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Spatio-Temporal Characteristics on Spectra and Particle Motion of Harmonic Tremors at Sakurajima Volcano, Japan

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Synopsis

Eruptive activity with Vulcanian type has been continued at the summit crater of Sakurajima since 1955. Harmonic tremors have been observed several hours after B-type earthquake swarms or immediately after explosive eruptions. Here, we call the first one HTB (Harmonic Tremor following B-type) and second one HTE (Harmonic Tremor after an Eruption). Particle motions and spectra of HTB and HTE were analyzed. Spectra both of HTB and HTE have peaks at fundamental frequencies and higher frequencies of multiple integers of them. Peak frequencies of HTB were kept in a certain range. In contrast, those of HTE gradually increased. Spectra of HTB, which occurred on July 20, 1990, have fundamental frequencies ranging 1.4 Hz – 1.7 Hz stably and at least 9 peaks of higher modes. While the fundamental frequencies of HTE, which occurred 3 minutes after an explosive eruption at 11h15m on October 11, 2002, gradually increased from 0.8 Hz to 3.7 Hz. The peak frequencies of higher modes of HTE were also gradually increased according to shift of the fundamental mode toward higher frequency. Particle motion analysis showed that Rayleigh waves are dominant from prograde elliptical motion at the deepest borehole station HAR and retrograde motions at the other stations. Love waves were sometimes mixed at the stations south and west of the craters. The distribution patterns of Rayleigh and Love waves of HTB are similar to those of HTE.

Keywords: Sakurajima volcano, harmonic tremor, spectrum, particle motion

1. Introduction

Harmonic tremors have been observed at volcanoes with long-term active eruptivity, such as Sakurajima, Japan, Langila, Papua New Guinea, Arenal, Costa Rica, Mt. Erebus volcano, Antarctica, Lascar, Chile and Mt. Semeru, Indonesia. Harmonic tremor is characterized by regular peaks of spectra, composed of fundamental frequency and its overtones. Temporal change of fundamental frequency has been recognized at several volcanoes. Fundamental frequency of harmonic tremor, which occurred on February 24, 1975, at Sakurajima volcano, increased gradually from 0.5 Hz to 1.3 Hz for 12 minutes (Kamo et al., 1977). Similar patterns of increase in fundamental frequency were reported at Langila volcano, with increase in fundamental frequency from 1 Hz to 1.6 Hz (Mori et al., 1989), and from 1.9 Hz to 3.2 Hz (Benoit and McNutt, 1997) and from 0.5 Hz to 3.2 Hz (Hagerty et al., 2000) at Arenal volcano. In contrast, harmonic tremor, which occurred on May, 1998, at Mount Erebus volcano, showed decreasing fundamental frequency from 3Hz to 1Hz for ~10 minutes. In addition to the increase and decrease trend patterns, fundamental frequency of harmonic tremor fluctuates in a certain range. Fundamental frequency of harmonic tremor on June 23, 1975 at Sakurajima fluctuated in the range of 0.9 Hz - 1.8 Hz for 16 hours (Kamo et al., 1977). Similarly fundamental frequency fluctuated in the range of 0.5 Hz – 1.7 Hz at Mt. Semeru, with (Schlindwein et al., 1995) and in the range of 0.55 Hz – 0.70 Hz at Lascar volcano (Hellweg, 1999).

Particle motions of harmonic tremor have been analyzed to estimate wave types. Dominant direction particle motions of harmonic tremor appear both in longitudinal and transverse direction to the crater of Sakurajima volcano (Nagamune, 1975). Furthermore, Kamo et al. (1977) reported that polarization pattern of harmonic tremor are different among modes and simple wave types could not be determined due to the complexity of vibration patterns. Similar complexity of particle motions has been observed at Lascar volcano. The particle motion of harmonic tremor at the volcano could not be interpreted as simple wave type of P-, SV-, SH- and Rayleigh waves at fundamental frequency and its overtones (Hellweg, 1999). Although it is reported that S-wave was included in harmonic tremor on April 25, 1994 at Arenal volcano, from linearity of particle motion (Benoit and McNutt, 1997), the particle motion of harmonic tremor of the volcano are elliptical and are not composed of a simple wave type consistently (Hagerty et al., 2000). Most of the previously studies on particle motion of harmonic tremor have not identify a simple wave, due to inconsistency of particle motion pattern among stations.

Some models of source mechanism for harmonic tremor have been proposed based on the analysis of harmonic tremors. Spectra characteristic of harmonic tremor at Mt. Semeru, could be caused by repetitive of triggering of sources (Schlindwein et al., 1995). Benoit and McNutt (1997) proposed source model of resonance of a 1D vertical conduit for harmonic tremor at Arenal volcano. Hellweg (2000) proposed three physical source models, those are, eddy shedding, slug flow, and soda bottle, relating the fundamental frequency and power spectrum of harmonic tremor and showed relation to fluid dynamics variables, such as dimension or conduit size, kinematic viscosity of fluid flow and flow velocity.

Most of the previous models mentioned above are mainly based on the spectra characteristic of harmonic tremor, however little intent has been given on its particle motion characteristic. In addition, in most of the previous studies on harmonic tremor, seismic data were obtained by temporary observations or short-term part in the long period activity. The characteristics of harmonic tremors have not been discussed with changes of the volcanic activities.

