Microgravity Environment of Space Flyer Unit*[1]

By Susumu SASAKI*[2]

Key Words: Spacecraft, Microgravity, G-Jitter

Abstract

SFU (Space Flyer Unit), a reusable space platform, was launched by the third H-II rocket in March 1995 and was retrieved by the Space Shuttle STS-72 in January 1996. During the 10 months mission at the altitude around 480 km, various kinds of experiments including material processing and biology utilizing microgravity environment were conducted. SFU carried an environment monitor on the platform which contains a 3-axis accelerometer with a frequency response up to 30 Hz. The microgravity environment was measured by the accelerometer intermittently for totally 260 h during the mission. G-jitter of typically 50 μg rms (root mean square) which peaked in the frequency range from 10 to 25 Hz was observed all the time. The intensity of the g-jitter was modulated by the orbital motion. The frequencies of the g-jitter seem to be associated with the natural frequencies of the SFU structure. In the lower frequency range below 1 Hz, vibrations excited by the solar array paddles were observed at the day/night transition. The perturbations by the thruster firings for the orbit change and attitude control were also measured and analyzed.

1. Introduction

SFU was developed as the first reusable space system in Japan to provide a superior experimental environment for space science and technology research.[1] It was designed to be launched either by the Japanese expendable rocket H-II or the Space Shuttle, and to be retrieved by the Space Shuttle. The total weight is about 4,000 kg including payloads. The attitude is controlled either by a reaction control system using thrusters or a reaction wheel system. The nominal attitude is sun-pointing mode maintained by the reaction wheels with magnetic torquers. The performance of the SFU first mission is summarized in Table 1.

One of the outstanding features of unmanned SFU is the capability of providing a high-quality microgravity environment. For the manned spacecraft such as the Space Shuttle orbiter and the Mir station, it has been reported that the crew activities and the life support systems considerably degrade the microgravity environment.[2,3] In order to assure the high-quality microgravity environment for SFU, a special consideration to suppress the mechanical disturbances was given to the design of the onboard systems. The experiments requiring the high quality microgravity environment were configured not to be operated in parallel with the experiments which could generate mechanical disturbances, and were conducted in the attitude control mode maintained by the reaction wheels (Normal Mode).

Even for the unmanned spacecraft carefully designed for microgravity experiments, still there are microgravity disturbances inherent to the nature of the spacecraft.[4] The residual microgravity level would affect the physical processes involved in the microgravity experiments.[5] The measurement of the actual microgravity environment during the experiments is required to assess the results.

On SFU, there was an environment monitoring system consisting of an SFU Environment Monitor (SEM), a Space Plasma Diagnostic Package (SPDP), and four Payload unit box Environment Monitor (PEM), which have been developed to study systematically the gas, plasma, electromagnetic, optical, and acceleration environments.[6] There were totally five 3-axis accelerometers to monitor the microgravity environment in the system; one in SEM and four in PEMs. Besides the accelerometers in the environment monitoring system, there were three 1-axis accelerometers in the Exposed Facility Flyer Unit (EFFU), a mission instrument on the SFU platform, to measure the microgravity environment inside the EFFU.[7] The SEM accelerometer was operated intermittently with a high sampling rate up to 62.5 Hz to provide information on the high-frequency disturbance. The sampling rate of the SEM accelerometer was higher by about 6 times than that for Eureca (EUropean REtrievable CArrier), which was launched in 1992 as the first spacecraft for a specified microgravity environment. The PEM accelerometers were operated almost continuously throughout the mission at a low sampling rate of less than 0.25 Hz. In this paper, using the results obtained by the SEM accelerometer, the microgravity environment of SFU is presented and discussed.

---

*[1] Received December 19th, 1997.
*[2] The Institute of Space and Astronautical Science, Sagamihara, Japan.

Table 1. Performance of the SFU first mission.

