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Low-Frequency Vibration Environment for Five Shuttle Missions

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SUMMARY

This paper reviews the Microgravity Science and Applications Division's (MSAD) program to record and analyze the Shuttle's vibration environment. This program provides microgravity science investigators with time and frequency analyses of the acceleration environment during their experiments' operation. Information is also provided for future investigators on the expected Shuttle vibration environment. As background, the two major elements of the program are discussed, the Space Acceleration Measurement System (SAMS) and the Acceleration Characterization and Analysis Project (ACAP). A comparison of the acceleration measurements from five Shuttle missions is discussed.

ACRONYMS

ACAP	Acceleration Characterization and Analysis Project
IML	International Microgravity Laboratory mission series
MPESS	Mission Peculiar Equipment Support Structure
MSAD	Microgravity Sciences and Applications Division
RMS	Root Mean Square
SAMS	Space Acceleration Measurement System
SL-J	Spacelab J Mission
SLS-1	First Spacelab Life Science Mission
STS	Space Transportation System
USML	United States Microgravity Laboratory mission series
USMP	United States Microgravity Payload mission series

INTRODUCTION

This paper briefly reviews the acceleration measurement and analysis research sponsored by the Microgravity Science and Applications Division (MSAD) of the National Aeronautics and Space Administration's Office of Life and Microgravity Sciences and Applications. The goal of MSAD is to develop a comprehensive research program in fundamental sciences, combustion science, materials science, and biotechnology to attain a structured understanding of gravity-dependent physical phenomena and those physical phenomena obscured by the effects of gravity. Implicit in this goal is a requirement to measure and understand the acceleration environment during on-orbit microgravity experiments. In order to measure and record these accelerations, MSAD developed the Space Acceleration Measurement System (SAMS). To aid the principle investigators' comprehension of the huge amounts of data recorded during their experiments, MSAD instituted the Acceleration Characterization and Analysis Program (ACAP).

A description of the SAMS instruments and the ACAP is given followed by a summary of the low-frequency data measured from recent Shuttle flights: the first Spacelab Life Sciences (SLS-1), which flew on STS-40 (launched June 5, 1991); STS-43 (launched August 3, 1991); the first United States Microgravity Laboratory (USML-1), which flew on STS-50 (launched June 25, 1992); Spacelab-J (SL-J), which flew on flight STS-47 (launched August 12, 1992); and the first United States Microgravity Payload (USMP-1), which flew on STS-52 (launched October 22, 1992).

SPACE ACCELERATION MEASUREMENT SYSTEM

The primary objective of the SAMS project is to provide an acceleration measurement and recording system capable of serving a wide variety of microgravity science and technology experiments. SAMS is designed to measure and record low-gravity accelerations at as many as three experiment sites simultaneously. There are two versions of the SAMS instrument, the Middeck/Spacelab module units and the Spacelab Mission-Peculiar Equipment Support Structure (MPESS) configuration units (refs. 1 and 2). Typically, a SAMS instrument will bring back over a gigabyte of data from a mission and has collected as high as 4.7 gigabytes (GB) on the first International Microgravity Laboratory (IML-1), which flew on STS-42 (launched January 22, 1992).

The Middeck/Spacelab module SAMS configuration is designed for installation in the habitable environments of the Space Shuttle middeck and the Spacelab module. The unit consists of a main unit and three triaxial sensor heads. All four flight-certified Middeck/Spacelab module SAMS units have flown on at least one mission.

The front panel of the main unit provides crew access to control switches, indicators, and optical disks during the mission. The main unit contains electronics for control and data processing. Two optical disk drives provide continuous data recording during a mission.

The three remote triaxial sensor heads are connected to the main unit by three sensor head cables. The triaxial sensor heads detect accelerations with three orthogonal, single-axis acceleration sensors. Two sensor models with advertised sensitivities of 1 μg and 10 ng may be used. These single-axis sensors utilize a pendulous proof-mass and force-rebalance coils to sense accelerations. The three remote triaxial sensor heads may each be mounted on or near an experiment to measure accelerations experienced by the experiment.

