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Center for Microgravity and Materials Research
The University of Alabama in Huntsville

THIRD ANNUAL REPORT

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Period of Performance
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RESIDUAL ACCELERATION DATA ON IML-1: DEVELOPMENT OF A DATA REDUCTION AND DISSEMINATION PLAN

PREPARED BY:

MELISSA J. B. ROGERS
J. IWAN D. ALEXANDER (Principal Investigator)
RANDY WOLF

Center for Microgravity and Materials Research
The University of Alabama in Huntsville
Huntsville, Alabama 35899

1. Introduction

The main thrust of our work in the third year of contract NAG8-759 has been the development and analysis of various data processing techniques that may be applicable to residual acceleration data. Our goal is the development of a data processing guide that low-gravity principal investigators can use to assess their need for accelerometer data and then formulate an acceleration data analysis strategy. The work on this contract has focused on the flight of the first International Microgravity Laboratory mission (IML-1). We have contacted those IML-1 principal investigators identified as interested in acceleration data and asked for their input regarding *our evaluation* of their accelerometer data needs. We are in the process of generalizing the processing guide so that investigators on future low-gravity missions can use it as a model for a residual acceleration data processing plan.

We are also developing a data base management system to handle large quantities of residual acceleration data. This type of system should be an integral tool in the detailed analysis of accelerometer data. The system will manage a large, graphics data base in support of supervised and unsupervised pattern recognition. The goal of the pattern recognition phase is to identify specific classes of accelerations so that these classes can be easily recognized in any data base. The graphics aspect of the management system includes several data visualization techniques that help the user better understand the nature of the acceleration signal being studied.

The data base management system is being tested on the Spacelab 3 (SL3) MESA residual acceleration data. In addition to working with that data base, during the third annual period we have processed STS-32 HISA data and accessed portions of the STS-40 SAMS data base.

We discuss the data processing guide and our development of the data base management system in section 2. Our implementation and testing of data processing techniques on several accelerometer data bases is outlined in section 3.

2. Data Processing

Data Processing Guide: The data processing guide, as distributed to IML-1 investigators, was included as Appendix A of the NAG8-759 fifth semi-annual report. We are in the process of generalizing the guide so that investigators on future low-gravity missions can use it to assess their need for accelerometer data and to model their data processing plan. The generalized Acceleration Data Processing Guide will be included in the final report for this contract. The guide consists of three sections of questions. Part A pertains to the location and timing of an experiment. Part B identifies times during the mission when an experiment may experience potentially intolerable accelerations and when the experiment may have increased sensitivity to accelerations. The information provided can be used before the mission to identify sections of accelerometer data that may be of interest to an investigator. Post-flight selection of data segments is based on the responses to Part C which addresses the experiment tolerance to quasi-steady accelerations and vibration (g-jitter).

Details of the processing guide were presented at the NASA LeRC International Workshop on Vibration Isolation Technology for Microgravity Science Applications, April 1991, and the AIAA 30th Aerospace Sciences Meeting, January 1992. These papers are included in Appendices A and B.

Data Base Management System: A data base management system is being developed to serve as the core of future residual acceleration data analysis. The system being developed provides data base management, pattern recognition, and data visualization capabilities to assist the analysis of the large quantity of residual acceleration data typically recorded during a low-gravity Orbiter mission.

The system will be based on the ANSI/SPARC model; the raw acceleration time series will constitute the internal layer. The conceptual layer will be created using data reduction techniques. This layer will consist of time windows of significant acceleration events. Any given time window will be described by one or more representation schemes. Potential representation schemes include time histories, spectral representations, and ergodic averages. Data visualization will be used to gain a basic understanding of the characteristics of the data that cannot be gained in any other fashion.

The data base management aspects will be realized through the Cdata Data Base Management System.[1] Cdata is an inexpensive relational data base system which is commercially available. The C source code is provided with the system and thus it is fairly easy to port from one computer system to another.

Pattern recognition techniques will be applied to the conceptual layer to identify characteristic acceleration signals. Both supervised and unsupervised pattern recognition will be used to assign signals to their respective pattern class. The supervised pattern recognition will stem from operator interaction with the data visualization portion of the system. The unsupervised recognition will be performed using the isodata algorithm and syntactic recognition.

The system is being tested on SL3 residual acceleration data and, when fully developed, will be suitable for use with other residual acceleration data bases. We have submitted an abstract discussing the data base management system to the COSPAR World Space Congress 92 meeting. This abstract in included in Appendix C.

3. Implementation on Existing Data Bases

For the first two years of NAG8-759, we used the SL3 MESA acceleration data base to develop and test various data processing techniques. During the third annual period, we continued to process the SL3 data, and we also received Honeywell In-Space Accelerometer (HISA) data from STS-32 and SAMS data from STS-40 (SLS1). Our work on the HISA data base complements the time history reports published in 1991 by the investigator team for the Fluids Experiment Apparatus.[2,3] The HISA was attached to this experiment. We present some results of this analysis later in this section.

Several time slices of SAMS data from the SLS1 mission were acquired from ACAP during the third annual period. We used the information provided in the ACAP STS-40 Quick

Look Report[4] to aid in our identification of various acceleration sources. We include some SAMS plots in this section.

The data base management system is being tested on the SL3 MESA residual acceleration data base. At the present time, this is still the data base to which we have easiest access. We anticipate using the system to manage and process IML-1 SAMS data when that data base becomes available from ACAP later in 1992.

Details of HISA operation on STS-32 are given in several post-flight reports.[2,5] We have submitted an abstract discussing our HISA data analysis to the COSPAR World Space Congress 92 meeting. This abstract is included in Appendix C. The HISA contains a triaxial arrangement of Sundstrand QA-2000 sensors. Data were recorded at both 1 Hz and 50 Hz sampling frequencies, but do not represent instantaneous acceleration. Rather they are averages of acceleration impulses between two sample periods. The data were digitized so that positive and negative averages were recorded separately. Because we are generally more interested in the magnitude of the acceleration vector at a location than in the individual axial acceleration readings (except for experiments with severe directional sensitivity), we used the six data files (± x, ± y, ± z) to form the vector magnitude with the root-sum-square method. Examples of HISA recordings of primary reaction control system firings, orbiter maneuvering system (OMS) firings, and crew treadmill activity are given in Figs. 1-5.

We transformed the HISA time histories into the frequency domain in a similar manner. Each of the six data files were Fourier transformed to give amplitude and power spectra. The six spectra were then combined for each window studied, Figs. 1-5. That this representation is appropriate is supported by testing on SLS1 data and by visual analysis of the calculated spectra. Standard structural modes were readily identified in the various spectra.. The lowest frequencies are, unfortunately, obscured to some extent by a remnant effect of the "±" digitization. The lowest frequency component resulting from a Fourier transformation of a time series is a representation of the d.c. or mean value of the series. The "±" digitization of the HISA data creates an artificial nonzero mean that translates into the d.c. component of the corresponding spectrum. Analysis of the 1 Hz HISA data, however, can be used to assess the frequency content below 0.5 Hz.

We have included five examples from the HISA data base. Fig. 1 shows a time history and amplitude spectrum for part of a firing sequence of the primary reaction control system. A high magnitude pulse occurs about 5 seconds into the record, with possible lower magnitude thrusts occurring at about 45 and 90 seconds. The amplitude spectrum indicates that several Orbiter structural modes are excited during this period, most notably in the 3, 5, 7, 10, and 13 Hz regions. The 17 Hz component which is related to the Ku band antenna dither and a nearby Orbiter structural mode is excited. The lower magnitude, narrow band signals at 16 and 20 Hz are somewhat unusual, and are being analyzed.

Fig. 2 shows the same types of plots for data collected during an OMS burn. The burn shows a pulse-like, high magnitude acceleration response at the mid-deck location of the HISA. Structural modes in the 3, 5, and 7 Hz range are excited.

Figs. 3-5 show HISA data collected during a period of crew exercise on the mid-deck treadmill. The treadmill was located approximately 7 feet from the HISA. Fig. 3 represents about one-half hour of data and shows different levels of vibrational g-jitter related to the different stages of the crew exercise protocol. Fig. 4 shows a time slice, and corresponding amplitude spectrum, of Fig. 3 during the higher magnitude phase. Fig. 5 is a slice from one of the lower magnitude phases. The most interesting aspect of these plots is the difference in the amplitude spectra. The spectra alone could be used to identify that the crew member was in a different exercise stage.

This is explained as follows. The higher magnitude segments of the treadmill data are dominated by a 2.7 Hz component. This frequency is related to an Orbiter structural mode and is being driven by the footfalls of the pilot as he exercises that stage of the protocol. In Fig. 5, a slower exercise rate is present (walking versus jogging, for example) and is represented by a lower frequency of footfalls. The 1.8 Hz component may be a higher harmonic of the 0.9 Hz component, or the two components may represent the crew member's upward and downward movements which differ in magnitude due to the treadmill restraint system. In this case, the 3.5 Hz structural mode is excited, possibly related to a doubling of the 1.8 Hz mode.