Weight	3,850 kg (launch), 3,500 kg (retrieval)
Dimensions	Main structure: 4.46 m in diameter, 2.8 m high, Octagonal truss structure Solar array paddle: 24.4 m long, 2.4 m wide
Orbit	330 km (initial), 486 km (mission), 472 km (retrieval), Inclination 28.5°
Power	2,800 watt (total), 850 watt (for experiment)
Attitude control	3-axis stabilization: Reaction control system (3 N × 12, 23 N × 4), Reaction wheel (3 Nms), Magnetic torquer
Orbit change	Orbit change thruster (23 N × 8)
Data recorder	4 Mbit, 80 Mbit
Experiments	Two-dimensionally deployable/high voltage solar cell array experiment, Space plasma diagnostic package, Electric propulsion experiment, Materials experiment under microgravity, Space biology experiment, Infrared telescope in space, Exposed facility flyer unit, Gradient heating furnace, Mirror heating furnace, Isothermal heating furnace

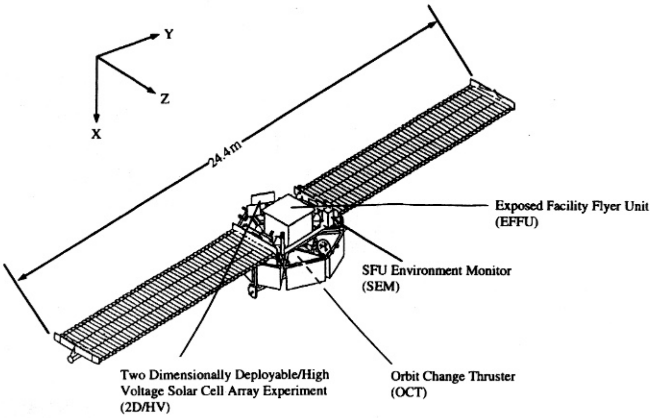

Fig. 1. Location of the SFU Environment Monitor (SEM) and other major instruments.

2. SEM Accelerometer

Figure 1 shows the location of the SEM on the SFU platform. The coordinates in the figure define the three axes for the SEM accelerometer and the SFU body. The sensor is a servo-type accelerometer which is composed of a pendulum and a magnetic torquer. The displacement of the pendulum by acceleration is detected and is forced back to zero by the magnetic torquer. The acceleration level is derived from the feedback current to the magnetic coil. The bias level for zero gravity is quite sensitive to the temperature. The temperature coefficient was between $-15.7\,\mu g/°C$ and $-8.1\,\mu g/°C$ in the acceptance test before launch. The change of the coefficient during the mission was found to be less than 1.7% in the post mission calibration test. The sensor temperature of each axis was always monitored for data correction. The zero bias also varies due to a change of internal mechanical stress in a long term. Actually, the post-mission calibration test showed that the zero bias had changed by $200\,\mu g$ at maximum during the mission. Thus the accelerometer does not provide information on the microgravity level in a steady state.

Table 2. Characteristics of the SEM accelerometer.

Measurable range	High gain: -880–$+880\,\mu g$ (20°C) Low gain: -12.4–$+12.4$ mg (20°C)
Resolution	High gain: $10\,\mu g$ Low gain: $100\,\mu g$
Bias change	$+20$–$-210\,\mu g$ (post-flight test)
Temperature coefficient	-8–$-16\,\mu g/°C$
Sampling rate	62.5–1.0 Hz
Temperature resolution	0.5°C

The measurable range of the accelerometer at 20°C is from $-880\,\mu g$ to $+880\,\mu g$ for the high gain channel and from -12.4 mg to $+12.4$ mg for the low gain channel. Both high and low gain analog data are converted into 8-bit digital data. The maximum resolution is $10\,\mu g$. The SEM has two operation modes: a standard mode and an acceleration measurement mode. In the standard mode, the acceleration data are sampled either at 31.3 Hz, 7.8 Hz, or 1.0 Hz. In the acceleration measurement mode, they are sampled either at 62.5 Hz, 15.6 Hz, or 2.0 Hz. Due to the restriction of data recording capability, the acceleration data were sampled typically at 2 Hz for more than 2 h and at 62.5 Hz in 30 min operation. Since the filter for the A/D converter cuts only the frequency components more than 30 Hz, the spurious frequency components associated with the sampling rate can not be rejected except for 62.5 Hz sampling. Table 2 summarizes the characteristics of the SEM accelerometer.