The SAMS configuration for the Spacelab MPESS incorporates two sealed enclosures for operation in the harsh thermal and vacuum environment of space. The control unit contains electronics for control and data processing. Each data storage unit contains four disk drives. A SAMS MPESS configuration can accommodate one or two data storage units and support three triaxial sensor heads. The two flight-certified SAMS MPRESS units made their first flight on the USMP-1 mission.

The optical data disk used by SAMS has a capacity of 200 megabytes (MB) per side. For Middeck/Spacelab module applications these disks are accessible to the crew and can be changed during the mission to allow essentially unlimited data-recording capability. For the Spacelab MPESS applications, the design can accommodate up to six optical disk drives, and, in addition, raw data from this unit may also be downlinked to the Payload Operations Control Center for near-real-time data display and analysis. This capability was used extensively on the USMP-1 mission to facilitate telescience operations.

To date, the SAMS units have flow six missions and collected over 14.8 GB of data: SLS-1 (0.57 GB); STS-43 (2.79 GB); IML-1 (4.7 GB); USML-1 (1.36 GB); SL-J (2.45 GB); and USMP-1 (1.1 GB recorded, 1.9 GB downlink).

ACCELERATION CHARACTERIZATION AND ANALYSIS PROGRAM

Developing cause and effect relationships between low-level, on-orbit accelerations and microgravity science experiments is important in assessing experimental results and developing future experiments and facilities. The ACAP provides leadership in three primary areas: (1) acts as the project scientist for flight accelerometers and performs and coordinates flight data analyses; (2) assists investigators and mission scientist in understanding and evaluating the acceleration environment of microgravity experiment carriers; and (3) collects and organizes the effects of the acceleration environment on experiments in order to influence future missions.

As the project scientist for SAMS, ACAP works with the mission scientist and investigators to maximize the use of SAMS by determining the placement of the three triaxial sensor heads, the low-pass filter cutoff settings, and data rates.

After every SAMS mission, ACAP provides a summary report characterizing the mission's acceleration environment. The summary report is issued 2 to 3 months following a mission. ACAP also provides a detailed report on the technical operation of the SAMS instrument in a Sensor Report issued approximately 6 months following each flight. These two reports document the acceleration histories of the flights.

To assist the investigators and mission scientist in understanding the acceleration environment, ACAP draws on its knowledge of the carrier acceleration environment to work with the experimenters and avoid potential problems. For example, analyses of mission data may show large acceleration disturbances at certain frequencies that may perturb a planned experiment which is susceptible to accelerations in that frequency region.

ACAP collects and organizes the data on the effects of accelerations on microgravity experiments. The Space Station (SS) program has worked with MSAD and ACAP to develop a specification for the SS acceleration environment. ACAP has been able to supply information on past Shuttle flights and will work with SS to gather information on disturbances, in particular, crew disturbances, on future Shuttle flights.

Two to three times a year ACAP coordinates and conducts the Microgravity Measurement Group (MGMG). The MGMG serves as an international forum for discussing acceleration results with investigators, new acceleration measurement techniques, and vibration isolation technology. There have been 10 MGMG meetings since the first meeting was held in 1988. A major focus of these meetings has been to discuss coordination in these areas among the different space agencies sponsoring similar types of activities. The minutes from each MGMG meeting are routinely distributed to the participants and international space agencies.

ACAP has distributed four summary reports to microgravity investigators (STS-40, -42, -43, and -50) and is completing analyses on two others (STS-47 and -52) (reports unpublished at time of this report's printing).

MEASUREMENT TECHNIQUE

Although there have been occasional measurements of the Shuttle and Spacelab module acceleration environment by assorted sensors over the past decade, the analysis of data from the multiple flights of the SAMS instrument provides the capability to accomplish a systematic and complete characterization of the vehicle over a comprehensive set of operating conditions. The objective of the characterization is to provide microgravity investigators a basis for assessing the impact of the vehicle acceleration environment on their experiments and specifying design or operational controls to mitigate the effects of disturbances which would otherwise adversely affect the experiments. To this end, this paper summarizes the salient features of the observed background environment of the vehicle over the frequency range from a few tenths to 6 Hz.