Similar phenomena can be seen in STS-40 and STS-43 SAMS data.[3,5] We have analyzed a limited amount of STS-40 SAMS data obtained from ACAP. The SAMS sensors for this mission were located in the Spacelab module, Fig. 6. Figs. 7-9 show some details of a one hour long window of data during which crew members were using both the mid-deck treadmill and the Spacelab ergometer. During this particular time slice, there was also a period of vernier engine firing. This activity is probably responsible for the vehicle modes that are more excited relative to the exercise related modes than in the HISA data.

Fig. 7 shows a time history and the corresponding amplitude spectrum for the SAMS Rack 7, Y-axis accelerometer head. Note that the frequency components at about 1.2, 2.4, and 3.2 Hz are probably related to the pedalling and walking frequencies on the ergometer and treadmill. The 3.7 and 4.7 Hz frequencies represent excited structural modes. Fig. 8 shows a time slice from late in the one hour period, where it appears that there is no crew exercise. Note the change in overall magnitude at about 2500 seconds in Fig. 7. From the amplitude spectrum in Fig. 8b, we can see that the exercise has finished by the absence of the exercise related frequency components. The reduced magnitude 4.7 Hz component implies that this mode was excited by either the exercise activity or the vernier firings which which were not used during this period.

Fig. 9 shows a section of data from early in the exercise period that includes a series of vernier firings. Two firing episodes are recognized by an overall shift of the acceleration time series off of the typical zero mean. In the frequency domain, this translates to an increased d.c. component, Fig. 9b.

The above is typical of the type of analysis that is necessary to create an Orbiter acceleration environment characterization. Detailed study of data windows in both the time and frequency domains must supplement the ACAP Quick Look overviews of mission acceleration data.

References

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Figure Captions

Fig. 1. Example of a primary reaction control system firing recorded by the HISA in the mid-deck of Columbia on STS-32, 50 Hz data. a) Acceleration vector magnitude, b) Combined amplitude spectrum.

Fig. 2. Example of an orbiter maneuvering system firing recorded by the HISA in the mid-deck of Columbia on STS-32, 50 Hz data. a) Acceleration vector magnitude, b) Combined amplitude spectrum.

Fig. 3. Example of acceleration level during crew treadmill exercise period recorded by the HISA in the mid-deck of Columbia on STS-32, 50 Hz data. Note the different acceleration levels corresponding to different stages of the treadmill exercise protocol.

Fig. 4. Segment of higher magnitude data from Fig. 3. a) Acceleration vector magnitude, b) Combined amplitude spectrum. Note the 2.7 Hz structural mode excited by footfall frequency.

Fig. 5. Segment of lower magnitude data from Fig. 3. a) Acceleration vector magnitude, b) Combined amplitude spectrum. Note the lower footfall frequency.

Fig. 6. Location of SAMS sensors in the Spacelab on Columbia during STS-40.

Fig. 7. Example of acceleration level during crew treadmill exercise, ergometer usage, and vernier reaction control system firings as recorded by SAMS Rack 7, Y-axis accelerometer head in the Spacelab on Columbia during STS-40, 25 Hz data. a) Acceleration vector magnitude, b) Combined amplitude spectrum. Note 1.2, 2.4, and 3.2 Hz components probably related to the pedalling and walking frequencies on the ergometer and treadmill. The 3.7 and 4.7 Hz components represent excited structural modes.

Fig. 8. Segment of data from Fig. 7. Crew exercise and vernier firings are complete. a) Acceleration vector magnitude, b) Combined amplitude spectrum. Note absence of exercise related frequency components.

Fig. 9. Segment of data from Fig. 7. At least two vernier firings can be seen showing a characteristic shift in the acceleration mean level. a) Acceleration vector magnitude, b) Combined amplitude spectrum. Note increased d.c. component in spectrum related to mean offset.

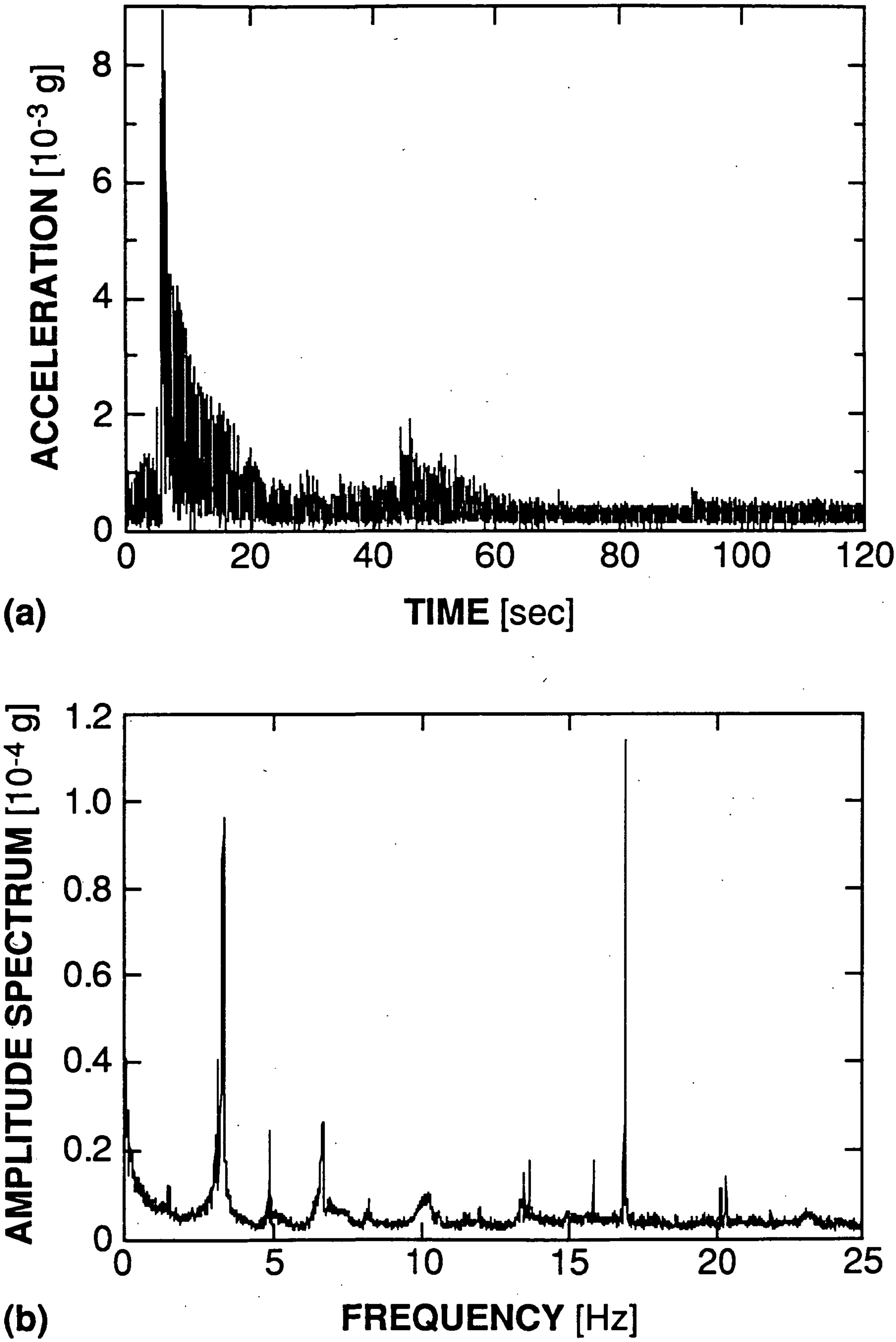
ACCELERATION [10-3 g]
8
6
4
2
0
0
20
40
60
80
100
120
(a)
TIME [sec]
AMPLITUDE SPECTRUM [10-4 g]
1.2
1.0
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
(b)
FREQUENCY [Hz]

