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CHAOTIC PHENOMENA OBSERVED IN SEISMIC RESPONSE AND AFTER-EVENT BEHAVIOUR OF VARIOUS SYSTEM

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SUMMARY

This paper deals with the chaotic phenomena, which will be brought by numerical simulation on seismic induced disaster for establishing countermeasures. Recently real-time countermeasure systems are widely discussed by the Government and local government in Japan. Also, the concept of numerical shaking table has been discussed. Especially, in US, tests by a real shaking table are decreasing because of more use of a numerical shaking table for practical purpose.
The author shows his experiences on chaotic behaviors, that is, response of a beam with gap supports, behavior of de-railed high-speed train and simulation on seismic induced fire. For establishing countermeasure to seismic disaster, chaotic behavior in numerical simulation is very harmful as well as for a numerical simulation.

INTRODUCTION

Chaotic motions of a structure have been discussed as a nonlinear behavior since large computing systems become available for numerical simulation. The phenomena, which is called as "chaos" , was known more than 70 years ago, but this naming was made rather recently. The advance of computing system made easy their numeral simulation, and it becomes clear that many nonlinear systems show the chaotic behavior. During dynamic tests, the system behaved very badly in the sense of response for sinusoidal excitation, that is, those behaviors came from unskilled technique of testing, however, actually these are chaotic phenomena. This fact gives very strict impact to us ; for example, Blocky(1) reported on its impact to safety assessment in ICOSSAR'97. We usually treat a some event as a deterministic event, or random event. But the chaotic state has more uncertainty, even all phenomena can be solved by a computer simulation, including a seismic induced disaster. The author has been working on the seismic disaster prevention, one for the development of shaking table, and another for the prevention of seismic induced disaster. The result of the simulation was treated as a series of deterministic events, and we understood the result might be the worst by setting parameters of simulation to be the worst according to our experience. However, an each event is chaotic often because of the system nonlinearly. The author studied several events in these viewpoints; the seismic response of a piping system with gap supports and the dynamic behavior of de-railed trains, and also spreaded fire. It is rather easy to pick up the chaotic phenomenon during and after a destructive event, but it is very difficult to understand their result as a series of events which show chaotic states. In this article, the author tries to explain some examples, which he has been working for, and to understand how our simulation result.

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2. WHERE IS CHAOTIC PHENOMENA IN SEISMIC DISASTER

The developments in nonlinear dynamic analysis by computational approach brings chaotic phenomena in every nonlinear phenomena from the beginning of the event, seismic wave generation at the fault to disaster as shown in Fig.1. In this paper, the author tries to discuss three cases of his research from various chaotic phenomena in disaster simulation as follows:
i) Response of a multi-gap system. ii) Model test and simulation of the de-railed high-speed train.
iii) Simulation of spreaded fire in the urban region. The author presented the concept of a numerical shaking table[2] [3] in relation to the seismic disaster simulator, which has been developed as a project of NIED, the National Research Institute for Earth Science and Disaster Prevention, whose 3-D 1,200 ton shaking table is a part of the project. The role of numerical shaking table is for producing damages of various kind of structures caused by a certain destructive earthquake. The simulation of a model response must be done up to its failure. This is nonlinear response and failure simulation. After crashing of a structure, various type of development of disasters. Here, the author chooses two subjects above. Of course there are many processes of disasters, and these two are only examples, but they have typical characteristics as numerical models.
One of the purpose of the disaster simulation is to estimate the number of deaths and injures. During these processes, we must treat failure procedure of structures to debris, but it is difficult to treat it numerically. This part must be done by a shaking table test or other mechanical means. The failure process is one of the chaotic process, but currently almost impossible to simulate it. On the other hand the use of actual shaking table is gradually decreased especially in U.S. However, we should note its limitation as mortioned above.

3. RESPONSE OF PIPING SYSTEMS

A critical point in industrial plants, as well as power stations including nuclear power plants, is piping systems. Their dynamic characteristics are very complicated even in the linear domain. Actual systems have various nonlinear features. They have many gaps in their supporting systems. To make the behavior clear in this view point, the author tries to simulate the response of a simple beam with several gap support. Some ten years ago, Watanabe worked on the behavior of a simple beam with one gap support[4]. Its response is stable or bi-stable. Recently, the author studied on experiments of two or three gap supports, and he judged that the response might be chaotic, if number of supports exceed three. The response of a simple beam on a shaking table with sinusoidal excitation is usually sinusoidal, but in some cases, those amplitude is fluctuated. Some years ago, we understood it as "almost periodic motion," and also we understood that this phenomenon was caused by unskilled experiments. The definition of a term of "almost periodic motion" had been not so clear in some text books in 1930's. Ueda, who had been working for the analysis of nonlinear systems by using an analog computer, pointed out that the phenomenon observed by his computation might be more complicated than a simple almost periodic motion. This is one of the presentations of the concept of "chaos" . Anyway, most of engineers understood "chaos" observed in their business as a result of unskilled technique. The author tried to clarify that the response of a simple cantilever beam with multi-gaps might be chaos.