This particular frequency range was chosen because of the importance of the lower frequencies to many of the microgravity investigations and the uniform availability of data over this range from the several missions flown by the SAMS instrument. The evaluation presented here shows representative data samples from the Spacelab module, the Middeck, and the Spacelab MPESS. As such, the observations form an empirical description of the vehicle environment. The consistency of these data further implies that the observations would be typical of any STS mission and can be used as a general guide for a first level assessment of vehicle influences in this frequency range.

The mission configuration and measurement range for the SAMS accelerometers used in this analysis are shown in table I. This table shows the comprehensive nature of the presented measurements which include samples from three different vehicles and all primary microgravity payload locations except for Get Away Special canisters. The measurement range has been included in the table since the instrumentation settings were not uniform across the data set. The range indicates the cutoff point for the internal SAMS filters which, for some cases, was below the 6 Hz presented in this paper. The affected measurements have not been corrected for the filter attenuation since the corrected data would not materially affect the conclusions to be drawn herein; however, for general interest, the sharp filters attenuate the instrument response by about a factor of two in the 5- to 6-Hz range in those particular sets filtered at 5 Hz.

MISSION COMPARISONS

Figure 1 shows a comparison of data from three Spacelab module missions from accelerometers mounted in Spacelab module experiment racks during a set of conditions labeled as Routine Crew Activity. The definition of this condition is somewhat subjective and was based more on the absence of special vehicle or crew activity than on a positive set of criteria. The data intervals were selected after inspecting mission video and/or mission logs to determine that (1) no crew exercise was in progress; (2) no vehicle maneuvers were being conducted; (3) no special operations were in progress (water dumps, Remote Manipulator System, satellite launches, etc.); and (4) the majority of the crew was engaged in quiet operational tasks. In addition, the survey plots from the entire mission were inspected in each case to verify that the selected data were indeed representative of the overall mission environment. The data in each plot are a power spectral density calculation performed on 50 sec of raw SAMS data and presented in units of $\mu g/\sqrt{Hz}$. The RMS value for the data on each plot is shown in the upper right. The coordinate system is the vehicle "structural system" in which the X-axis is down the length of the vehicle toward the aft, the Y-axis is the right wing, and the Z-axis is perpendicular through the top.

It is immediately evident, to first order, that the characteristics of all three data sets are very similar. The dominate feature in each is the presence of distinct spectral lines at specific frequencies. The X-axis is the quietest of the three with a faint peak between 3.5 and 4.0 Hz. The Y-axis shows two peaks in the 3.5- and 5.5-Hz range. The Z-axis is dominated by the largest disturbance of the group at about 4.7 Hz. The origin of these peaks is apparently from the excitation of vehicle structural modes, and their behavior (as will be shown in later examples) is consistent with this model. To date, however, the authors are unaware of any published study which establishes the location and possible variability of the modes and thus are relying on information communicated in informal conversations.

The comparison of observational examples for routine crew activity is continued in figure 2. In this figure the upper panel was chosen from a second location on STS-40 to show that the basic environment is a general condition within the Spacelab module experiment racks (compare this panel with the simultaneous measurement in the upper panel in fig. 1). The second and third panels show the vehicle environment from the two measurement examples which were taken from missions in which the Spacelab module was not present. Of these two, the STS-52 measurement from the Spacelab MPESS appears to fit fairly well within the bounds established in figure 1. This observation implies there is no large scale variation in the experiment vibration environment for this frequency range between Spacelab module and Spacelab MPESS locations. In addition, there is an implication that the Spacelab module has no appreciable effect on the dynamics of the vehicle in the range; however, a conclusion on this point should be substantiated by an analytical study.

The data set from STS-43, taken at a Middeck locker location, appears to vary the most within the five mission sets. In this case the response near 3.5 Hz is the dominate feature in the data and is present on all three axes. In addition, the apparent mode near 5.1 Hz is sufficiently different in frequency from the approximately 4.7-Hz mode observed in the other cases to raise the possibility that it is due to a separate response.