FIG. 1

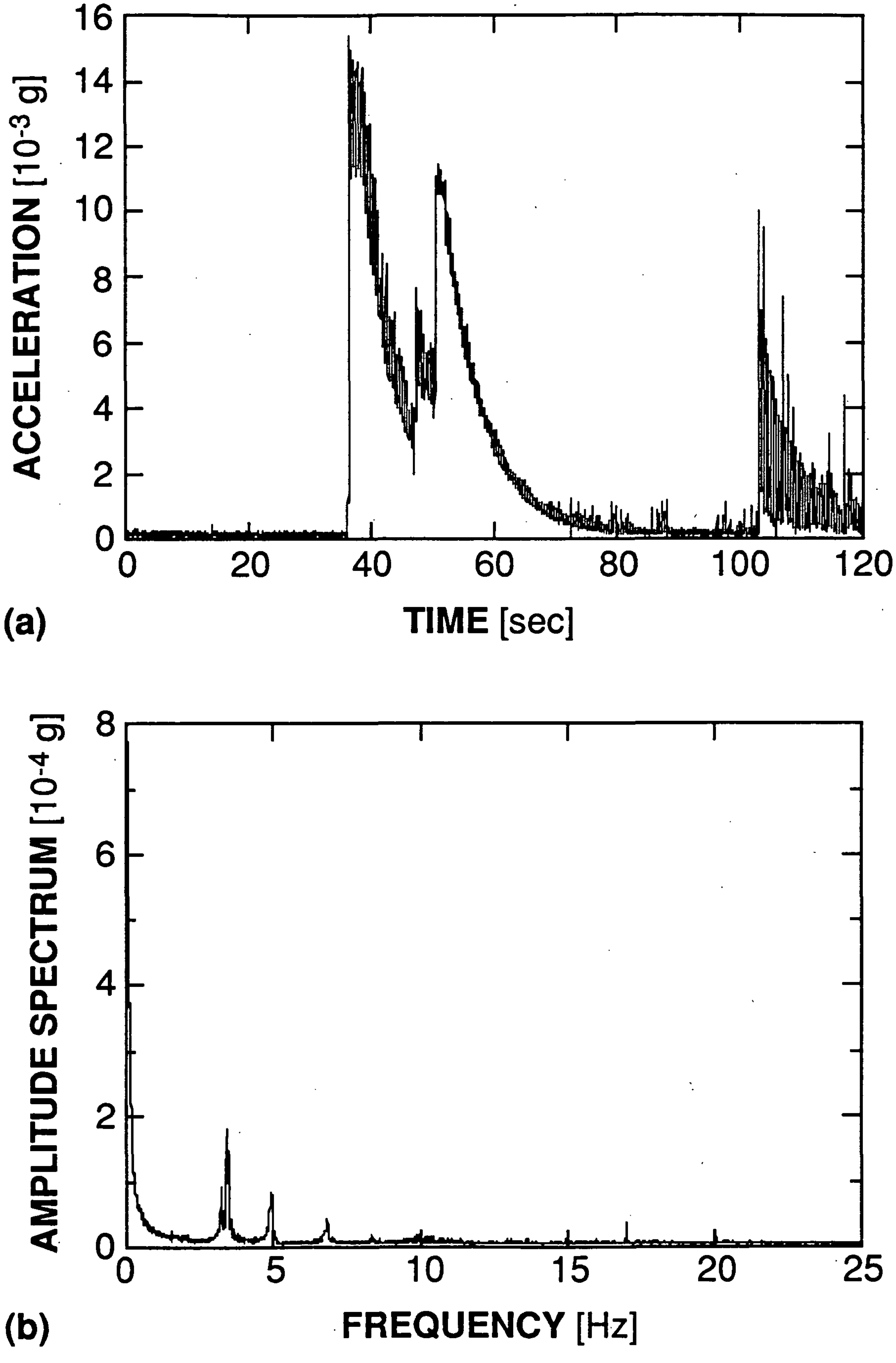
16
14
12
10
8
6
4
2
0
ACCELERATION [10^{-3} g]
0
20
40
60
80
100
120
(a)
TIME [sec]
8
6
4
2
0
AMPLITUDE SPECTRUM [10^{-4} g]
0
5
10
15
20
25
(b)
FREQUENCY [Hz]

FIG. 2

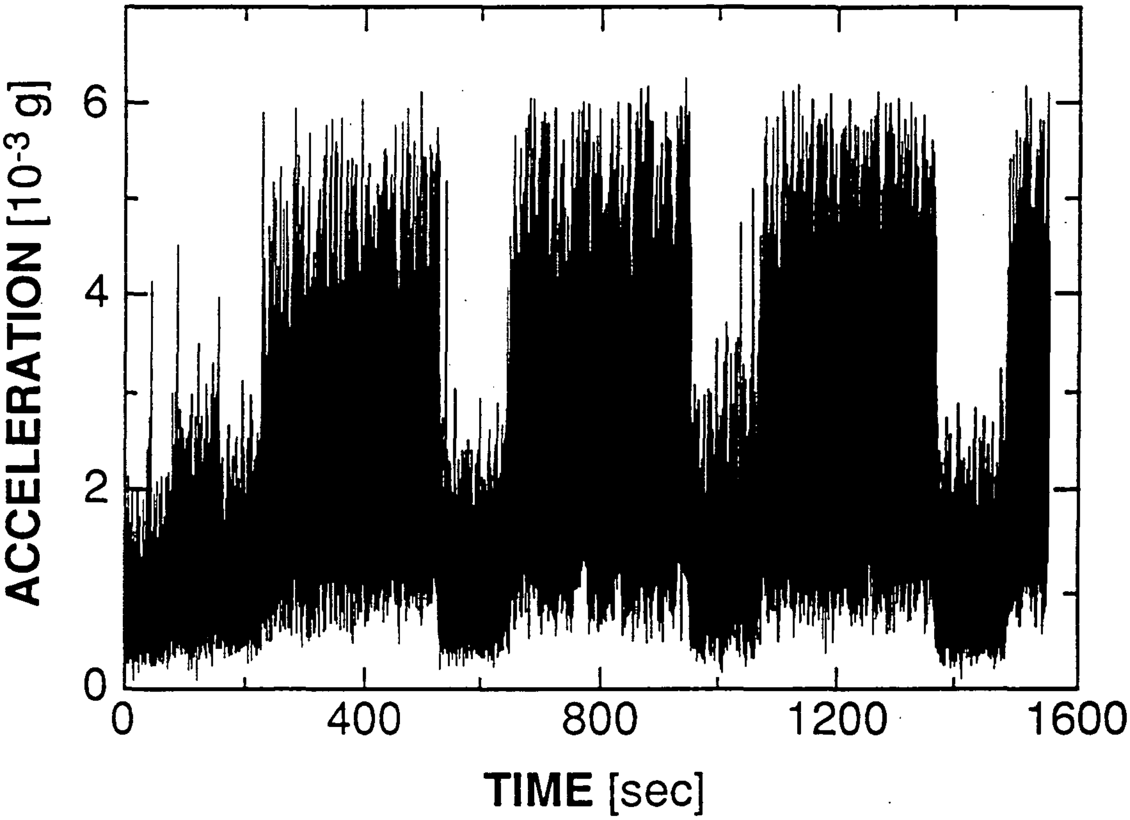

FIG. 3

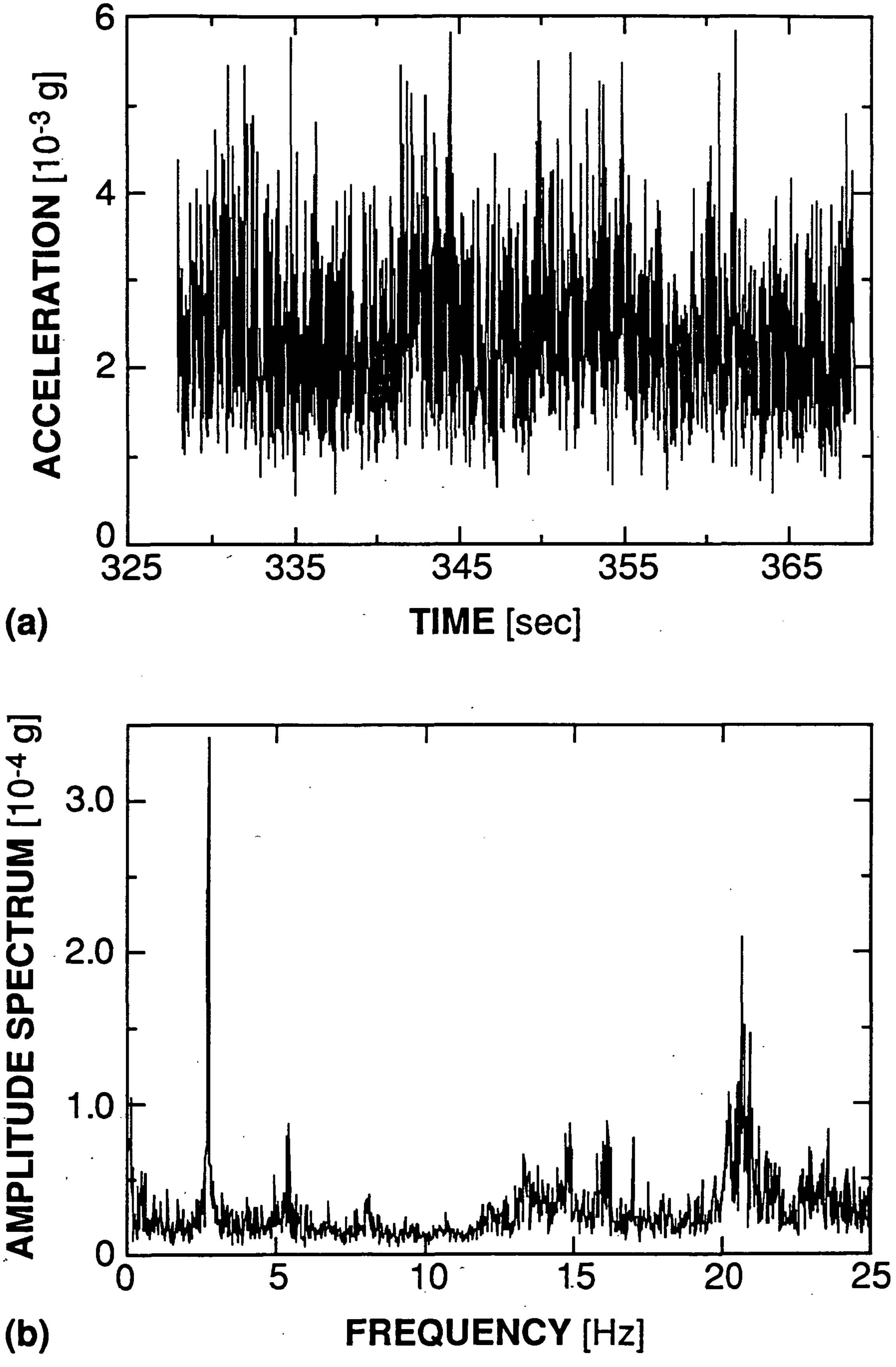
ACCELERATION [10-3 g]
0
2
4
6
325
335
345
355
365
(a)
TIME [sec]
AMPLITUDE SPECTRUM [10-4 g]
0
1.0
2.0
3.0
0
5
10
15
20
25
(b)
FREQUENCY [Hz]