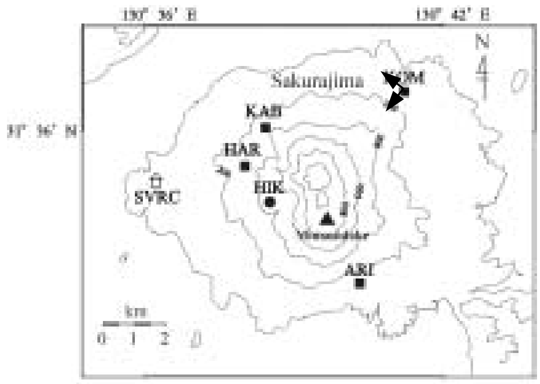


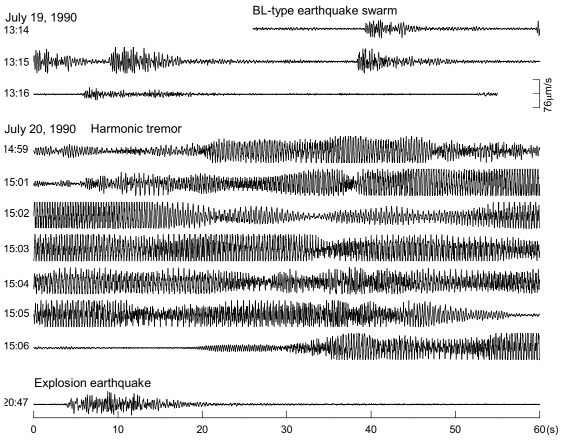
Fig. 1 Location of seismic stations used in this study. Squares and circle denote borehole and ground-based seismometers, respectively. Triangle shows location of the summit crater of Minamidake. SVRC: Sakurajima Volcano Research Center to register seismic records.

Sakurajima volcano has continued eruptive activity at the summit crater of Minamidake since 1955. More than 7,000 vulcanian explosions occurred by the end of 2004. In the time sequence of seismicity from occurrence of A-type earthquake, swarms of B-type earthquakes to increase in explosivity (Kamo, 1978), harmonic tremors were frequently observed after swarms of B-type earthquake, and sometimes after explosive eruptions. In this study, we investigate the spatio-temporal properties of harmonic tremors of Sakurajima volcano, based on its spectra and particle motion analysis and discuss their relationship to the volcanic activity during the period from 1982 to 2002. We use seismogram observed by permanent borehole seismometers, which have sufficient azimuthal coverage of the active crater, to reduce the ground surface noise and complicity of waveforms due to surface layers formed by pumice and ash (Iguchi, 1995).

2. Observation

Sakurajima Volcano Research Center (SVRC), Kyoto University operates seismic stations at Sakurajima volcano. Five of them are used in this study (Fig. 1). The stations, HIK, ARI, HAR, KAB and KOM are distributed 1.7 - 4.4 km apart from the active crater, Minamidake, and the station HIK is the closest. All the seismometers are installed in boreholes at depths of 85 – 290 m below the ground surface, except station HIK. A seismometer at station HAR is installed at the deepest

(a)



(b)

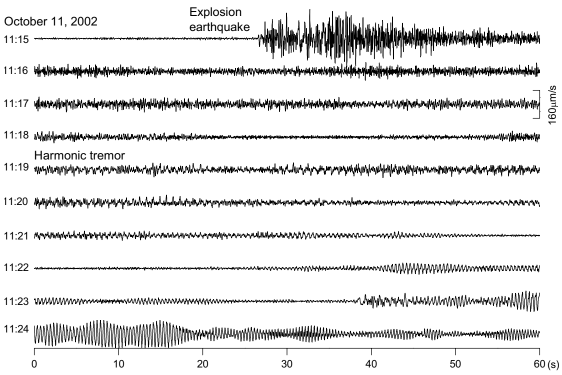


Fig. 2 Two types of harmonic tremors. The seismograms were observed by a vertical component seismometer at station HIK. (a) Apart of records (13h14m - 13h16m on July 19, 1990) of BL-type earthquake swarm which began at 02h35m, HTB from 14h59m - 15h07m on July 20, 1990 and the following explosion earthquake at 20h47m. (b) Explosion earthquake and the following HTE records from 11h15m - 11h25m on October 11, 2002.

borehole of 290m. Each station is equipped with three-components and 1 Hz short-period seismometer. The sensors of two horizontal components are oriented to the direction to the crater (L: longitudinal component) and perpendicular to the crater (T: transverse component). Seismic signals from the stations are transmitted to SVRC via telephone lines or radio waves and were recorded on analog magnetic tapes before May 2001. The analog records were digitized with sampling rate of 200 Hz and 12 bit resolution for analysis. Since May 2001, the seismic signals have been digitized at a rate of 200 Hz and 22 bit resolution at the stations and 1s packet data are transferred to SVRC by UDP protocol.

3. Classification of harmonic tremor

Eruptive activity has continued at the active summit crater of Sakurajima volcano since 1955. Various kinds of volcanic earthquakes have occurred proceeding to the eruption activity. Typically, precursory seismic activity was initiated by occurrence of A-type earthquakes at depth of > 5 km SSW of the crater, and the hypocenters migrated to a shallow part (1-4 km) beneath the summit crater. B-type earthquakes swarmed at a shallow depth beneath the crater (Kamo, 1978). During the swarms, waveforms of B-type become monotonic gradually, and the successive occurrence of monotonic B-type earthquake are transferred to harmonic tremor (Nishi, 1984). Several hours after the swarms of B-type earthquakes, a sequence of explosive eruption occurred (Kamo, 1978). The explosive eruptions accompany explosion earthquakes and following volcanic tremor which is generated by continuous emission of volcanic ash. In an unusual case, volcanic tremor has harmonic waveform a few minutes after the beginning of an eruption (Iguchi and Tameguri, 2003).

