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Phase portrait of non-linear low frequency volcanic tremors and structure estimation of differential equation system

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On September 1, 2004, a middle-scale eruption occurred at Mt. Asama, Japan. Before the eruption, we had observed several kinds of low frequency volcanic tremors and low frequency long-lasting volcanic events since October 2003. Takeo (2010) revealed the non-linear dynamics of these low frequency tremors and long-lasting events using an embedding method of time delays and a surrogate data analysis, and made clear that there existed a deterministic non-linear dynamics in the tremor and event excitations, which could be modeled with the system dimension between 3 to 7 (prospective dimension 3 or 4).

In this paper, we formulate a new topological approach for structure estimation of differential equation system exciting the non-linear low frequency volcanic tremors and long-lasting events based on a phase portrait analysis and a potential estimation. The basic concept of this approach is that the time series data exemplify a variable of differential equation exciting these tremors and events. The typical period of them are several to ten seconds, meaning that the wavelengths are longer than one or two kilometer. These signals were recorded by the seismometers installed at the crater rim, so the waveforms were not affected by wave propagation effect, and exemplified the excitation dynamics correctly. Therefore, it will be expected that we directly infer the structure of differential equation system.

At first, we divided the time series data (x) into several terms and made phase portraits of x vss. dx/dt and/or x vss. dˆ2x/dtˆ2 to examine differential structure in the particular term. As a typical example, we picked up a long-lasting low frequency event occurred at 12:34 on June 12, 2004. We employed a FIR low-pass filter with a cut-off frequency of 1 Hz to omit high frequency component. Before the event, the phase portrait of x vss. dˆ2/dtˆ2 (x, dˆ2x/dtˆ2) depicts two linear lines with different negative gradients and the portrait of x vss. dx/dt (x, dx/dt) does two circles with different radii. These phase portraits mean that the solution of differential equation consists of sinusoidal waves with two different frequencies and amplitudes. In the initial part of the event, the phase portraits dramatically change; (x, dˆ2x/dtˆ2) consists of several lines in which some of them have negative gradients and others do positive gradients. (x, dx/dt) consists of several circles but some of them are separated by cusps, and some turnaround orbits depict quick movements. The existence of positive gradient in (x, dˆ2x/dtˆ2) and of cusps in (x, dx/dt) indicates that a system potential with a number of local minimal surface is thought to exist and the solution jumps across a local maximal pass when some amount of energy is supplied. The quick movement of phase portrait suggests that the differential equation system includes a relaxation oscillator.

The results mentioned above reveal the source dynamics of these non-linear tremors and long-lasting events could be modeled by the differential equation system including a relaxation oscillator and with the system dimension between 3 to 7 (prospective dimension 3 or 4). Takeo (2010) proposed a hydraulic control valve model with the system dimension of 4 as a candidate of source model of these events. (x, dx/dt) and (x, dˆ2x/dtˆ2) phase portraits of this model have similar characteristics of the observed phase portraits, meaning this model is a leading candidate. During the first stage of eruption activity in Kirishima volcano in 2011, we also observed the analogous non-linear volcanic tremors. We will analyze these tremors using the same approach, and will examine other possible candidates of differential equation system.

Keywords: Volcanic tremor, Non-linear dynamics, Low frequency oscillation