FIG. 4

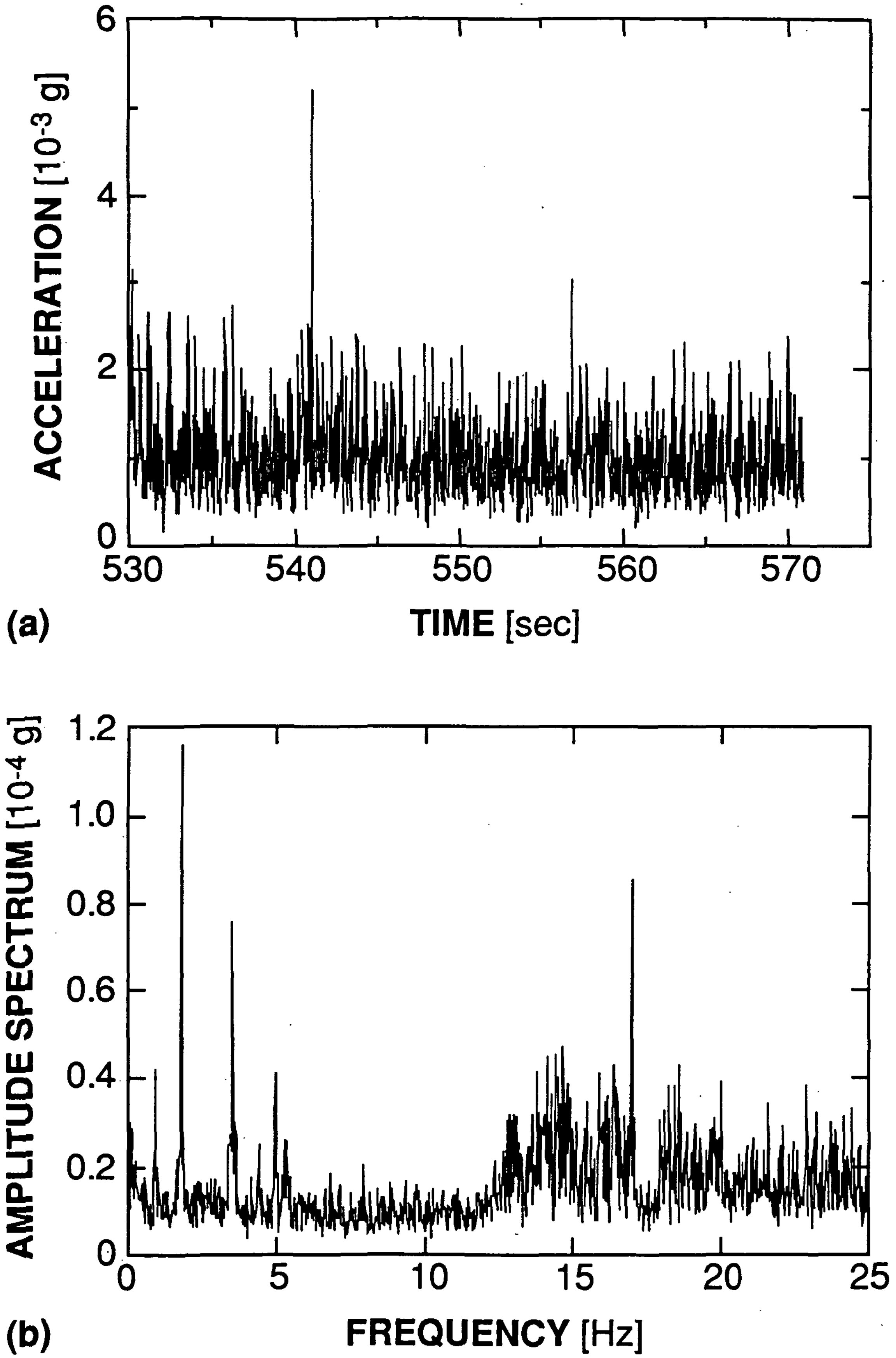
ACCELERATION [10^{-3} g]
6
4
2
0
530
540
550
560
570
(a)
TIME [sec]
AMPLITUDE SPECTRUM [10^{-4} g]
1.2
1.0
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
(b)
FREQUENCY [Hz]