The examples in figure 3 were selected to bound the extremes in the vibration environment over the subject frequency range. Inspection of survey plots over the sets of mission data and a comprehensive set of operating conditions show the dominate contributing factor in this particular frequency band to be related to the level of crew activity. The upper panel in this figure shows the quiet levels during a period of crew sleep. Note the change of scale between the graphs in figure 3 and the scale of the graphs of figures 1 and 2. The observation is still dominated by the structural modes, but the general level has decreased by about an order of magnitude.

The second two plots in this figure were selected from periods of particularly robust exercise and are chosen to show the levels of disturbance which are possible if no measures are taken to suppress the effects of this type of activity. Again, note the change of scale in the graphs. The ergometer exercise in this figure was conducted in the Spacelab module on a bicycle-type device pedaled at a frequency of about 1.2 Hz. The fundamental pedaling frequency is just visible on the compressed scale in the X-axis. The third harmonic of the motion, approximately 4.8 Hz, appears to interact strongly with the Z-axis mode at about 4.7 Hz.

The treadmill exercise was performed on the Middeck, well separated from the accelerometers in the Spacelab. Again, the fundamental running motion at about 1.25 Hz is just visible in the X-axis plot. In this case, the third harmonic falls at about 5 Hz, which appears to be sufficiently separated from the 4.7-Hz Z-axis mode that the mode is not substantially excited. The large response at 2.5 Hz, however, implies the possible presence of a mode near that frequency which is not normally excited.

Due to the known disturbances of crew exercise, a program has been initiated at the NASA Johnson Space Center to develop means of isolating the exercise equipment such that the generated disturbances fall into a more acceptable range for sensitive experimentation. The most comprehensive test of this approach was performed on the STS-50 mission. Although the details of the isolation approach is beyond the scope of this paper, a set of representative data taken during this mission is shown in figure 4 to demonstrate the substantial improvement which can be obtained.

Three cases are shown in this figure. In the upper panel, the effects of undamped ergometer exercise in the flight deck is shown to establish the baseline. Note the plot scale on this top panel is the same as in the exercise cases in figure 3, while the scales in the other two plots are set to the levels of figure 1. The middle panel shows the effect of isolating the exercise device by passive elastic cords. The bottom panel shows the results of an active device. It is apparent from the data that this initial program was effective in reducing the disturbance levels to near those of the routine activity level. The major exceptions are the presence of the fundamental exercise frequency in the X-axis for the passive isolation and the enhanced level of the 4.7-Hz mode in the Z-axis for both systems.

CONCLUDING REMARKS

This set of data shows the background vibration environment for experiments in both the Spacelab module and the Spacelab MPESS to be consistent from mission-to-mission in the 0.1 to 6 Hz range. A major difference is the Middeck environment characteristics; however, even in this case the variation seems to be primarily related to the detailed behavior of the structural modes. The data show that the general background is characterized by a few sharp spectral peaks which stand well above the general, or an averaged average, background. This is true even when the disturbances are driven by exercise. Therefore, simple models which seek to describe the environment in terms of average levels are not sufficient to communicate its true characteristics. Because the modes play such a dominate role in the environment in this frequency range, it would appear appropriate to initiate a limited structural study of their likely sources and responses to determine if there is any ready means of damping or decoupling the excitation sources.

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2. DeLombard, R.; Finley, B.D.; and Baugher, C.R.: Development of and Flight Results From the Space Acceleration Measurement System (SAMS). NASA TM-105652, (Also, AIAA Paper 92-0354, 1992).