Based on the time sequence of the occurrence of seismic events at Sakurajima volcano, harmonic tremors are classified into two types; HTB (Harmonic Tremor after B-type earthquakes swarm) and HTE (Harmonic Tremor after Eruption). HTB follows B-type earthquake swarm and precedes explosive eruption several hours before. While, HTE occurs a few minutes after an eruption. Seismic records before and after HTB at 14h – 15h on July 20, 1990 (JST=9h+UTC) are shown in Fig. 2a. A swarm of B-type earthquakes began at 2h on July 19, 1990 and continued to 19h. Nineteen hours after the B-type earthquake swarm, HTB began to occur at 14h06m on July 20. The HTB continued for 2 hours. An explosive eruption occurred at 20h47m, 5 hours after the termination of the HTBs. An example of waveform of HTE is shown in Fig. 2b. Explosive eruption occurred on 11h15m27s on October 11, 2002 and volcanic tremor succeeded. The waveform of the tremor seemed to become harmonic at 11h19m, three minutes after the beginning of the eruption. The HTE continued for 12 minutes.

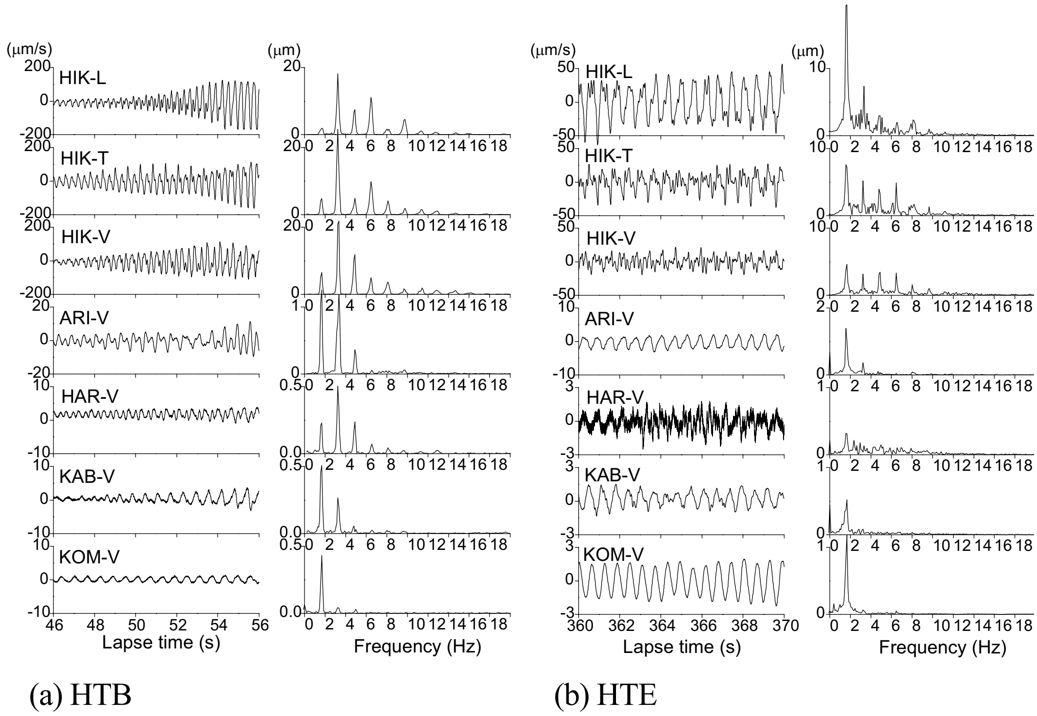


Fig. 3 Spectra of HTB and HTE. (a) Spectra of HTB in the three-component at station HIK and vertical component at stations HIK, ARI, HAR, KAB and KOM. Analyzed seismograms are shown in left side with the lapse time from 15h35m00s on July 20, 1990. (b) Spectra of HTE. Left seismograms are shown with the lapse time from 11h15m00s on October 11, 2002. High-frequency component at station HAR is caused by construction of road.

4. Analysis

4.1 Spectra

We applied FFT algorithm to HTB and HTE to analyze their spectra. Fig. 3a shows spectra of 10.24s record of HTB, from 15h35m46s on July 20, 1990. Spectra of three components of HTB at station HIK have common peak frequencies. The spectra have lowest peak at 1.6 Hz, and higher peaks appear at frequencies of multiple integers of the lowest peak, such as, 3.2 Hz, 4.8 Hz, 6.4 Hz, 8.0 Hz, 9.6 Hz, 11.2 Hz, 12.8 Hz and 14.4 Hz. The spectra of vertical component of HTB at five stations represent similarity of peaks frequencies among all the stations (Fig. 3a). Peaks of 1.6Hz, 3.2Hz and 4.8Hz are clearly recognized, however peaks of higher than 4.8Hz are not clear at distant stations. This may be due to anelastic attenuation through wave propagation.