3.1 Numerical Simulation by Using Analog Computer and its Modification

In Watanabe's thesis,[4] the test and theoretical analysis of a single-degree-of-freedom system with a gap was made. He found some nonlinear behaviors including sub-harmonic resonance in lower frequency area compare to the linear eigen-frequency of the system. He also found that the tuned response was unstable in this region. He wanted to make clear the nonlinear behavior in this region more detail. To prove this, a more systematic survey on effect of several parameters to the response behavior would be required. But in 1970's, the ability of computing devices was very limited. Watanabe and Maezawa worked to apply the technique of an analog computer. Its ability of numerical integration was more powerfull than that of a digital computer. But the model of a beam was still a one-degree-of-freedom system. Watanabe and Shibata wanted to expand to a two or more degrees-of-freedom system, but there was another difficulty. Contact points of the analog computer were not so stable. It was rather difficult to make the simulation on several-degrees-of-freedom system. To express the fundamental characteristics of a beam with a gap, a five or more degrees-of-freedom system, was needed. SIMLINK software was available to substitute an analog computer's function. The author therefore decided to analyze the behavior of a beam with two or more gaps by using SIMLINK, instead of an analog computer.

3.1.1 Fundamental Approach to Analysis by Analog Computer

Starting from the dynamic equation as eq. (3.1),

$$m \frac{d^2 x}{d t^2} + kx + f\ (x, \dot{x}) = q \cos \omega t \qquad (3.1)$$

converting into the equations for the computations, where α is the scale factor for displacement and β is that of time. In the restoring force including reaction force, $F(X, \dot{X})$ is a nonlinear term to express a characteristic of bumping gaps (in Fig.4). In the case of linear $F(X, \dot{X}) = 0$ is held.
This relation seems to be complicated but only for expressing the characteristics of triangular bumper, and easy to input them to the analog computer. The damping factor of the beam is lower than the effect of bumper, which was silicon damper. This effect is coming from the hysterisis, therefore, the author neglected the damping term to become clearer the physical behavior of the system. Of course, we can introduce more sophisticated pattern for damping. Characteristics can be expressed by using switching elements with comparators in SIMLINK as well as an analog computer. Through this approach, the actual behavior of a single-degree-of-freedom system was compared to the theoretical solution under some assumptions can be obtained as Watanabe did it.

3.1.2 Numerical Solution on Multi-gap Cantilever Beam

A cantilever beam (Fig.2), which was used for the shaking test by Matsumoto, was employed for a model of numerical simulation. Three gaps, carted by the synthesized rubbess, made by the same method done by Watanabe, were used. Solved by SIMLINK similar to an analog computer, and a 10 and then a 20 mass system with three bumpers were mainly examined, and compare to the previous test result. The purpose of developing more masses is to expand the system to four or more bumpers. The stiffness matrix is the usual form and the mass matrix is that if a simple lumped mass system's one, and no damping elements are added.

3.2 Response State and Its Feature [5]

The author tried to calculate the response curve under the following limited conditions: the gap distances e_0, and exciting amplitude e or a, position of gaps. In general, this system has many parameters that we can change. A typical case is where $e/e_0 = 1.0$, and the position of gaps are corresponding to the model in Fig.2. Number of gaps, whose characteristics is as shown in Fig.4, is three. Approximate pictures of the change of responses are shown in Fig.4. In this case, the number of masses is 10. In Fig.4, some details of the response of of the beam are shown. In this case, where $e/e_0 = 1.0$, no simple sinusoidal resonance type peak is observed. All figures, Fig.4 and Fig.5, are shown in time history, phase plain loci and spectrum respectively. If the response is a simple sinusoidal waveform, the locus is a simple elliptic circle, but even at the top of peaks, they fluctuated as shown in some of the figures in Fig.6. That is, the response is almost periodic, or pseudo-resonance. The author tried also for a 20 mass system, and those are similar, even though there are some different. The amplitudes of peaks are different at both peaks as well as the frequencies. Also their loci are different. The 20 mass system behaved as more fluctuated state in both peaks[5]. The more detailed nonlinear feature will be discussed in the original paper. Under some conditions where $e/e_0 = 4.0$ with three gaps, test results were unstable and no definite stable response curve could be developed. Then the author tried to simulate it, and obtained the same result. The amplitude is almost steady but the locus is densely fluctuated as mentioned before.

