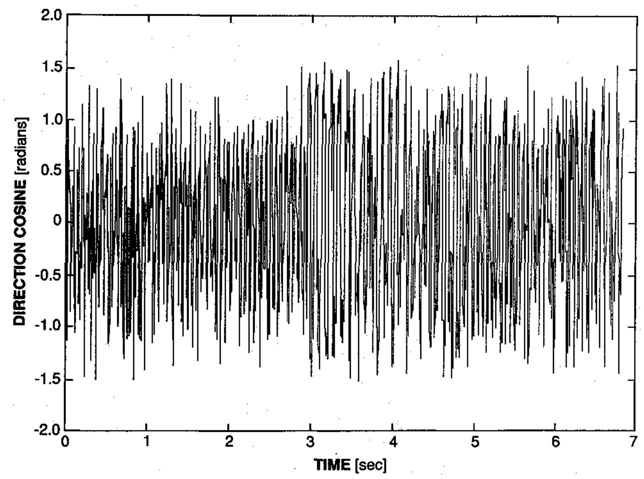

Fig. 6 Orientation of measured acceleration shown in Fig. 1 with respect to recording axis, $\alpha = \cos^{-1}(a_1/a)$. Note rapidly fluctuating behavior with marked change in character approximately three seconds into the window, representing large disturbance.

to these Spacelab modes, there are orbiter modes related to similar frequencies. A frequency of 5.2 Hz represents the fuselage first normal bending mode and 7.4 Hz represents the fuselage first lateral bending mode.[16]

In the analysis of SL3 residual acceleration data, 5- and 7-Hz frequency components were identified in the amplitude spectra of several windows we investigated. We compared examples of filtered SL3 data to power spectral densities from Hamacher et al.[8] (Fig. 4). Their data were collected at 107 samples/s with a bandwidth of 10 Hz. We identified several windows ($T_w = 6.8$ s) in the SL3 data that had fairly significant components present at frequencies < 10 Hz, and applied a 13-Hz Butterworth filter[12,16] to the data to aid in the comparison. The data were also rotated into coincidence with the recording axes of the D1 accelerometer system (orbiter structural axes) (Fig. 5). The various components do not line up exactly, but this is not surprising due to the different data collection and analysis techniques used. In addition, we do not know whether the sources of these two disturbances were at all similar. It is notable, however, that, even with the higher sampling and cutoff frequencies used for the SL3 data, these components are discernible above the background.

The final phase of processing the data windows discussed earlier is the calculation of direction cosines to determine acceleration orientation. For all windows tested and for all axes of data, the orientation of accelerations fluctuates rapidly between the positive and negative recording axes (Fig. 6). This is as expected for a system such as the orbiter where there are potential sources of disturbances at almost every point. Even barring sources of large accelerations, such as thruster firings and crew activity in the vicinity of accelerometers, other factors such as mechanical devices, general crew motion, and the steady acceleration sources contribute to a continuously fluctuating background level. When specific high-magnitude and/or oscillatory disturbances occur, a change in the character of the acceleration orientation can be seen. If a characteristic orientation of certain acceleration types can be determined, such information will aid in the analysis of experiments that are sensitive to disturbances in a particular direction. At this stage, however, it appears as if the accelerations recorded during SL3 fluctuate rapidly in orientation for most types of disturbances.

Discussion

Several general comments can be made about the low-gravity environment of the orbiter during the SL3 mission and about the future of residual acceleration measurements and low-g experimentation in orbiting space laboratories. The SL3 residual acceleration data are very noisy; background levels are consistently above limiting values deemed potentially intolerable to experiments. The general background level is $\leq 4 \times 10^{-3}g$ and consists of a broad range of frequencies, with rapid fluctuations in orientation.