TABLE I.—MISSION AND MEASUREMENT CONFIGURATION

Number	Mission	Vehicle	Sensor head location	Measurement range, Hz
STS-40	First Spacelab Life Science (SLS-1)	Columbia	Spacelab rack	0 to 5
STS-43	TDRSS Launch	Atlantis	Middeck locker	0 to 50
STS-47	Spacelab J (SL-J)	Endeavor	Spacelab rack	0 to 50
STS-50	First U.S. Microgravity Laboratory (USML-1)	Columbia	Spacelab rack	0 to 5
STS-52	First U.S. Microgravity Payload (USMP-1)	Columbia	Cargo bay	0 to 10

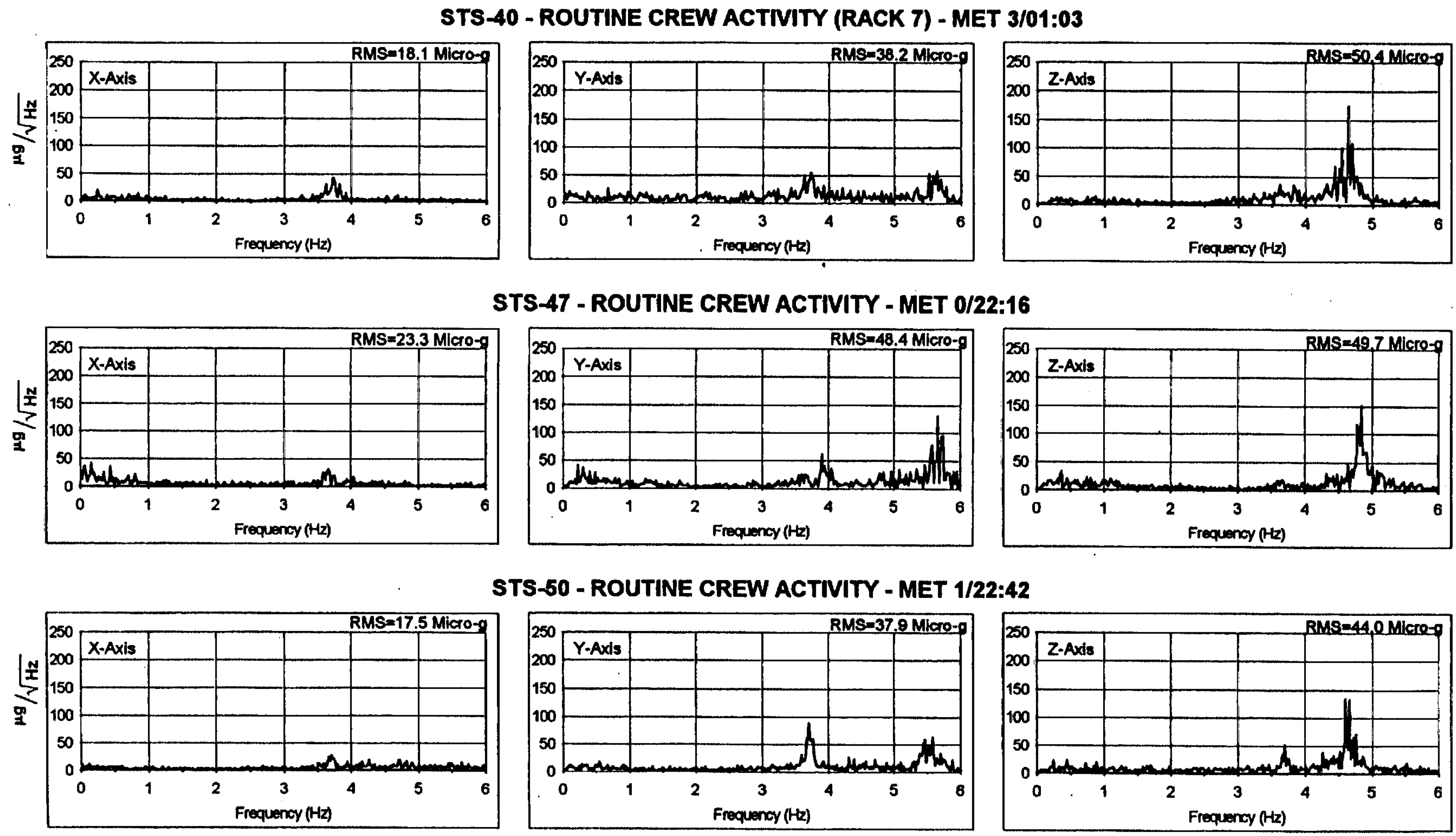

Figure 1.—Vibration environment during routine crew activity in Spacelab module.