The acceleration measurement was conducted about 210 times during the mission. The accelerometer was usually turned on to monitor the microgravity environment during the furnace operation for material processing experiments, and occasionally turned on to detect the mechanical disturbances during the other experiments. It was also used to measure the background microgravity environment and the disturbances induced by the thruster firings. The longest period for continuous measurement was 4.5 h which corresponds to three orbital revolutions. The total measurement time was about 260 h during the mission.

3. Microgravity Measurement

The residual atmospheric drag at the altitude of 480 km is estimated as low as $0.1\,\mu g$. The tidal acceleration, generated by unbalance of the gravitational force and centrifugal force for the SEM located at about 1.5 m apart from the center of mass of SFU, is less than $0.5\,\mu g$. Both are far less than the resolution ($10\,\mu g$) of the SFU accelerometer.

3.1. G-jitters Figure 2 shows a typical example of the microgravity measurement in the 3 axes during the furnace experiment. The attitude control was performed

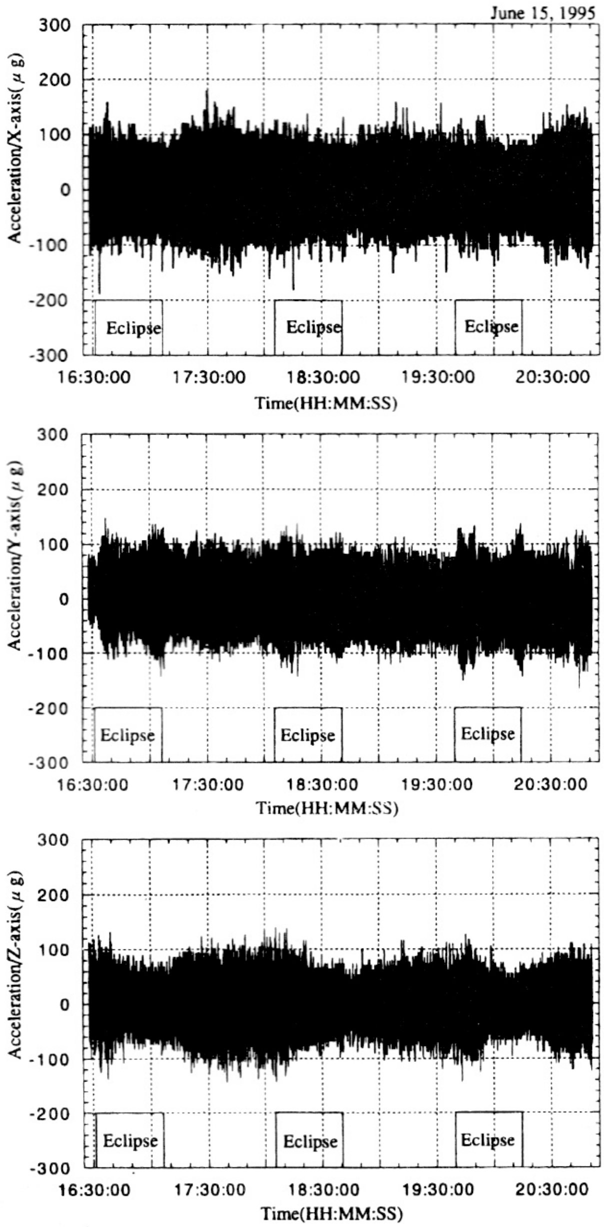

Fig. 2. Typical example of the microgravity measurement in x, y, and z axes for 4.5 h.

in the Normal Mode during this period. Each panel shows variations of the g-jitter for three orbital revolutions. The sampling rate is commonly 2 Hz. The sensor temperature increased by approximately 15°C during the 4.5 h, but the temperature effect is corrected by the temperature calibration data. The amplitude of the g-jitter is modulated by the orbital motion which is especially evident for the z axis. The characteristic feature of modulation is different for each axis, but the basic pattern of modulation is quite reproducible. The modulation for the x and z axes is almost in phase, but that for the y axis is more complicated. The rms intensity of the data shown in Fig. 2 is approximately 42 μg in the x axis (A_x), 48 μg in the y axis (A_y), and 39 μg in the z axis (A_z). The rms intensity for A_x and A_z in the daytime is larger by about 10% than that in the nighttime, while that for A_y in the daytime is smaller by about 10% than in the nighttime. The g-jitter shown here was generally observed throughout the mission independently of the attitude with respect to the flight direction.