FIG. 5

SPACELAB MODULE

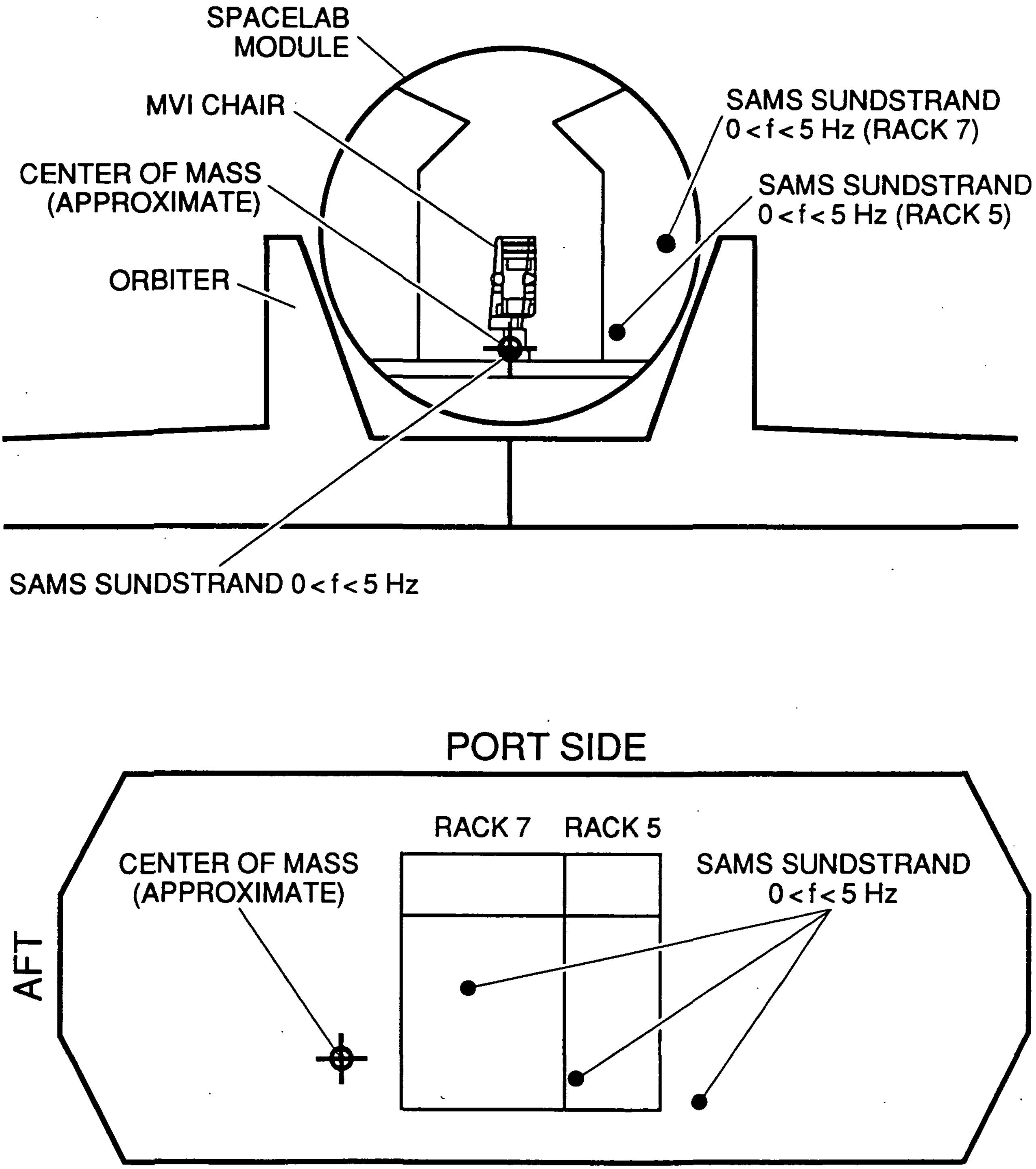

FIG. 6

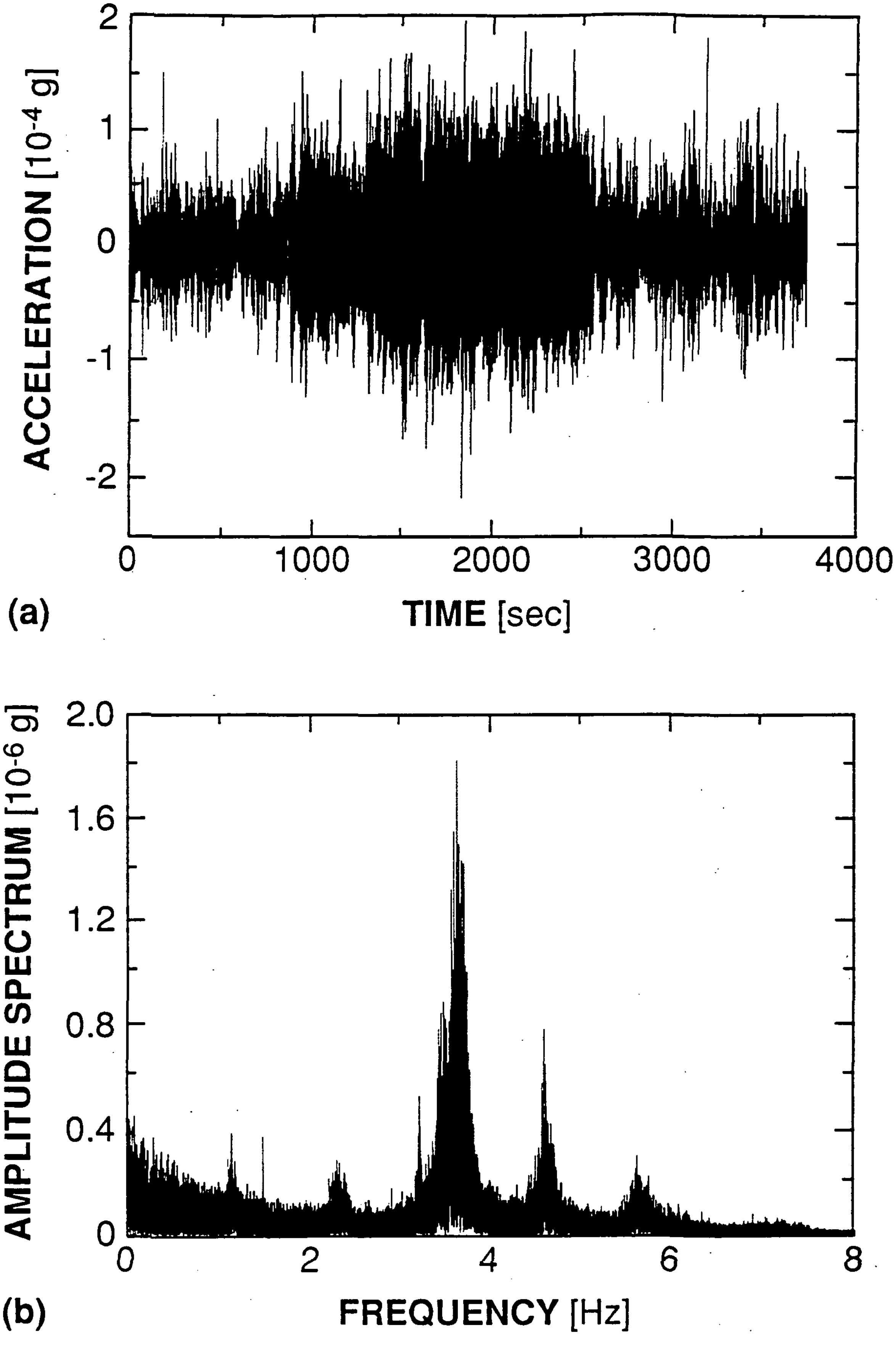
2
1
0
-1
-2
ACCELERATION [10-4 g]
0
1000
2000
3000
4000
(a)
TIME [sec]
2.0
1.6
1.2
0.8
0.4
0
AMPLITUDE SPECTRUM [10-6 g]
0
2
4
6
8
(b)
FREQUENCY [Hz]

FIG. 7

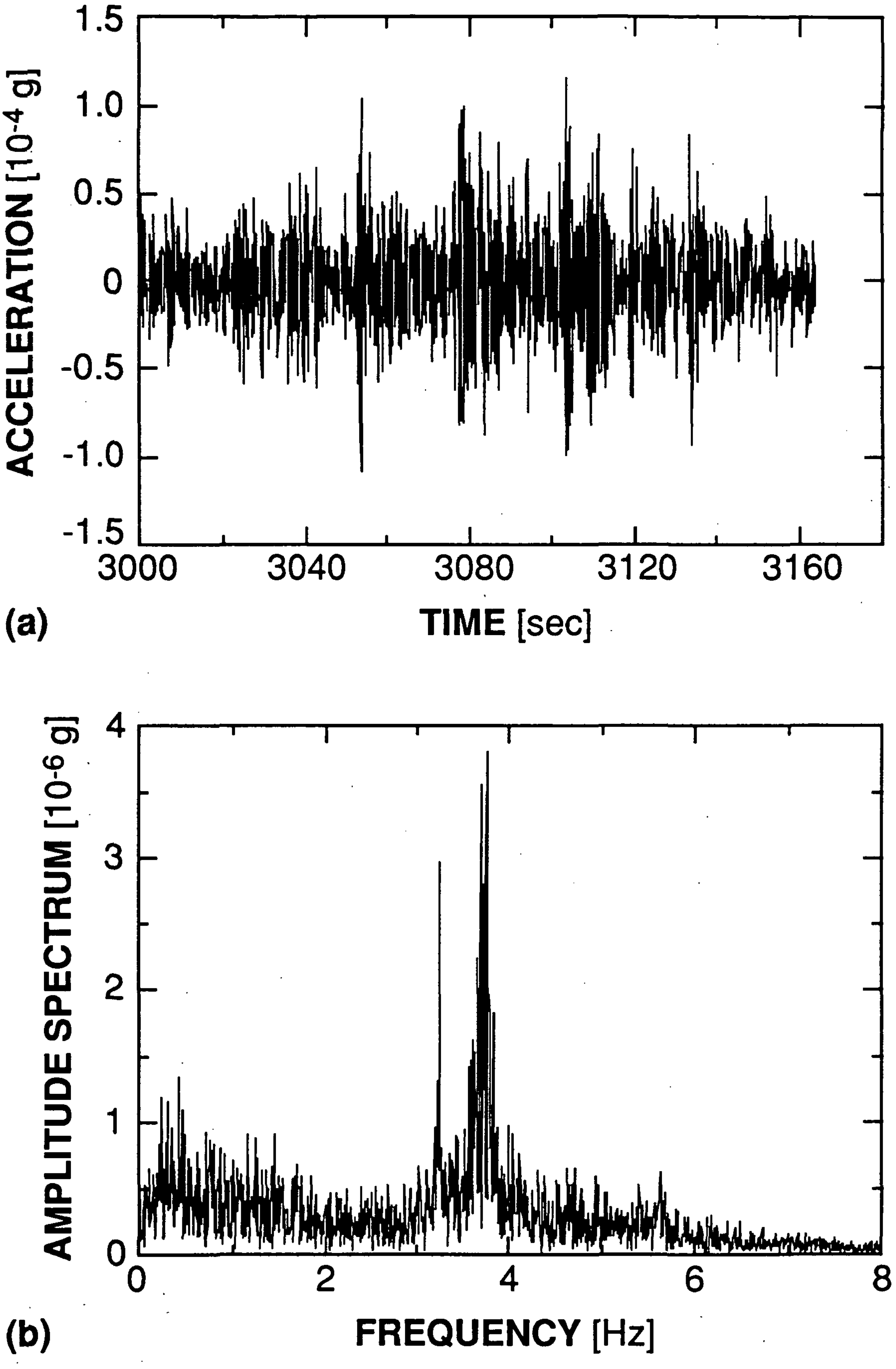
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
ACCELERATION [10^-4 g]
3000
3040
3080
3120
3160
(a)
TIME [sec]
4
3
2
1
0
AMPLITUDE SPECTRUM [10^-6 g]
0
2
4
6
8
(b)
FREQUENCY [Hz]