Fig. 3b shows spectra of HTE seismogram for 10.24s from 11h21m00s on October 11, 2002. The spectra of vertical component at station HIK have lowest peak frequency of 1.6 Hz and overtones at 3.2 Hz, 4.8 Hz, 6.4 Hz, 8.0 Hz, and 9.6 Hz. The same peaks frequencies are recognized in longitudinal and transverse components. Lowest peak of 1.6Hz can be identified at the other stations, but peaks higher than 1.6Hz is detected only at stations HIK and ARI and however these are not clear at further stations.

Although peaks of higher frequency are not identified clearly at further stations, the peaks of lowest peak are same among the 3-components at all the stations for both of HTB and HTE. This fact suggests that appearance of dominant peak frequencies are mainly caused by sources and decrease in amplitudes of higher frequency peaks are caused by wave propagation through anelastic medium of volcanic body. Dominant peaks appear at frequencies of multiple integers of the lowest peaks for HTB and HTE as usual harmonic tremors. The lowest peaks are regarded as fundamental mode, and the frequencies of 3.2, 4.8, 6.4Hz and son on correspond to second, third, fourth modes, respectively.

To grasp temporal change of peak frequencies, we calculate running spectra by shifting the time windows of 20.48 s for HTB and 5.12 s for HTE by 10s. Fig. 4 shows temporal change of spectra of HTB. The fundamental

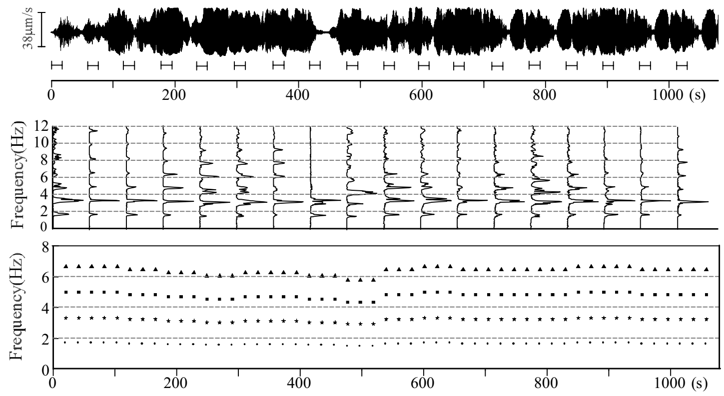


Fig. 4 Temporal change of peak frequencies of HTB. The first trace is seismogram of vertical component recorded at station HIK. Second one is a gathering of FFT spectra in time windows of 20.48 s. The time windows are shown in the first trace by bars. Third is plot of the peak frequencies every 20 s. Dots, stars, squares and triangles show lowest, second, third and fourth peaks of the spectra, respectively. Time scale is lapse time from 15h35m31.56s on July 20, 1990.

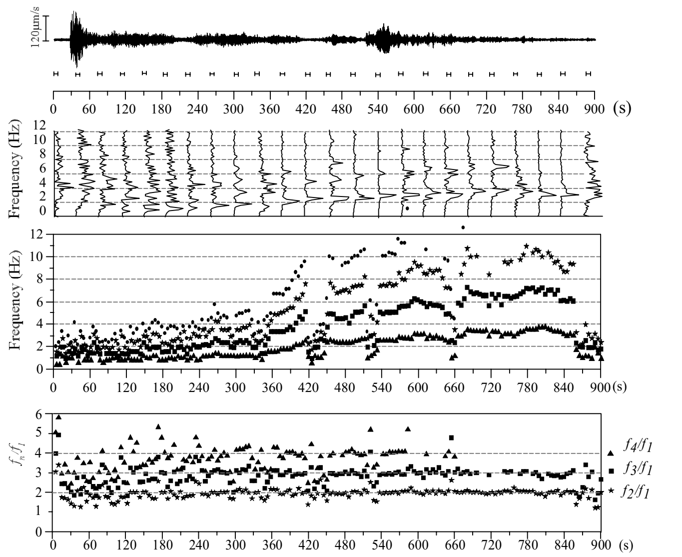


Fig.5 Temporal change of peak frequencies of HTE after explosive eruption at 11h15m on October 11, 2002. Top is seismogram of vertical component recorded at station HIK. Examples of FFT spectra in time windows of 5.12 s are shown in the second. Third is plot of the peak frequencies every 5 s. Dots, stars, squares and triangles show lowest, second, third and fourth peaks of the spectra, respectively. Bottom is a plot of frequency ratios of second, third and fourth peaks to the lowest peak.

frequency of HTB, which began at 15h35m on July 20, 1990 is 1.6 Hz and frequencies of second, third and fourth modes are 3.2, 4.8, 6.4 Hz, respectively, at the beginning of the spectrogram. The fundamental frequency fluctuates in a narrow range of 1.4 - 1.7 Hz for 1100 s and the frequencies of higher modes (2nd, 3rd, 4th mode) also fluctuate in rages of 3.14 – 3.30 Hz, 4.68 – 4.99 Hz and 6.18 – 6.66 Hz, respectively, corresponding to the fundamental mode. The ratios of frequencies of higher modes to fundamental one are equal to multiple integers. The temporal change of peak frequencies can be described as;

$$f_n(t)=n f_1(t), \quad (1)$$

where $f_1(t)$ is fundamental frequency and n is positive integer ($n \geq 2$).