3.3 Some Features of Non-Steady Responses

When the author tried to calculate the fractal dimension by applying a circle on the locus, and change the radius, the number of dots was changed. The author estimate that the fractal dimension might be $\nu = 2.41$ at 39.2 Hz from the distribution of points of loci. Fluctuation of distribution of peaks was observed, and this is significant for practical probabilistic matter. If observation time exceeded 20 sec, the distribution becomes similar to the normal distribution. This was unexpected by the author and has a significant meaning in some cases.

3.4 Seismic Response

How those characteristics would affect to their seismic response, it is not known. If the characteristics are chaotic one, the response analysis might have very large unstable uncertainty, and it is different from the uncertainty induced by bi-stable. There are chaotic systems, but we don't know their actual behavior under destructive seismic conditions. One of the reasons, most of them have rather high damping ratio, but piping systems, discussed here, have very low damping sometimes.

4. BEHAVIOR OF DE-RAILED TRAIN

4.1 Railway Accident

An airplane crashing is always a top news through the world, but a train crashing is not so. However, there are many serious railway accidents in the world every year. There are various types of train crashing. In the case of Indian Accident, August 1999, coaches piled up by a head collision. This study started from an accident of the local train in Japan. The author tried to establish the standard procedure for PSA analysis of the railway accident (in Fig.7) [6] [7]. During this process, he recognized that the behavior of a derailed train was the most difficult part in the flow of calculation. Especially, in some seismic countries, including Japan, have or will have a high-speed railway system like TGV, or Shinkansen. The condition of their derailing under a seismic condition is partially known, but their behaviors after derailing are quite complicated as mentioned.

4.2 Model Test

The author tried to simulate it after the model test. Because the result of the behavior of derailed train in the model test, which was done by using 1/80's model consisting of three coaches, showed interesting result. The results, whose initial condition were the same within model test accuracy, spreaded to three types as shown in Fig.8. And each type formed some distributions independently. The author's group made such model tests for several types of accidents. The typical one was as follows: the track was ended at the point, and a train went to smooth plane. Other heavy coach corresponding to four-coach mass pushed three-coach train. The results in Fig.8 showed for this case.

4.3 Simulation and Result

The simulation was made on two, three coach model, that is, a train of rigid bars connected pin-joint hinges. But in this case, the result of simulation was quite simple, and deterministic, of course. Then, the author addd two bogies on each coach. These bogies were pined to a coach without any constraint. During simulation process, the author found the very unstable state numerically. The author tried to change the time interval Δt for simulation to precise and found very sensitive to this. He changed it to several digits accuracy, but there was still the boundary of stable and unstable. He judged that the phenomena, which were obtained from this simulation, were chaos, because the result was very sensitive to change on numerical conditions.

For the comparison to the result of model test, he needed the more complicated condition for his simulation model. Especially the behavior of each bogie is very significant for the instability of the train. In this simulation, an each bogie was free and received uniform friction forces on each wheel, but it was received no turning moment from ground surface. According to the observation during the model test, free motions of bogies and their effect for steering of the coach was significant for the behavior of a whole train. This type of the behavior, we need more sophisticated program for multi-body problem, and also we need to establish the effect of the ground resistant as random input.

5. SEISMIC INDUCED FIRE

5.1 Simulation of Deaths in Kwanto Earthquake-1923

About one hundred forty thousand lives were lost in Kwanto Earthquake-1923 in Tokyo area. Direct loss from crashing of structures were estimated ten or twenty thousands. Others were killed by the spreaded fire in the downtown of Tokyo mainly. During the Second World War, this area had the second fire from the bombing, and approximately one hundred thousand lives were lost under very strong dry wind from the northwest in winter season. Therefore, in 1950s and 1960s, the target for preventing the seismic disasters was mainly on a seismic induced fire. However, in those years, the development of large size computer was not enough to simulate of fire spreading phenomenon, because the size of the computer was poorer than a current desk top P.C.. Early 1970's, Fujita started the research on the computer simulation of spreading fire[8] with the author's group. He employed the concept of cellar-automaton, at that time we didn't have this naming. And also a two-state variable, "fire" or "no fire" on each mesh areas is employed. He started from Hamada's equation of fire boundary velocity, and converted it to the finite differential equation and later also the ordinary differential equation and by solving them he could get the formula of fire flow. Then he tried to simulate some previous spreader fires in Japan. One of them is Tottori Fire in 1952. Tottori City, approximately 100,000 population, faced on Japan Sea, was burnt under strong south wind storm in spring. There were many restarting of the fire flows by sparks. The simulation of the fire itself was successful, if he put in those secondary origins. However, we noticed that it was impossible to predict those secondary origins, because their exact points couldn't predict in advance. Therefore, the simulation of spreaded fire was practically impossible because of the run fire. The prediction of those second, third origins might be one of chaotic phenomena. If we treat it like uniform fire flow, as to treat the turbulent flow without discussing on each vortexes. It might be possible to get a some solution, but it is not the exact simulation, and only the average state of fire spreading. In conclusion, it is possible for a moderate size fire with a moderate weather condition. Unless, it is impossible, even though we don't know whether or not it directly connected to a chaotic phenomenon.