FIG. 8

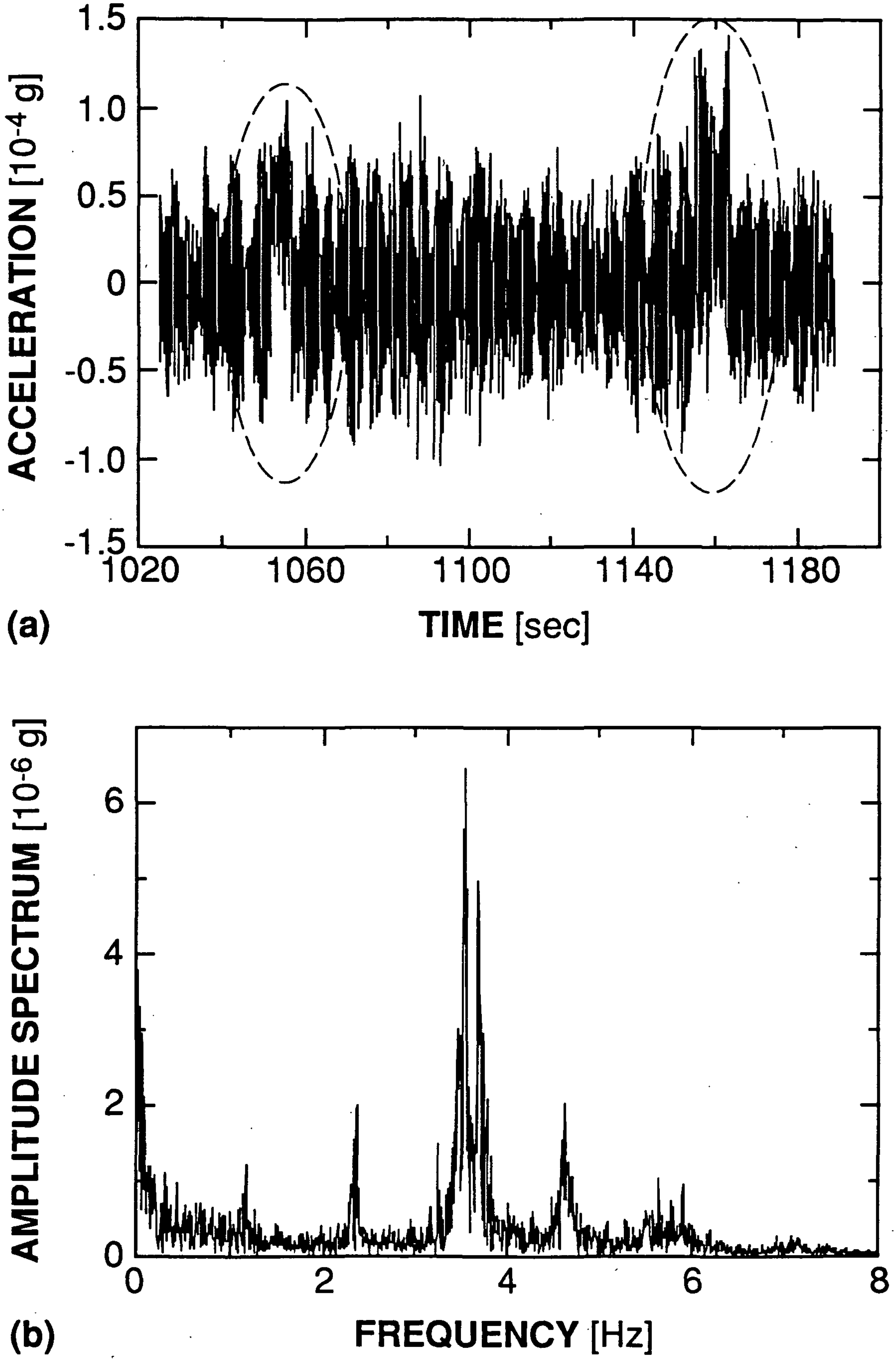
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
ACCELERATION [10-4 g]
1020
1060
1100
1140
1180
TIME [sec]
(a)
6
4
2
0
AMPLITUDE SPECTRUM [10-6 g]
0
2
4
6
8
FREQUENCY [Hz]
(b)

FIG. 9

Appendix A. Development of a Residual Acceleration Data Reduction and Dissemination Plan, M.J.B. Rogers

Presented at the International Workshop on Vibration Isolation Technology for Microgravity Science Applications, NASA Lewis Research Center, April 1991.

DEVELOPMENT OF A RESIDUAL ACCELERATION DATA REDUCTION AND DISSEMINATION PLAN

Melissa J. B. Rogers
Center for Microgravity and Materials Research
University of Alabama in Huntsville
Huntsville, Alabama 35899

ABSTRACT

A major obstacle in evaluating the residual acceleration environment in an orbiting space laboratory is the amount of data collected during a given mission: gigabytes of data will be available as SAMS units begin to fly regularly. Investigators taking advantage of the reduced gravity conditions of space should not be overwhelmed by the accelerometer data which describe these conditions. We are therefore developing a data reduction and analysis plan that will allow principal investigators of low-g experiments to create experiment specific residual acceleration data bases for post-flight analysis. The basic aspects of the plan can also be used to characterize the acceleration environment of earth orbiting laboratories.

Our development of the reduction plan is based on the following program of research:

- The identification of experiment sensitivities by order of magnitude estimates and numerical modelling [1],
- Evaluation of various signal processing techniques appropriate for the reduction, supplementation, and dissemination of residual acceleration data, and
- Testing and implementation of the plan on existing acceleration data bases.

Discussions of the basic analysis techniques we are using and of the results of our analysis of the Spacelab 3 data base can be found in references [2-5]. Three initial aspects of residual acceleration data that can be analyzed are the acceleration vector magnitude and orientation and the relative strengths of the frequency components that make up the data window of interest. The acceleration time history can be subjected to a variety of statistical analyses and can be manipulated into a range of data presentation styles aimed at the identification of potentially intolerable acceleration events while reducing the number of data points plotted.

The orientation of the residual acceleration vector with respect to some set of coordinate axes is important for experiments with known directional sensitivity. Orientation information can be obtained from the evaluation of direction cosines.

Fourier analysis is commonly used to transform time history data into the frequency domain. Common spectral representations are the amplitude spectrum which gives the average of the components of the time series at each frequency and the power spectral density which indicates the power or energy present in the series per unit frequency interval.

The data reduction and analysis scheme developed involves a two tiered structure to 1) identify experiment characteristics and mission events that can be used to limit the amount of accelerometer data an investigator should be interested in and 2) process the data in a way that will be meaningful to the experiment objectives. A general outline of the plan follows:

LEVEL ONE

1. Pre-flight identification of acceleration sensitivity to determine frequency and magnitude ranges of interest and experiment tolerance limits.

2. Pre-flight identification of times at which the experiment is liable to be vulnerable, i.e., some experiments may be more sensitive at specific stages (e.g. protein crystal growth during the nucleation stage).
3. Preliminary post-flight analysis of experimental results to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.

LEVEL TWO

1. Selection of time windows of interest using a threshold detection routine based on sensitivities identified in Level One, Step 1 above.
2. Use of data decimation techniques, when appropriate, to reduce the number of data points needed to evaluate lengthy windows of data.
3. Specific analysis of windows of data identified in Level One and the first step of Level Two, including estimation of mean and mean squared values, determination of the acceleration vector orientation, and spectral analysis to investigate the magnitude of the frequency components for the specific time window of interest.
4. Evaluation of accelerometer data in conjunction with experimental results to identify causal relationships and revise sensitivity limits.

Cross-correlation analysis of accelerometer data and experimental output is suggested as a viable means of identifying causal relationships between specific acceleration events and noticeable experiment perturbations [4].

We have devised a contact sheet for IML1 principal investigators that gives an overview of the basic types of residual acceleration data processing that can be useful, including example plots. In order to make this more meaningful to the investigators, we have suggested specific data windows that should be of interest to them, based on the current mission timeline and our evaluation of their experiment sensitivity to acceleration. The use of such a plan will make the evaluation of the residual acceleration environment during a particular experiment considerably less time consuming than processing the entire accelerometer data base.

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Appendix B. Experiment Specific Processing of Residual Acceleration Data,

M.J.B. Rogers and J.I.D. Alexander

AIAA 92-0244

Experiment Specific Processing of Residual Acceleration Data

M.J.B. Rogers and J.I.D. Alexander
Center for Microgravity and Materials Research
The University of Alabama in Huntsville
Huntsville, Alabama 35899

30th Aerospace Sciences Meeting & Exhibit

January 6-9, 1992 / Reno, NV

AIAA-92-0244

EXPERIMENT SPECIFIC PROCESSING OF RESIDUAL ACCELERATION DATA

Melissa J. B. Rogers and J. Iwan D. Alexander
Center for Microgravity and Materials Research
University of Alabama in Huntsville
Huntsville, Alabama 35899 USA

Abstract

A synthesis of experimental output and correlated accelerometer data is necessary for investigators to fully understand the results of low-gravity experiments. Both quantitative and visual correlation techniques can be used to determine the effects of quasi-steady and higher frequency accelerations on these experiments. In addition to improving our quantitative understanding of experiment sensitivity, the results of experiment and accelerometer data processing will lead to the systematic characterization of the Spacelab acceleration environment. This will enable investigators to plan their experiments so as to minimize residual acceleration effects and, therefore, take advantage of limited flight opportunities.

Modelling of low-gravity experiments has indicated that different classes of experiments are sensitive to different types of residual accelerations. Current space accelerometer systems measure high magnitude, high frequency, transient and oscillatory residual accelerations ($\leq 10^{-2}$ g, 0.1 - 100 Hz). Lower amplitude, low frequency ($< 10^{-4}$ g, < 0.1 Hz) accelerations due to atmospheric drag and gravity gradient effects are also present. These quasi-steady accelerations are generally overwhelmed in recorded data by transient and oscillatory accelerations. We will introduce a simple, passive accelerometer system developed to measure low frequency accelerations. The results of this experiment will improve our understanding of the quasi-steady accelerations experienced in the Spacelab with respect to both the general low-g environment and the effects on low-g experiments.

To test the idea that recorded acceleration data and experimental responses can be usefully correlated, we have produced model responses for experiments using actual acceleration data and made correlations between experiment response and the accelerometer time history. We have used Spacelab 3 accelerometer data as input to a variety of experiment models and have obtained sensitivity limits for particular experiment classes. These modelling results differ from earlier sensitivity estimates because the models use actual acceleration data in addition to simple sinusoidal and transient/pulse accelerations. The results of this type of modelling, order of magnitude estimates, and investigator input are being used to create experiment specific residual acceleration data processing schemes for interested IML-1 investigators. The detailed plan will help identify data windows to study, based on experiment sensitivity to accelerations and preliminary analysis of experiment results.