Fig. 5 shows temporal changes of spectra from the explosive eruption at 11h15m on October 11, 2002. As shown in Fig.2b, volcanic tremor followed the explosion earthquake and the waveform gradually became harmonic. To estimate the beginning of HTE, we evaluate frequency ratios of higher modes to fundamental one. For harmonic tremor, the frequency ratio of the second mode to the fundamental one expected to be ≈2. The ratio converged 2 at the time of 130 s and kept at 2 until 860s (Fig. 5). The ratios of third and fourth modes became 3 and 4, respectively, at 260s. Here we recognize that HTE started at 130 s and terminated at 860 s from the spectra ration. At 130 s when HTE appeared, the fundamental frequency was 0.8 Hz. The fundamental frequency gradually increased and attained 3.7 Hz at the time of 810 s. The frequencies of second, third and fourth modes are 1.6, 2.4 and 3.2 Hz at 130 s, respectively. The peak frequency of second mode increased from 1.6 to 7.2 Hz (810 s), corresponding to increase in frequency of fundamental frequency. The peak frequencies of higher modes are also integers multiple of the fundamental mode and the ratios of higher modes to fundamental mode are 1.99 ± 0.13, 2.99 ± 0.14, and 3.97 ± 0.27 for second, third and fourth mode, respectively. Temporal change of peak frequencies of HTE can be approximated, similarly to eq. (1).

4.2 Particle motions

Spatio-temporal characteristics of particle motion of HTB and HTE were investigated in the fundamental and higher modes. We apply a band-pass filter (BPF) of band width of ±0.1Hz from center frequency corresponding to the peak frequency of each mode. Particle motions are examined plotting on the vertical cross-section directed to the crater and horizontal plane.

(1) Fundamental mode

Fig. 6 shows the particle motion diagram of fundamental mode of HTB for 40s from 15h35m32s on July 20, 1990. A BPF with pass-band of 1.5 - 1.7 Hz was applied. The particle motions at station HIK, the nearest station to the crater, show elliptical motion at 11-26 s and 30-40 s in the vertical planes. The rotations of elliptical motions are in the inverted direction with the wave propagation. Elliptical retrograde motions in the vertical plane are also recognized at station ARI in the time windows 10-30 s. Similar retrograde motions in the vertical plane are observed in the time windows of 16-28 s at station KAB and 16-40s at KOM. The particle motions show elliptical prograde only at station HAR. In the horizontal planes, transversal motions gradually changed to longitudinal ones at stations HIK and ARI. Longitudinal motions were dominant at stations HAR, KAB and KOM through the analyzed time windows. From the patterns of the orbits, most of the waves are composed of Rayleigh waves from the retrograde elliptical orbits. Prograde motions at station HAR may be caused by deeper seismometer from the ground surface. Dominant transverse component at the station HIK and ARI suggests mixing of Love waves.

Fig. 7 shows the particle motion of HTE following explosive eruption at 11h15m on October 11, 2002. Frequencies of BPF are selected according to the temporal changes of the fundamental frequency. BPF of 0.8-1.0 Hz, 0.7-1.1 Hz, 0.8-1.2 Hz, 1.1-1.3 Hz, 1.2-1.4 Hz and 1.1-1.3 Hz are applied to HTE in the time windows of 220-230 s, 230-240 s, 240-250 s, 250-260 s, 260-270 s and 270-280 s, respectively. Particle motions at station HIK are dominated by retrograde ellipsoidal motions in the vertical planes in all the time windows. Similar retrograde ellipsoids in the vertical planes are recognized at the stations ARI, KAB and KOM. Only the particle motions at station HAR show prograde ellipsoidal orbits. In the horizontal planes, transverse motions have larger amplitudes than longitudinal ones at stations ARI and KOM, and they are dominant as seen in the time widows after 230-240 s at station HIK and in the time windows of 250-260 s and 270-280 s at station KAB. Similarly to HTB, HTE is composed of Rayleigh waves mixed with Love waves.

(2) Higher modes

Particle motions of higher modes are compared with fundamental mode. Fig. 8 shows particle motions of fundamental and second to fourth modes of the same HTB event shown in Fig. 6 at station HAR. Elliptical prograde particle motions are also recognized in the second to fourth modes similarly to fundamental one. At the other stations, the particle motions show an evolution of elliptical to linear motion at station HIK and ARI and more linear orbit dominated by horizontal components at stations KAB and KOM.

Particle motions of higher modes of HTE at station HAR are compared with those of fundamental mode as illustrated in Fig. 9. Although all the particle motions exhibit prograde ellipsoids, longitudinal components are much larger than vertical and horizontal components in the second and fourth modes. Particle motion of the third mode is similar to fundamental mode. The orbit of 4th mode is more complicated. Retrograde motion is exhibited in the time windows of 220-230 s and the