Several characteristic signals have been identified in the SL3 residual acceleration data and grouped into four general categories: those caused by thruster firings, those mechanically induced, those induced by crew activity, and those of unknown origin. Most of these disturbances are transient and can have magnitudes as large as $10^{-2}g$ (Figs. 1). In the frequency domain, the amplitudes of the individual components associated with these disturbances are rarely greater in magnitude than $10^{-3}g$ and do not surpass any frequency limits used in this study (Figs. 1 and 2, Table 2). Further modeling of potentially sensitive experiments and further experimentation in orbiters should indicate whether such limits are realistic and what levels of disturbances may be detrimental to sensitive experiments.

Specific frequency components, 5 and 7 Hz, were discussed. Examples of such frequencies in the SL3 data were compared to examples from Hamacher et al.[8] Both crew activity within the Spacelab module and the firing of thrusters have been identified as sources that excite sets of modes at these frequencies. One set of modes is related to the Spacelab, whereas another set is related to the orbiter. For a given transient source, either or both sets of modes can be excited. Comparisons of acceleration magnitudes from individual axes may allow the identification of which specific modes are excited (Figs. 4 and 5).

To establish an acceleration characterization of a given orbiter, specific tests to distinguish between sets of modes will be necessary. Data from an array of accelerometers within the Spacelab module and throughout the orbiter, in conjunction with a well-documented time line of flight events, would aid in the assessment of what types of disturbances cause what levels of accelerations and how far the effects of such disturbances propagate throughout the craft. Tests involving known sources, for example, the opening and closing of specific doors in the Spacelab and the use of specific equipment by crew members, will also further the characterization of the orbiter environment.

Residual acceleration data collected in orbiting space laboratories have been described as random.[9] We raise some objections to this description and advocate care when not qualifying such comments. The basic question involved here is what aspect of the data is being described. The distribution of disturbance sources affecting the orbiter may best be described as temporally and spatially random. For example, during any given mission, disturbance sources such as the opening of latches and doors, the manipulation of equipment, and general crew motion, as well as thruster firings, water dumps, and other operational activities, occur in a random fashion, despite preflight scheduling of some operations. The likelihood of these disturbances occurring can be described by some probability distribution based on our knowledge of past missions.

The response of the orbiter at a given location (e.g., at the sensor site) to given disturbances, such as those stated earlier, however, can be predicted based on past experiments on the orbiter and modeling of the orbiter system. Such a response is considered deterministic. For example, as discussed previously, we know that certain activities within the Spacelab (hop and drop experiments, equipment manipulation) have associated characteristic frequency components, 5 and 7 Hz.[8] Among the identifiable orbiter modes, thruster firings appear to excite components in the 11-Hz range as well as orbiter structural modes around 5 and 7 Hz.[16] Future analysis of specific disturbance-acceleration-frequency response relations will result in a better understanding of the orbiter response to specific accelerations.

Conclusions

A prototype data reduction plan is being applied to SL3 residual acceleration data. The plan can be used to identify potentially intolerable acceleration events, to investigate acceleration orientation, to isolate and examine particular acceleration windows, and to identify probable acceleration sources. For the SL3 mission, a $4\times10^{-3}g$ time domain threshold limit was often exceeded and transient accelerations with magnitudes as large as $10^{-2}g$ were identified. Such acceleration events have frequency components (over 6.8-s to 3.6-min windows) no greater than $10^{-3}g$ and fluctuate rapidly in orientation. Although the occurrence of such accelerations in an orbiter is identified as both temporally and spatially random, the response of the orbiter is considered deterministic; it is this response, and the response of experiments, that we are ultimately interested in.

Continued monitoring of residual accelerations in orbiting space laboratories is important for several reasons. Such monitoring will help to better define the response of an orbiting system to typical disturbances and will also improve the accuracy of probability distributions used to define the occurrence of disturbance sources. These two factors are integral parts of the desired characterization of the low-gravity environment of orbiting space laboratories. Characterization of an orbiter's low-g environment, however, is not an easy task. Attempts made to date have only scratched the surface and additional data are needed to complete such a characterization.[1,3-9,16] A knowledge of experiment and orbiter responses will also help in the planning and development of future experiments and in the establishment of realistic time and frequency domain tolerance limits to be used in future analyses of residual acceleration data.

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Paul F. Mizera
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