1. Introduction

A synthesis of experimental output and correlated accelerometer data is necessary for investigators to fully understand the results of low-gravity experiments. Both quantitative and visual correlation techniques can be used to determine the effects of quasi-steady and higher frequency accelerations on these experiments. The results of such correlations improve our understanding of experiment sensitivities to accelerations and allow us to develop a characterization of specific acceleration sources on orbiting laboratories.

Investigation of low-gravity experiments indicates that all types of residual accelerations can affect experimental results.[1-5] Unfortunately, low frequency data that may be collected with conventional accelerometer systems are overwhelmed by higher frequency, higher magnitude g-jitter. We have, therefore, only been able to make numerical estimates of the magnitudes of quasi-steady accelerations. A simple, passive accelerometer has been developed, based on the concept of Stokes drag, that will be used to measure atmospheric drag and gravity gradient accelerations on Columbia during USML-1. The data collected will be used in conjunction with higher frequency acceleration data to map the low-g environment and for experiment - acceleration correlation.

The amount of residual acceleration data collected during a low-gravity mission is excessive. This makes the identification of interesting data windows and the processing of these windows difficult. We have, therefore, developed a residual acceleration data processing scheme that can be easily tailored for the analysis of a given space experiment. The plan will be used to select acceleration events from the data base that have the greatest potential for affecting the experiment being analyzed, and to process these data windows to best assess and characterize the acceleration environment. The resulting limited data base will be used to correlate acceleration events with experimental results.

An assessment of the use of the quantitative cross-correlation technique for experiment - acceleration data processing was presented at the 29th AIAA Aerospace Sciences Meeting[6] and is discussed briefly in section 2. The passive accelerometer is introduced in section 3. Section 4 includes an overview of the experiment specific data analysis plan and details of the processing techniques that can be used in experiment - acceleration data analysis.

2. Cross-correlation Analysis

Cross-correlation analysis has been identified as a viable means of assessing causal relationships between particular acceleration events and experiment results. This analysis technique is appropriate both for experiments sensitive to transient accelerations and for those sensitive to oscillatory accelerations.[6] It is a numerical process requiring both accelerometer and experiment data collected at the same sampling rate. In the case that regularly sampled data are not available, qualitative or unevenly sampled numerical data can be used to create a quantitative experiment data base using known characteristics of experiment-acceleration interaction.

We tested this technique on synthetic data representing the response of a directional solidification/melt convection experiment to acceleration data collected during the Spacelab 3 (SL3) mission. The experiment response was driven by a periodic acceleration imposed by the modelling process. A phase lag existed between the acceleration series and the experiment response, related to a "sloshing" effect of the melt. Cross-correlation analysis readily identified this periodic experiment response. The correlation between synthetic experiment and acceleration data including transient disturbances was also identified in our analysis.

3. Passive Accelerometer

A passive accelerometer has been developed to measure residual acceleration in an orbiting space laboratory caused by the atmospheric drag on an Orbiter and the gravity gradient effect related to the position of the accelerometer.[7] We expect these quasi-steady accelerations to have magnitudes in the micro-g range ($1\ g = 9.81\ ms^{-2}$) and frequencies on the order of the orbital frequency ($\leq 10^{-4}$ Hz). They cannot be extracted from the acceleration data collected with conventional accelerometer systems because of the relatively high magnitude and frequency background signals recorded.

The passive accelerometer is based on the concept of Stokes drag.[8] It consists of a fluid-filled glass tube containing a steel ball, Fig. 1. The system is attached to the Orbiter structure. When in use, the length of the tube is aligned with the Orbiter flight direction and the ball moved with a magnet to the distal tube end (relative to the flight direction). The ball is released and allowed to "fall" to the other end of the tube in response to the residual gravitational forces. The time required for the ball to travel a distance marked on the tube is measured. From this, and the fluid viscosity and ball size and density, the Stokes velocity and the residual acceleration experienced by the ball are calculated.

This measurement of the quasi-steady acceleration experienced in low-earth orbit will allow us to better assess the effects of residual acceleration on sensitive space experiments. These low frequency accelerations do not vary considerably between orbits at one location for a given mission. It is not necessary therefore, to take more than a few measurements at an experiment site during a mission. The use of this simple accelerometer will eliminate the difficult task of processing other recorded accelerometer data in an attempt to extract these accelerations from noisy, high magnitude, high frequency data.

4. Data Processing Plan

We propose a two level plan for the processing of residual acceleration data, to deal with the excessive amount of accelerometer data that results from typical low-gravity missions. This plan is outlined below.

Level One

1. Pre-flight identification of acceleration sensitivity to determine frequency and magnitude ranges of interest and experiment tolerance limits.
2. Pre-flight identification of times at which the experiment is liable to be most vulnerable. Some experiments may be most sensitive at specific stages, for example, protein crystal growth during the nucleation stage.
3. Preliminary post-flight analysis of experimental results to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.

Level Two

1. Selection of time windows of interest using a threshold detection routine based on sensitivities identified in Level One, Step 1 above.
2. Use of data decimation techniques, when appropriate, to reduce the number of data points needed to evaluate lengthy windows of data.
3. Specific analysis of windows of data identified in Level One and the first step of Level Two, including estimation

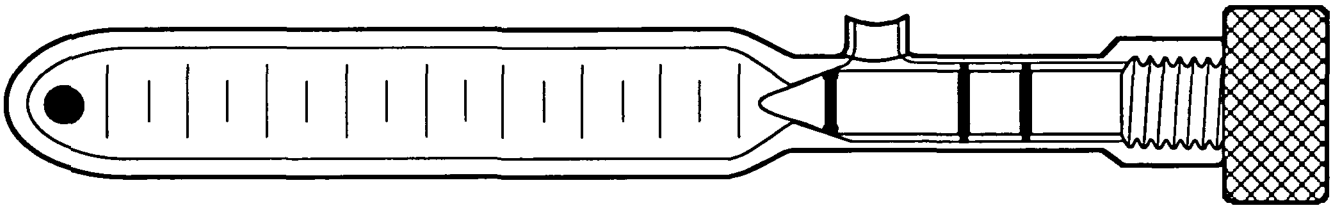

Fig. 1. Passive accelerometer.

of mean and mean squared values, determination of the acceleration vector orientation, and spectral analysis to investigate the magnitude of the frequency components for the specific time window of interest.

4. Evaluation of accelerometer data in conjunction with experimental results to identify causal relationships and revise sensitivity limits.

We addressed Level One processing in Rogers and Alexander (1991a & b).[9-10] Details of processing routines for Level Two analysis are discussed in this section.

4.1 Threshold Detection and Data Formatting

Segments of residual acceleration data which may be of interest to investigators can be identified by the use of a threshold detection routine. This is used to identify times when the magnitude of the recorded residual acceleration vector exceeds the sensitivity limits of a given experiment. It is assumed that the data represent, as accurately as possible, the residual acceleration environment that exists at the sensor location. This means that all temperature, instrument, and other biases should be properly removed from the data before analysis.

Specifics of this stage of processing include general data formatting, the calculation of various statistics, the formation of zero-mean series from the accelerometer data, the calculation of the acceleration vector magnitude, and the testing of the acceleration magnitude against sensitivity limits.

4.2 Fourier Transformation - Calculation of Amplitude Spectrum and Power Spectral Density

Fourier analysis is used to investigate the relative strengths of the frequency components of a given time series. Amplitude and power spectral densities give an indication of the dominant frequencies that compose the accelerations experienced at the sensor site. Specific frequencies are related to machinery vibration and rotation and structural modes of the Orbiter and Spacelab which are excited by a variety of internal and external sources.[9-12] A general outline of this stage of processing is:

- Read in three axes of zero-mean accelerometer data and transform each series into the frequency domain.
- Compute amplitude spectrum of each axis of data and normalize.
- Compute total magnitude of "amplitude spectrum vector" with a root-sum-square method.
- Compute power spectral density for each axis and total power spectral magnitude with a RSS method.
- Identify maximum valued frequency component from total magnitude information.
- Test total magnitude information against frequency domain limits, identify frequency and magnitude of occurrences over limits, and keep progressive count of these occurrences.

4.3 Rotation and Orientation

Rotation of residual acceleration data is necessary if the sensor heads are not aligned in the orientation of interest. It is necessary to know the angle of rotation between the existing and desired coordinate systems. Because we do not have detailed information about the acceleration sources, the structure of the vehicle and laboratory, and the nature of wave propagation through the structure, it is important to use acceleration data from the sensors closest to the region of interest.

The rotation convention that we use is as follows. When looking down a positive axis of rotation towards the origin, a counterclockwise rotation around that axis is considered positive. For both right- and left-handed coordinate systems, the following holds for positive rotations.