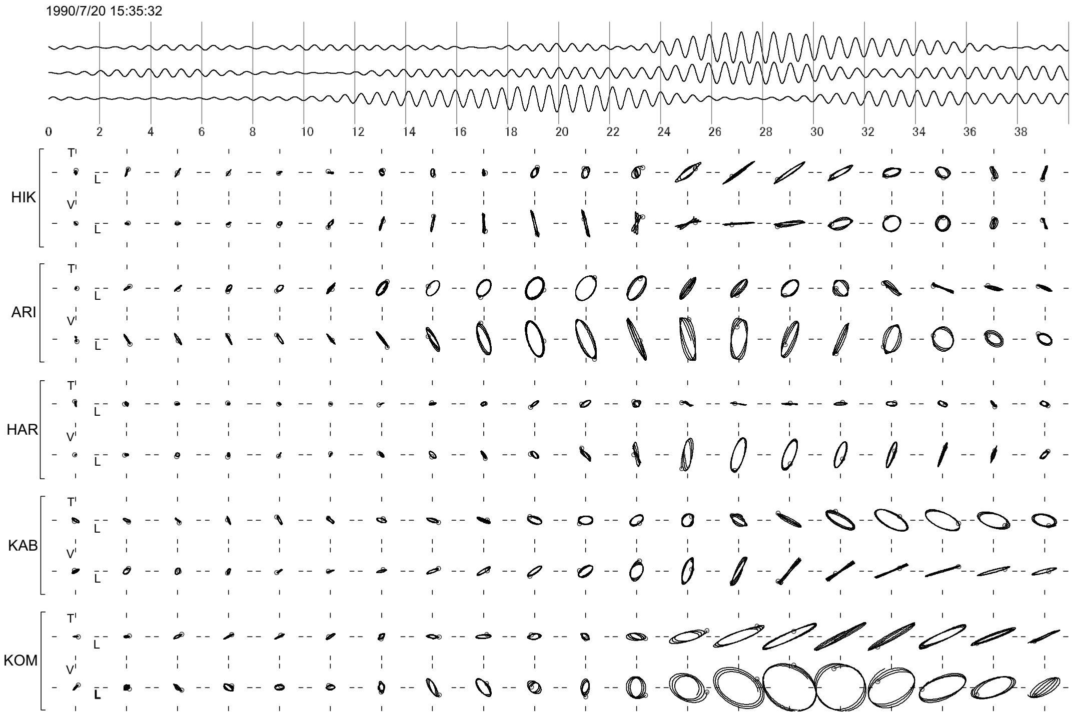


Fig. 6 Particle motion diagram for the fundamental frequency of HTB from 15h35m32s on July 20, 1990. Three traces at upper part represent seismograms band-pass filtered by 1.5-1.7Hz, in vertical, longitudinal and transversal components at station HIK, respectively. Lower part particle motions on the vertical and horizontal planes plotted every 2 s. The amplitude of particle motion at station HAR, KAB and KOM were magnified twice.

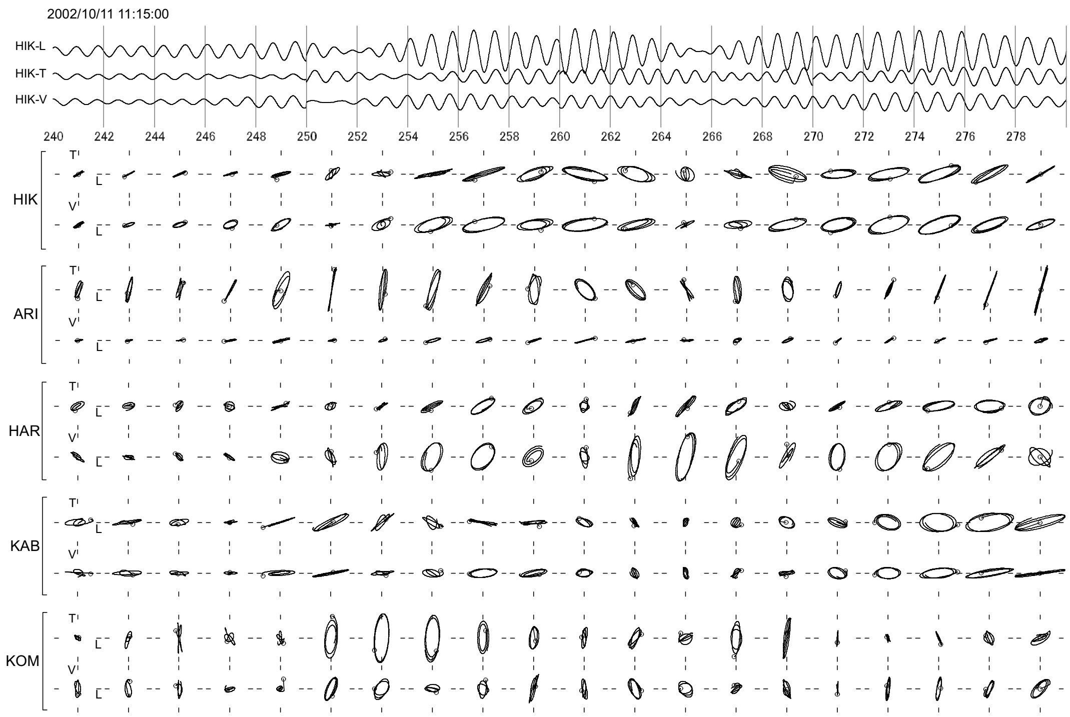


Fig. 7 Particle motion diagram at fundamental frequencies of THE from 11h19m00s on October 11, 2002. Upper traces represent band-pass filtered 3-components seismograms at station HIK. Lower part particle motions on the vertical and horizontal planes plotted every 2 s.