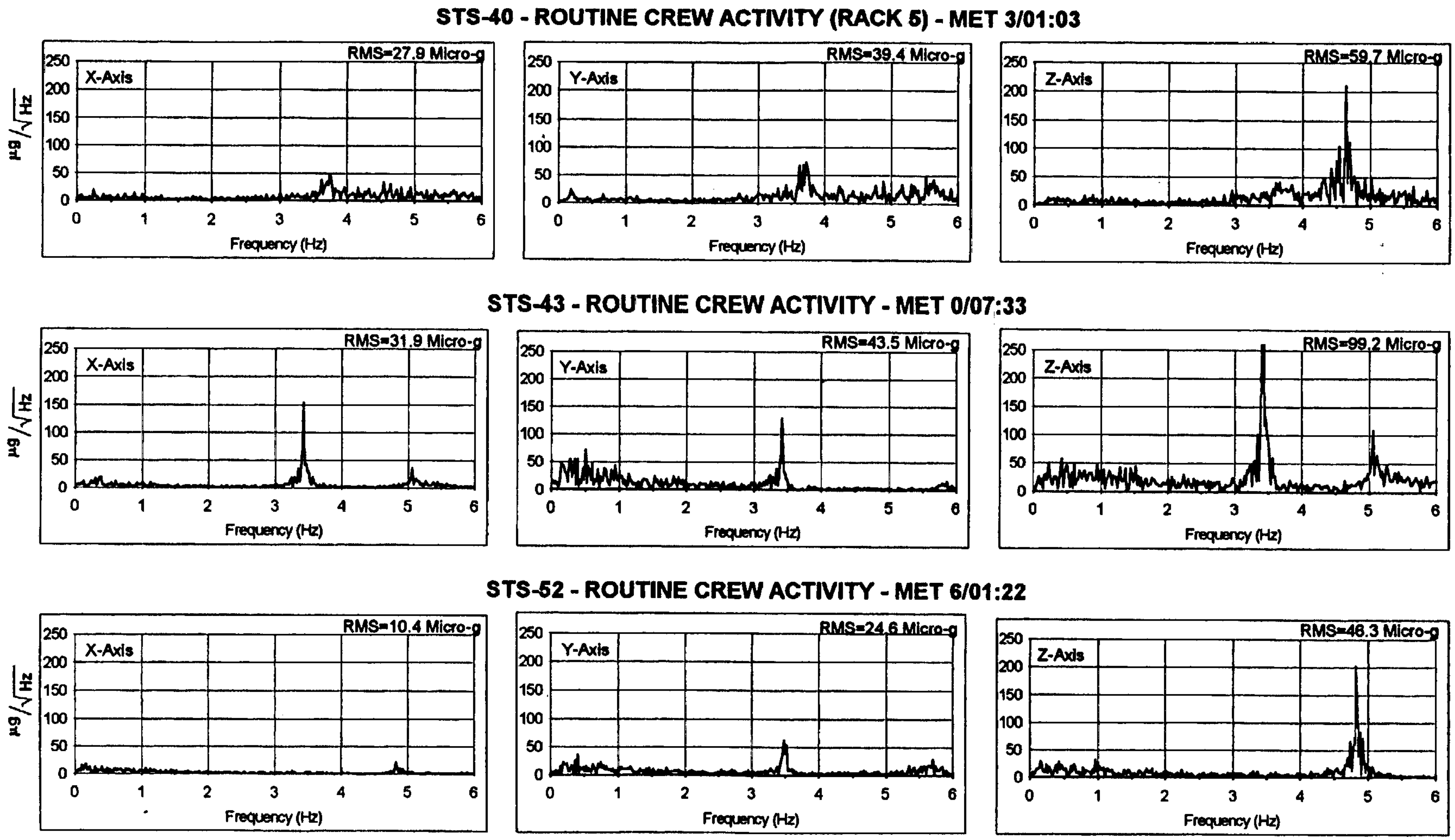

Figure 2.—Vibration environment during routine crew activity in Spacelab module and other mission configurations.