6. CONCLUDING REMARKS

We have been working for simulating the seismic induced disaster, and we continue this effort still for practical purpose in a local government levels as well as the National Government level. We should know the limitation of such efforts, especially the simulation in time-domain. We can estimate approximate image of the future disaster by the numerical simulation under a some assumption, and it might be beneficial for planning the strategy of disaster prevention, but it is very difficult to decide the details of a real operation after the event, so-called real time operation planning. The author is working for the 1,200 ton 3-D shaking table of the project in NIED, and this is a part of the Governmental Project for Seismic Disaster Prevention. We expect the testing up to failure of urban structures by this shaking table, but it is a new subject how to develop to the result of seismic induced disaster. Our project intends to estimate seismic induced disaster in advance or real-time. But it might be chaos. Then is the stable only for improving the structural design as to be no failure.

7. ACKNOWLEDGEMENT

This paper consists of these papers which the author concern these studies through their graduate jobs in University of Tokyo and Yokohama National University. He greatly appreciate their cooperations. Professor T. Fujita, University of Tokyo was worked together on a fire spreading in 1970's. The simulation of seismic disasters were made by the committee in Metropolitan Government of Tokyo. He also expresses his thanks for that they gave us the chance to work in this area.

8. REFERENCE

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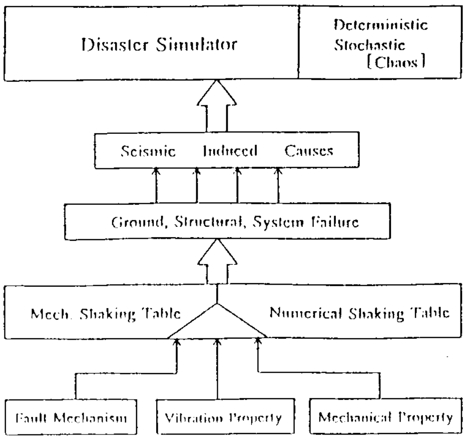