Rotation Axis	Direction of Positive Rotation
x	y into z
y	z into x
z	x into y

The acceleration components along the axes of a coordinate system of interest can be obtained from the original, recording axes by means of a transition matrix:

$$g_o = R_{oa}\, g_a .$$

The transition matrix R_{oa} is composed of direction cosines. R_{12} is the cosine of the angle between the x_o-axis and the y_a-axis in Fig. 2. The transition matrix can also be obtained through a change of vector basis. For a counterclockwise rotation:

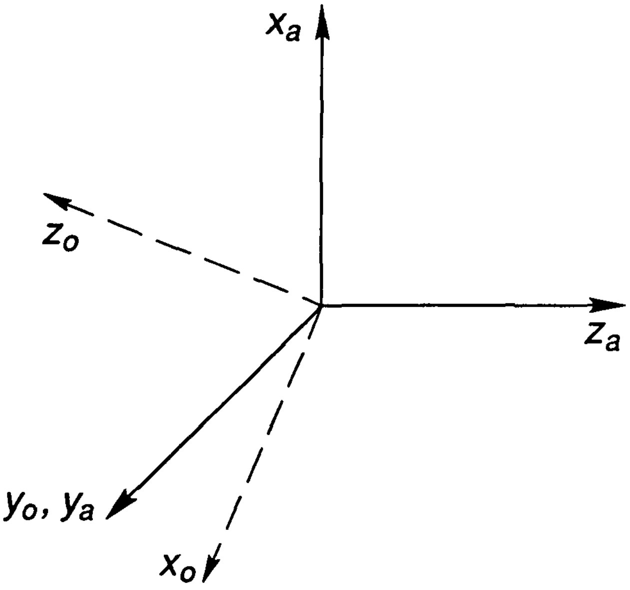

Fig. 2. Positive rotation of data from accelerometer coordinate system into Orbiter coordinate system. Rotation is about the y_a-axis.

$$R_{oa} \rightarrow \begin{bmatrix} \cos\theta & 0.0 & -\sin\theta \\ 0.0 & 1.0 & 0.0 \\ \sin\theta & 0.0 & \cos\theta \end{bmatrix}$$

where θ is the angle of rotation.[13-14]

The change of vector rotation matrix is generally easier to program and is therefore used in our processing. The rotation angle about a coordinate axis is the only information input to the program. For situations where rotation is about some axis other than a coordinate axis, the direction cosine rotation matrix must be used.

The orientation of the residual acceleration vector with respect to some set of coordinate axes is important for experiments with known directional sensitivity. The orientation of a vector in rectangular coordinates cannot be represented by a single value. Direction cosines are computed to denote the orientation of a recorded acceleration vector with respect to a set of coordinate axes. This stage of processing involves the input of the three axes of zero-mean accelerometer data, calculation of direction cosines of the acceleration vector with respect to coordinate axes, and calculation of amplitude spectra of direction cosine arrays if desired.

4.4 Filtering

Digital filtering is applied to data to investigate the time series patterns and magnitudes related to particular bands of frequencies. We give an example of a Butterworth filter as used for lowpass filtering. The Butterworth lowpass filter can be represented as:

$$|H(i\omega)|^2 = \frac{1}{\left[1 + \left(\frac{\omega}{\omega_0}\right)^{2m}\right]}$$

where m is the order of the filter, see Fig. 3. A general rule of thumb is that the attenuation outside the filter passband (defined by ω_0) in dB per octave is approximately 6m.[15-16] This stage of the processing routine is:

- Read in the three axes of zero-mean accelerometer data and transform into the frequency domain using an FFT, normalizing if necessary.
- Form the Butterworth filter, programming the above equation. The length of the filter should be the same as the number of points in the amplitude spectrum.
- Apply the filter to the data by multiplication of the filter with the amplitude spectrum of the data window.
- Return to the time domain with an inverse FFT (with appropriate normalization) to get filtered time series.
- Compute the magnitude of the filtered acceleration vector with a root-sum-square method.

5. Summary

To date, most Spacelab residual acceleration data collection projects have resulted in data bases that are overwhelming to the investigator of low-gravity experiments. We have proposed several techniques that will help an investigator limit the amount of acceleration data needed for the analysis of

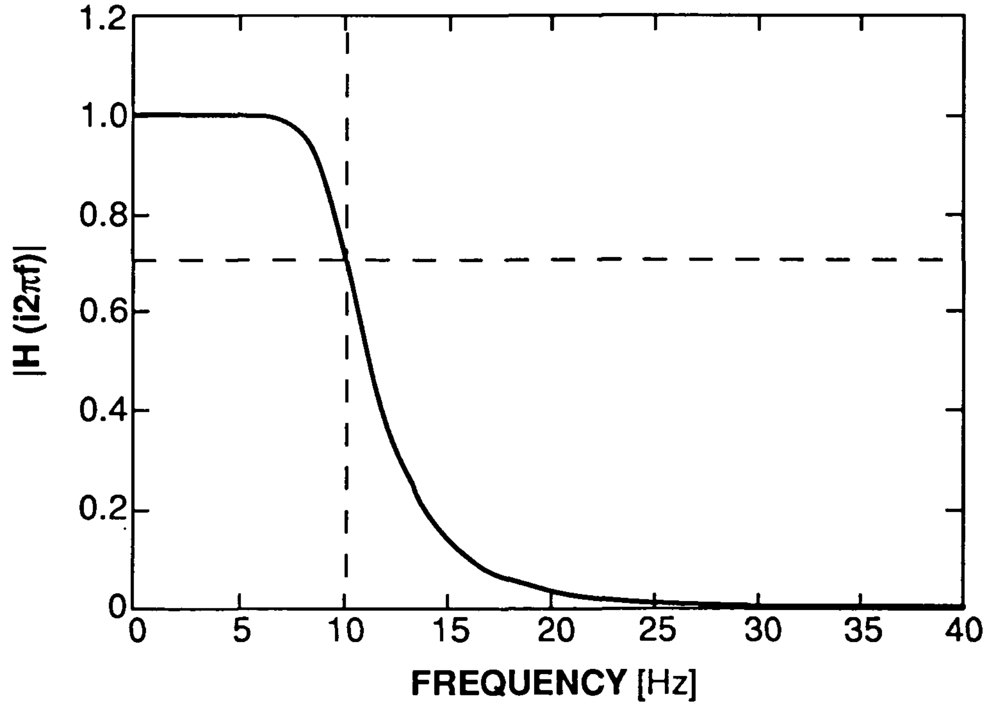

Fig. 3. Order m=5, 10 Hz lowpass Butterworth filter. Note that filter curve has value of 1/√2 at the cut-off frequency.

experimental results. A general processing plan is being used to assess the data needs of principal investigators of selected experiments on the IML-1 mission. Cross-correlation analysis is useful for the analysis of experiment response to both transient and oscillatory accelerations.

A simple, passive accelerometer will be flown in mid-1992 to examine the quasi-steady acceleration level that is overpowered in data recorded with more conventional accelerometer systems. Because these accelerations do not vary much at a given location from one orbit to the next, this system will be able to map the quasi-steady acceleration environment of an orbiting space laboratory with a limited amount of data collection.

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Appendix C. Abstracts submitted to the COSPAR World Space Congress 92 meeting.

A DATA BASE MANAGEMENT SYSTEM FOR RESIDUAL ACCELERATION DATA

R. Wolf, M.J.B. Rogers, and J.I.D. Alexander: Center for Microgravity and Materials Research, UAH, Huntsville, AL 35899 USA

We are developing a data base management system to handle the large quantity of residual acceleration data that results from a typical low-gravity Orbiter mission. The system will manage a large, graphic data base in support of supervised and unsupervised pattern recognition. The goal of the pattern recognition phase is to identify specific classes of accelerations so that these classes can be easily recognized in any data base. The data will be roughly partitioned following the ANSI/SPARC model. The entire mission time history will form the internal layer of the model. Data reduction techniques will identify limited time windows of interest. Time and frequency domain representations of these windows will compose the conceptual level of the model. The graphics aspect of the management system includes several data visualization techniques that help the user better understand the nature of the acceleration signal being studied. The data base management system is being tested on Spacelab 3 residual acceleration data and, when fully developed, will be suitable for use with other residual acceleration data bases.

DETAILED ANALYSIS OF HONEYWELL IN-SPACE ACCELEROMETER DATA - STS-32

M.J.B. Rogers and J.I.D. Alexander: Center for Microgravity and Materials Research, UAH, Hunstville, AL 35899 J. Schoess: Honeywell Inc., Bloomington, MN 55420 USA

The Honeywell In-Space Accelerometer flew in the mid-deck area of Columbia in January 1990 in support of the NASA Microgravity Disturbances Experiment (MDE). The MDE was designed to investigate the effects of g-jitter on the growth of indium crystals. This was the first Orbiter flight of an accelerometer resulting in well time lined examples of disturbances caused by Orbiter RCS firings, OHMS burns, and crew treadmill exercises. Acceleration vector magnitudes ranged from 10^{-4} g to $>10^{-2}$ g. Different phases of crew exercise on the treadmill can be identified in the data. Various Orbiter structural modes are identified in the magnitude spectra in the 1 to 10 Hz range. The sensitivity of a non-isothermal liquid bridge to residual accelerations was modelled and the results used to form time and frequency domain tolerance limits for a typical float zone experiment (including indium zones). Acceleration values recorded at the crystal growth site exceeded the time domain tolerance limits during PRCS firings, OHMS burns, and treadmill exercise. Frequency domain limits, however, were never exceeded.

Center for Microgravity and Materials Research
The University of Alabama in Huntsville