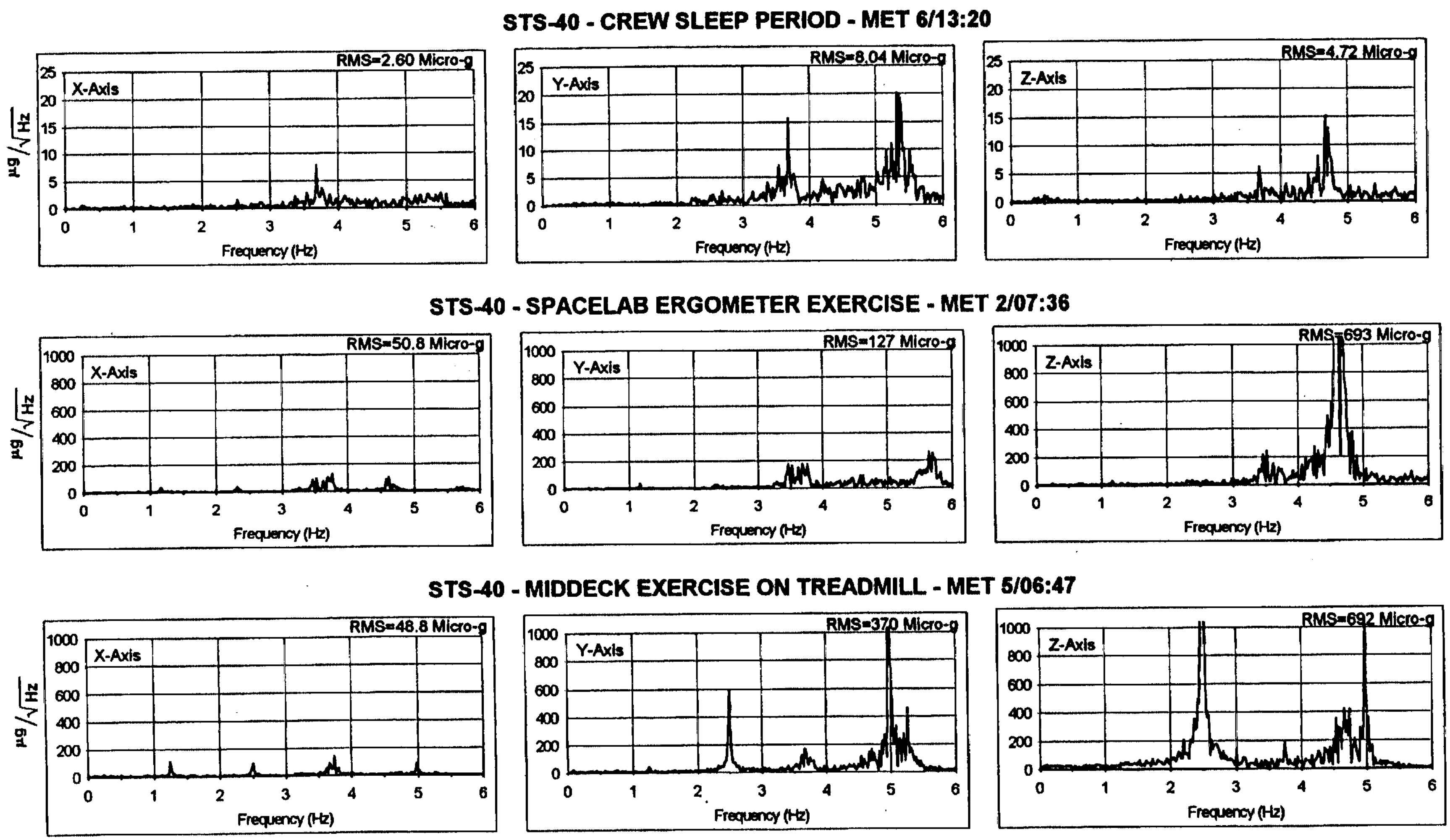

Figure 3.—Vibration environment compared over range of crew activity levels.