Figure 3 shows three typical examples of FFT analysis of the g-jitter for the data sampled at 62.5 Hz. The frequency spectrum is analyzed up to 31.25 Hz for 60 s data. The frequency resolution is 16.7 mHz. Line spectrums which peaked in the frequency range from 10 to 25 Hz are observed for the three axes. The spectrum pattern is different for each axis, but is reproducible for the same axis. Figure 4 shows the peak of the frequency spectrum averaged for 20 results which were obtained approximately every 10 days during the whole mission. The frequency of the peak is typically 16–17 Hz for the x axis, 10–11 Hz for the y axis, and 12–13 Hz for the z axis.

In the lower frequency range below 1 Hz, perturbations were occasionally observed especially in the x axis, but the intensity was much weaker than that in the range of 10–25 Hz. There were a variety of frequency spectrums in the low frequency range. The g-jitter below 1 Hz was sometimes observed at the transition between day and night. Figure 5 shows continuous 8 spectrums analyzed for 60 s each at the transition from night to day. A perturbation around 0.2 Hz was observed in the three spectrums just after the sunshine started. The same effect was also seen at the transition from day to night.

3.2. Thruster-induced disturbances The SEM accelerometer detected a number of temporary disturbances during the mission. They were generated by operation of the onboard mechanical systems, thruster firings, and rotation of SFU. The typical examples of the mechanical disturbance were: deployment and separation of a sunshade panel for the infrared telescope, deployment and retraction of the panel structure for the two-dimensional deployment experiment, and open/close operation of the valves in the thruster system. The information of the mechanical disturbance was practically useful to monitor the actuation of the mechanical system.

The disturbances generated by the thruster firings and associated rolling motion were repeatedly measured by the accelerometer and were analyzed quantitatively.

(1) Orbit change thruster: SFU has an Orbit Change Thruster (OCT) system consisting of eight 23 N thrusters near the center of the octagonal structure in the $+x$ plane, as shown in Fig. 1. Four of eight thrusters are backup. They were operated to lift the spacecraft from the initial orbit at 330 km to the mission orbit at 486 km. They were also used to maintain the mission orbit and to adjust the orbit for retrieval preparation. The operation of the OCT produced the largest acceleration of more than 1 mg in the $-x$ direction during the mission phase. Figure 6 shows an example of the disturbance during the OCT firing for 200 s. The acceleration in the