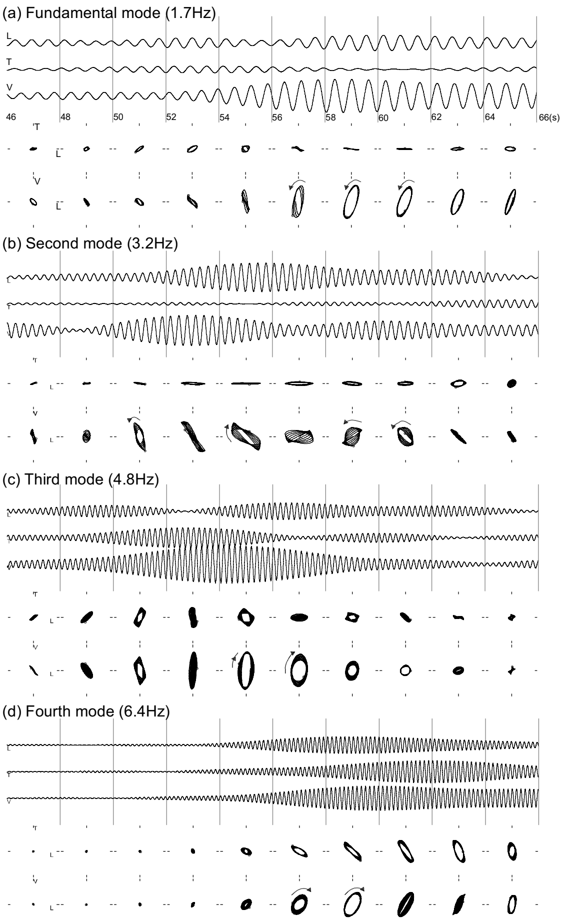


Fig. 8 Particle motion diagram at fundamental and higher modes of HTB. Seismogram and particle motions in the fundamental, second, third and forth modes are plotted from upper to lower. Upper parts represent band-pass filtered 3-components seismograms at station HAR and lower parts represent particle motion diagrams for 10 s from 14h58m00s on July 20, 1990, plotted every 2 s.

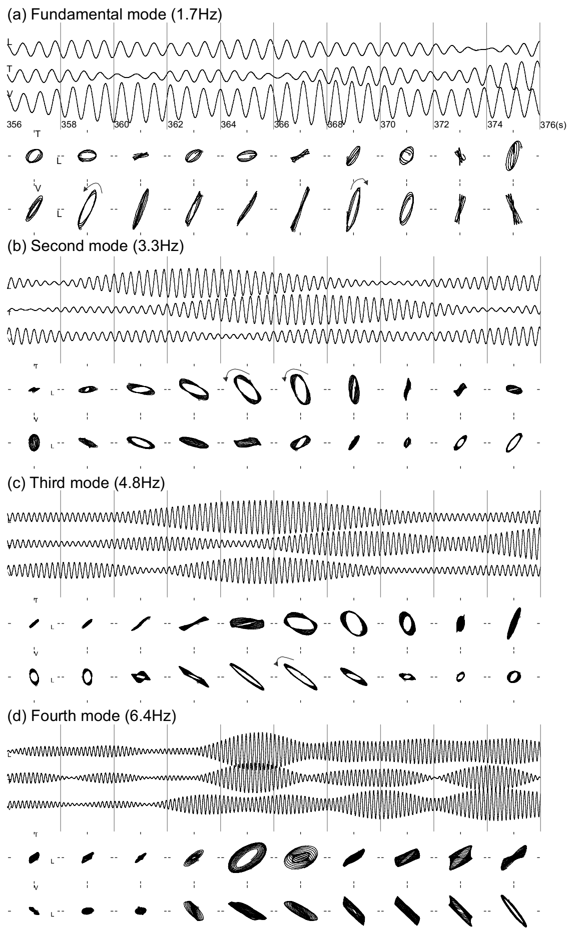


Fig. 9 Particle motion diagram at fundamental and higher modes of HTE. Seismogram and particle motions in the fundamental, second, third and forth modes are plotted from upper to lower. Upper parts represent band-pass filtered 3-components seismograms at station HAR and lower parts represent particle motion diagrams for 10 s from 11h19m00s on October 11, 2002, plotted every 2 s.

rotation changed to prograde in 305 s.

5. Discussions

5.1 Classification

Major difference between HTB and HTE is pattern of temporal change of peaks frequencies. Peak frequencies of HTB were kept in a certain range. On the other hand, those of HTE gradually increased. The peak frequencies of HTB at 14h57m on July 20, 1990 were kept in the range of f1 = 1.59 ± 0.06, f2 = 3.19 ± 0.14, f3 =4.78 ± 0.18 and f4 = 6.38 ± 0.24 for 1100 s. The sequence of HTB continued for two hours on the day, the peak frequencies continued to be similar till the end of the sequence. In contrast, the peak frequencies of HTE after the explosive eruption at 11h15m, October 11, 2003 increased from 0.8 Hz to 3.7 Hz.

We examined waveforms and time sequence of harmonic tremor at Sakurajima volcano during the period from 1982 to 2002 based on the criterion as described in the section 3, and classified into HTB and HTE types. During the period, 993 HTBs occurred and only 5 HTEs were recorded. Fundamental frequencies of the other HTBs during the analyzed period were also kept in certain ranges. The occurrence times of HTE are few minutes after explosive eruption. It is commonly recognized that time intervals between eruption and HTE are 100 – 150 s and the fundamental frequencies increased by a few hertz for several hundred seconds.