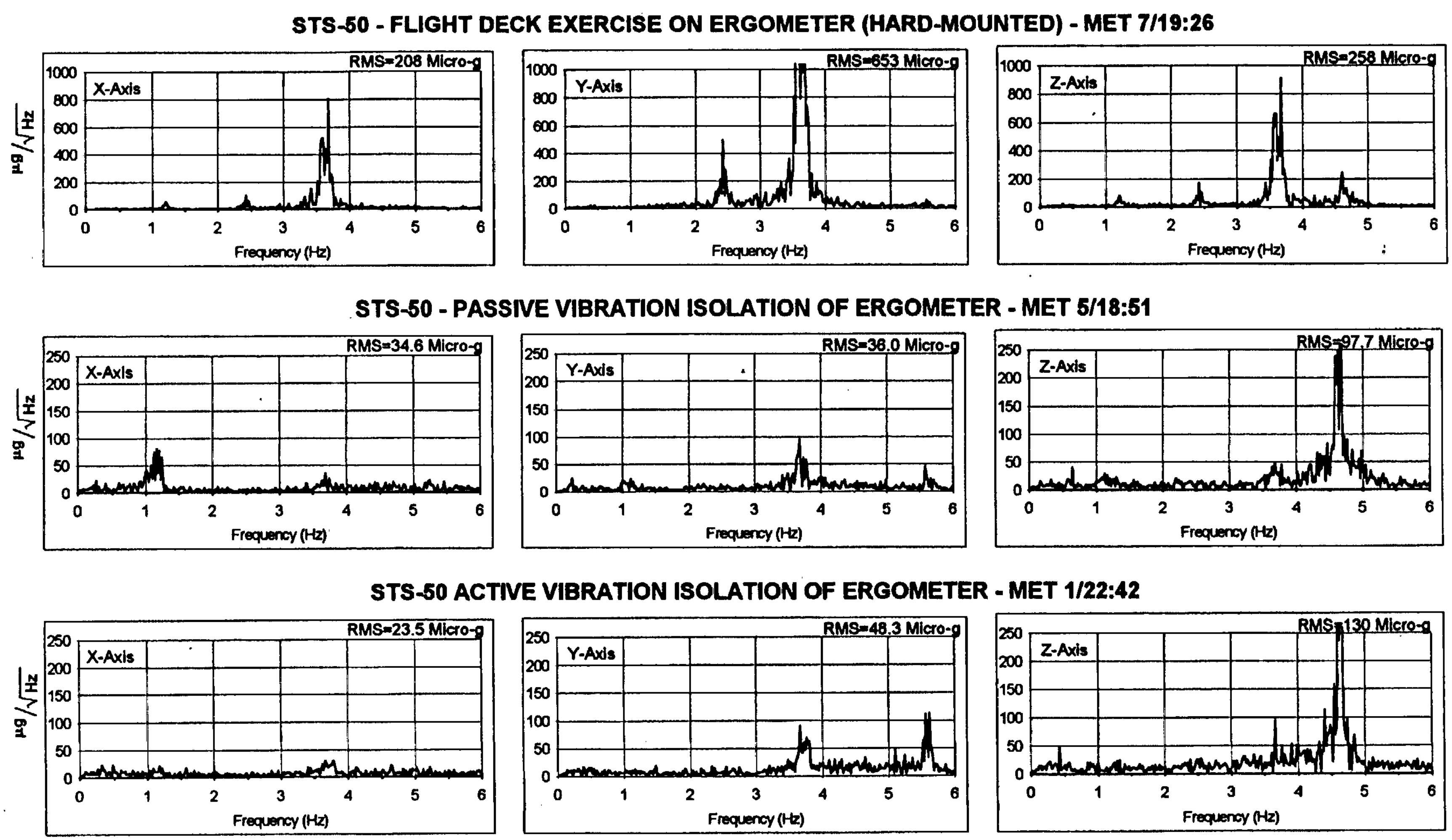

Figure 4.—Crew exercise equipment isolation effects on vibration environment.

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13. ABSTRACT ***(Maximum 200 words)***

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