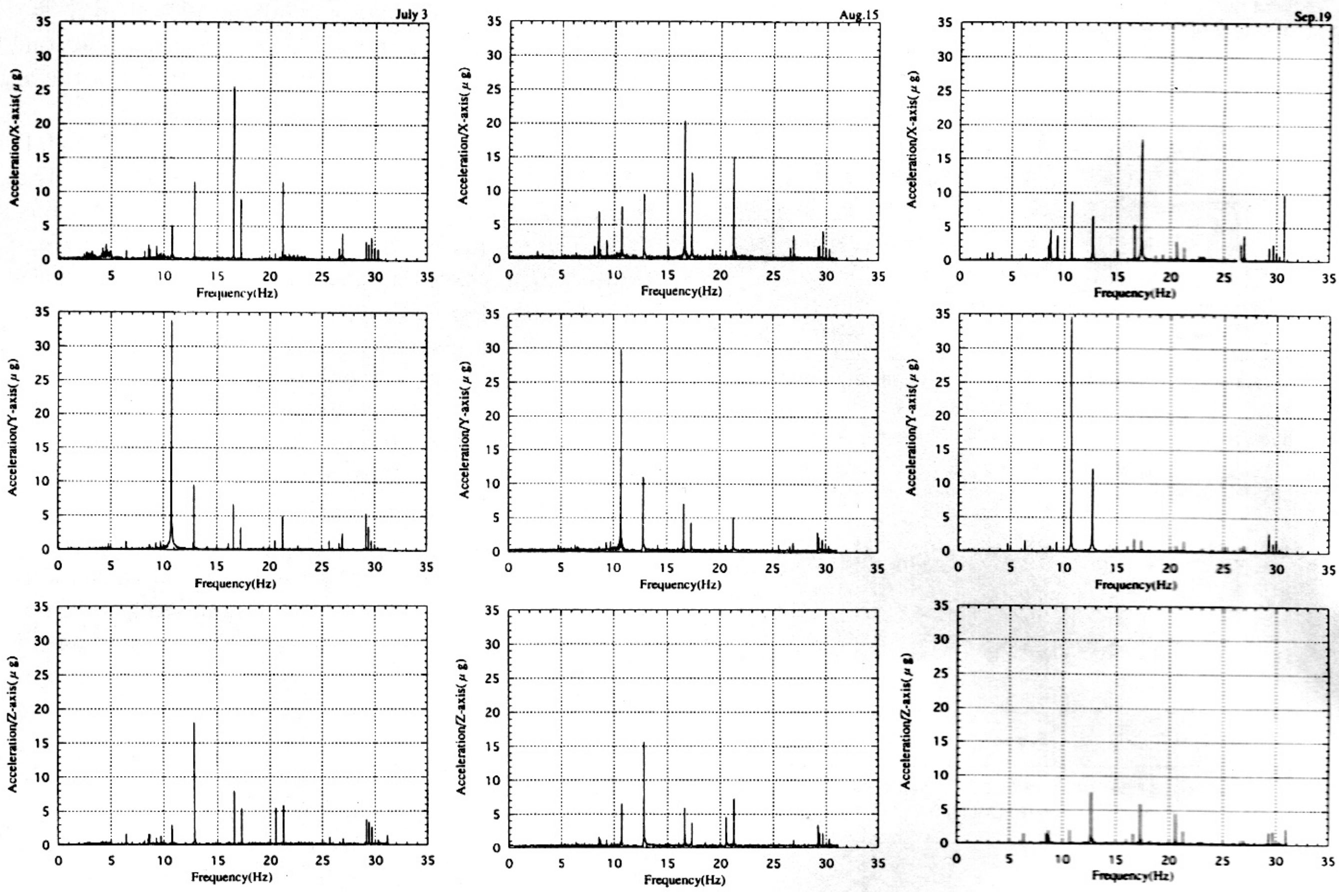

Fig. 3. FFT analysis of the perturbations. Three examples are given to show reproducibility.

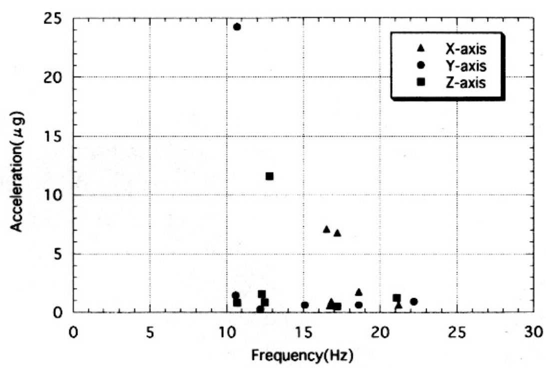

Fig. 4. Peak intensity of spectrum averaged for 20 examples.

x axis is $-2{,}300\,\mu$g on average. The FFT analysis is conducted for 200 s during the OCT firing. The result shows a broadband spectrum with dominant perturbations of less than 5 Hz as shown in Fig. 7. The strong disturbance continued for about 6 s after the termination of the firing. The FFT analysis for 60 s after the firing shows excitation of low frequency perturbations near 0.20, 0.26, 0.35, 0.44–0.50, 0.69, and 0.9–0.93 Hz.