Fig.1 Flow of Seismic Induced Disaster Simulator

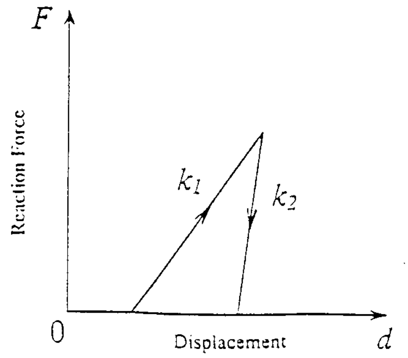


Fig.3 Schematic Drawing of Characteristics of Bumpers f

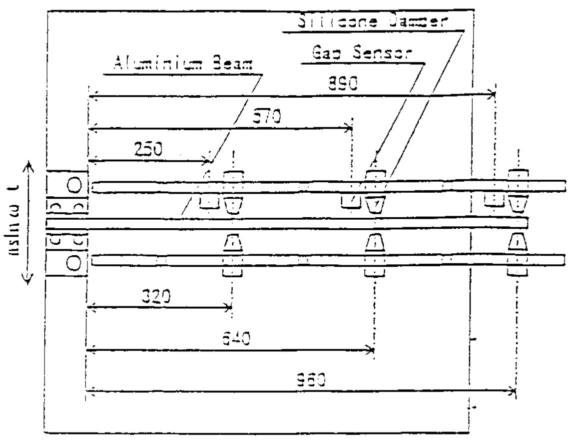


Fig.2 Model of Canti-lever with 3 Gaps

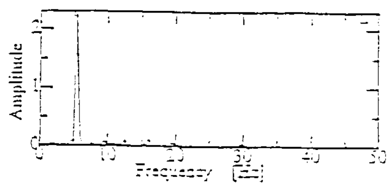
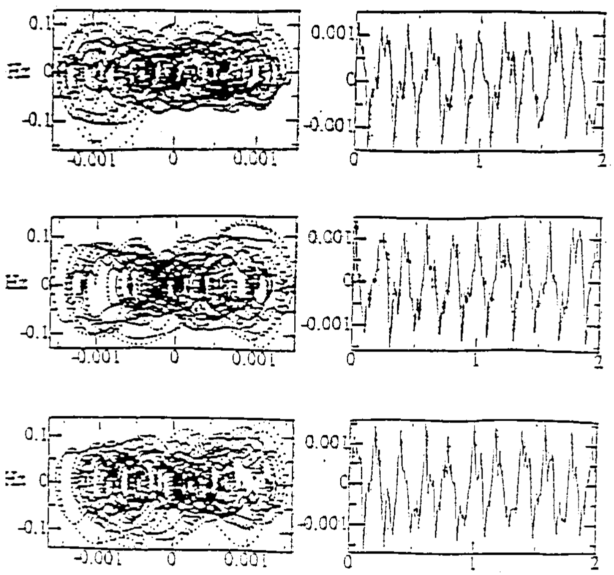


Fig.4 A Typical Example of Response in Frequency D



A Typical Example of Chaotic Response in Phase Plane and Time-History

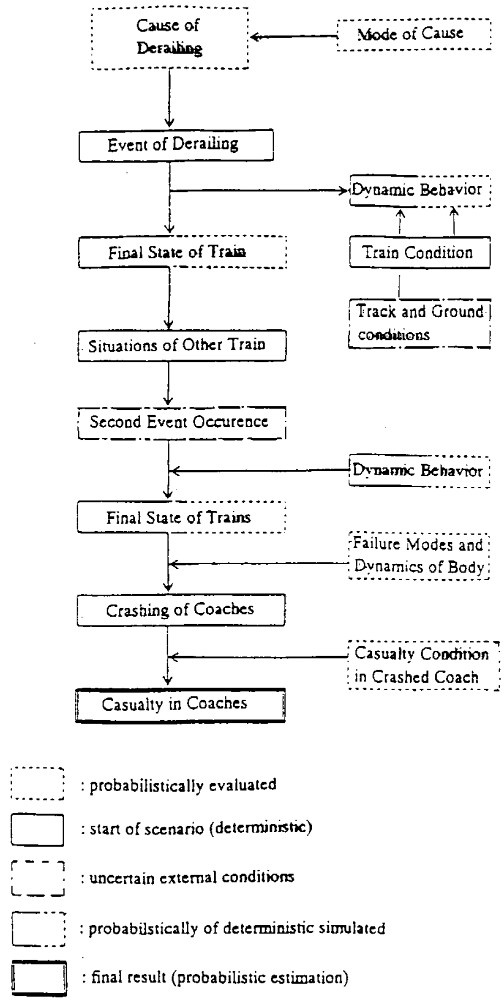
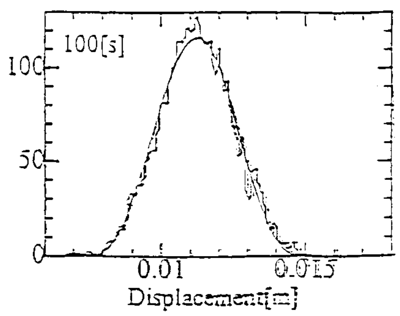


Fig.7 Flow Diagram of PSA Calculation of Train Accident



g.6 Distribution of Peak Amplitude at Second Resonance

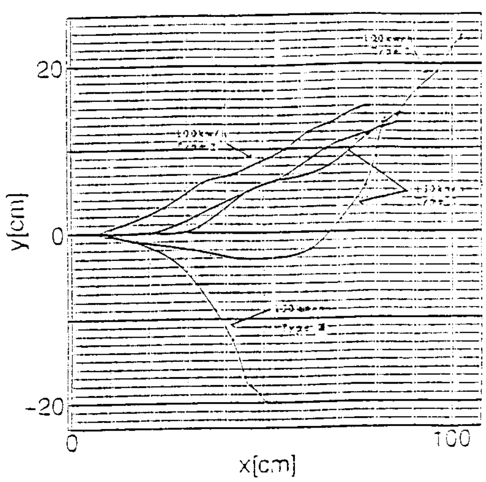


Fig.8 Schematic Loci of De-railed High-speed Trai Obtained by Model Tests