Kamo et al. (1977) showed two patterns of peak frequencies changes of C-type tremor. In the first case, peak frequencies of C-type tremor fluctuated in a certain range. Fundamental frequencies of the events on June 23-24, 1975 repeated increase-decrease pattern in the range of 0.9-1.8 Hz. The frequencies of higher modes also changed corresponding to the fundamental ones. We investigated seismicity before and after the activity of the C-type tremors. The sequence of C-type tremors occurs for 5 hours after BL-type earthquakes swarm on June 22, 1975. Based on the classification in this study, the event of June 23-34, 1975 can be classified as HTB. In the second one, peak frequencies gradually increased. Fundamental frequency of C-type tremor on February 24, 1975 gradually increased from 0.5 Hz to 1.3 Hz. This tremor occurred 2 minutes after an earthquake. We check the waveform of the earthquakes, and this is identified as BL-type earthquake. BL-type earthquakes are frequently accompanied with small-scale eruptions (Iguchi, 1994). It is possible that the BL-type earthquake prior to the C-type tremor on February 24, 1975 were accompanied with eruption and the following C-type tremor may be classified as HTE. The classification criterion proposed in this study is also applicable to the C-type tremor analyzed by Kamo et al. (1977).

5.2 Rayleigh waves

Particle motion analysis shows that both of HTB and HTE are dominated by Rayleigh waves. Although retrograde elliptical orbits are found at the 4 stations, particle motions are prograde only at station HAR, the deepest bore hole (290 m). Here we examine dependence of particle motion on observation depth to confirm existence of Rayleigh waves. Theoretical displacements of Rayleigh wave propagating in homogeneous half space (Lay and Wallace, 1995) were calculated. P-wave velocity of 2.5 km/s and S-wave velocity of 1.44 km/s were assumed based on P and S-waves velocity survey along the borehole (Internal report of SVRC). Poisson's ratio is calculated to be $\nu = 0.25$, and phase velocity of Rayleigh wave is $c = 1.31$ km/s (0.91 β). Theoretical vertical and horizontal displacements are compared with the observed one as shown in Fig. 10. As the fundamental frequency of HTB is 1.6 Hz, critical depth where the particle motion changes from retrograde to prograde estimated to be 160 m. The depth of the borehole of station HAR is 290m, exceeding the critical depth and the calculated particle motions are prograde. It coincides with observed particle motion of HTB. The depths of the other stations are shallower than the critical depth and they have theoretical retrograde motions as

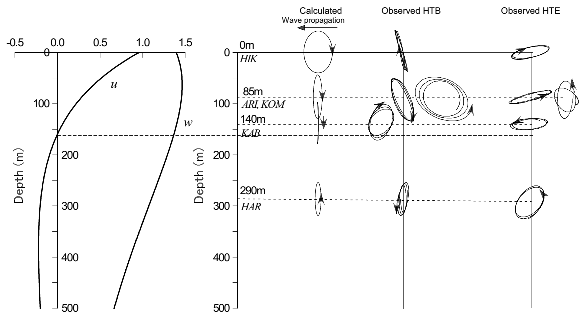


Fig. 10 Theoretical and observed particle motion of Rayleigh waves. Theoretical vertical and horizontal displacements with phase velocity of 1.31 km/s and frequency of 1.6Hz are shown in left side. Theoretical and observed particle motions at each station are shown in right side.

shown by the observation. Prograde motion at station HAR and retrograde motions at the other shallower stations are explained considering depth.

6. Conclusions

Harmonic tremors at Sakurajima volcano are classified into 2 types, based on occurrence time in the order sequence of types of volcanic earthquakes until explosive eruption. HTB occurs after B-type earthquake swarm, and HTE follows explosive eruption. The characteristics of particle motions and spectra are summarized as;

[1] Particle motion of HTB and HTE are dominated by Rayleigh and Loves waves. Spatial distribution pattern of Rayleigh and Love waves are similar to each other. Dominance of surface waves and similar distribution pattern suggest that HTB and HTE are generated by a similar source at a shallow depth.

[2] Although HTB and HTE have similar pattern of spectra, having fundamental peak and higher mode peak at frequencies of multiple-integers of the fundamental frequency, the temporal characteristics are different. Peak frequency of HTB is nearly constant. In contrast, peak frequencies of HTE gradually increase.

HTB is generated by resonance of gas pocket plugged by lava dome. Closed gas pocket system can maintain similar internal condition. HTE is associated with eruption. As a possible model for HTE, resonance of a gas pipe with a smaller pipe connected to atmosphere is applied. Increase in peak frequency may be caused by decrease in length of the gas pocket by ascent of magma head.

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桜島火山におけるハーモニック微動の時空間特性について

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要旨

桜島火山において発生するハーモニック微動について，群発性B型地震から推移して発生するもの（HTB）と爆発的噴火の直後に発生するもの（HTE）に分類した。両者のスペクトルは基本周波数とその整数倍にピークを持つ特徴がある。1990年7月20日に発生したHTBは基本周波数が1.4-1.7 Hzの範囲で一定であり，9つの高次モードが見られた。2002年10月11日11時15分の爆発的噴火の3分後に始まったHTEは，微動の初期の基本周波数は0.8 Hzであったが，時間が経つにつれ高周波側にシフトし，3.7 Hzまで増加した。HTEの高次モードも基本周波数の整数倍を保ちつつ高周波側にシフトした。両者の振動軌跡はRayleigh波が卓越しており，その回転方向は地震計を設置している深度が最も深いHAR観測点でprograde，他の観測点ではretrogradeであった。火口の南もしくは西の観測点では波形にLove波が見られ，HTB，HTEともに表面波の振動パターンは類似していた。

キーワード:桜島火山，ハーモニック微動，スペクトル，振動軌跡