(2) Reaction control system: The Reaction Control System (RCS) has twelve 3 N thrusters and four 23 N thrusters, but only 3 N thrusters were used during the mission. The RCS is operated for the 3-axis attitude control and unloading of the reaction wheels. One 3 N thruster generates a perturbation of typically $100\,\mu$g. Figure 8 shows an example of the perturbation generated by 1-s firing of a thruster which is located at 0.75 m apart from the SEM. The acceleration produced by the thruster firing is about $165\,\mu$g on average in the $+x$ axis direction. The disturbances after the 1-s thruster firing were generated by the shorter thruster firings of the other thrusters to restore the attitude automatically.

(3) Rolling: During the mission, SFU was rolled along the z axis for the attitude change between the sun-pointing mode and the earth-pointing mode, which generated a centrifugal force on SFU. The rolling was initiated and terminated by the RCS thruster firings. The angle velocity was 0.5 degree/s. Figure 9 shows a typical example of disturbance during the rotation for 180 degrees along the z axis. The rolling motion produced 10–15 μg disturbance in the $-y$ axis at the position of the SEM.

4. Summary and Discussion

G-jitter of $50\,\mu$g rms level was always observed during the mission. The intensity of the g-jitter is modulated by the orbital revolution. The FFT analysis shows that the peaks of the disturbance are in the frequency range of 10–25 Hz. Very similar spectrum was also obtained by the accelerometers inside the EFFU which were installed at different locations of the SFU platform. This means were analyzed. The induced acceleration measured by the SEM accelerometer was 2,300 μg for the OCT operation, 165 μg for the RCS operation, and 10–15 μg for rolling. These are the characteristics of the perturbations inherent to the SFU flight operation, which provide basic information on the SFU follow-on mission. On the other hand, the analysis of the perturbation generated by the known force is used for the on-orbit verification of the accelerometer. The analysis of the acceleration based on the thrust level and the SFU mass property shows that the acceleration induced at the SEM is 2,600 μg for the OCT operation, 130 μg for the RCS operation, and 13 μg during the rolling. The analysis results roughly agree with the measurements. The deviation between the measurement and analysis possibly comes from the ambiguity in the assumption of the actual thrust level for the thrusters.

Acknowledgment

The author is deeply indebted to the engineers of DENSO Corporation for development of the SFU environment monitor. He wishes to thank the SFU team members headed by Prof. K. Kuriki for promoting the SFU project. This research was supported by the Institute for Unmanned Space Experiment Free Flyer (USEF).

References

1) Kuriki, K., Ninomiya, K., Takei, M. and Matsuoka, S.: Lessons Learned from the Space Flyer Unit (SFU) Mission, 48th International Astronautical Congress, Turin, October, 1997.
2) Hamacher, H., Jilg, R. and Merbold, U.: Analysis of Microgravity Measurements Performed during D1, *Proc. 6th European Symposium on Material Sciences under Microgravity Conditions*, Bordeaux, France, 1986, pp. 413–420.
3) Granier, J.-P. and Faucher, P.: Microgravity Data Analysis and the MIR Environment, NASA CP 3272 (1994), pp. 761–769.
4) Minster, O., Innocenti, L. and Mesland, D.: Looking at Science on Board Eureca, ESA BR-80, May (1993).
5) Monti, R. and Savino, R.: Microgravity Experiment Acceleration Tolerability on Space Orbiting Laboratories, *JSR*, **33**, 5 (1996), pp. 707–716.
6) Sasaki, S., Watanabe, Y., Kaya, N., Yokota, T., Sagawa, E., Miyatake, S., Ota, M. and Tohyama, F.: Study of Spacecraft-Generated Environment on Space Flyer Unit, *Proc. of the 19th ISTS*, Yokohama, 1994, pp. 769–774.
7) Takei, M., Torii, Y., Fusegi, K. and Arafune, K.: Microgravity Environment during EFFU Operation, 20th ISTS, Gifu, May, 1996.
8) SFU Project: Space Flyer Unit (SFU) Mission Report (Core System), ISAS Report, Special Issue No. 35 (1997) (in Japanese).
9) Eilers, D. and Stark, H. R.: Eureca Microgravity Environment-Preliminary Flight Data, NASA CP 3272 (1994), pp. 869–891.