Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-11-7

ACTIVE CONTROL FOR EARTHQUAKE-INDUCED SLOSHING OF A LIQUID CONTAINED IN A CIRCULAR TANK

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SUMMARY

Presented in this paper is a new technique to actively control liquid sloshing for a circular tank by injecting air bubbles at a proper timing and duration, regulated by a microcomputer using the sloshing pressure singnal. A large shaking table driven by oil-hydraulic power and a circular test tank of 2 m diameter were used in experiments. The experiments showed that (1) injecting air bubbles into sloshing liquid effectively suppressed the sloshing oscillation, (2) a small amount of air - about 1% of the total liquid volume for each injection - was sufficient to suppress the sloshing, and (3) there existed an optimum timing for air injection, i.e., air bubbles should be injected so that they rise up to the top position of sloshing wave when the sloshing takes the higest level in its oscillation. We investigated an algorithm for controlling air-injection timing and duration to suppress earthquake-induced sloshing.

INTRODUCTION

Many reports on earthquake hazards describe the occurrence of sloshing oscillation of petroleum contained in large tanks during earthquakes--an occurrence of sloshing causes the petroleum to overflow and damages the tanks containing it. The urgent need to develop techniques to suppress earthquake-induced sloshing in such tanks cannot be overemphasized. Hayama(1) studied the absorbtion of sloshing energy by inversely installing a U tube in a tank. This is based on the principle of dynamic damper, and a large amount of kinetic energy may concerntrate in the U tube. Others, in Japanese industry, have applied for several patents(2)- (4) for sloshing-reduction devices. Hara and Shibata studied an active control of sloshing using a small test tank(5).

This paper shows the usefulness of a technique that suppresses liquid sloshing for a circular tank through the microcomputer-controlled injection of air bubbles. A circular tank 2034 mm in diameter and 1555 mm high was installed on a pneumatically-controlled shaking table and water was filled 1000 mm deep; and sloshing was then excited by a sinusoidal motion of the table. A microcomputer controlled the air-injection timing and duration using the table excitation signals, and the effect of air-bubble injection on sloshing suppression was investigated with changing air-injection timing and duration.

Experiments showed that the most effective air-injection timing for alternate air injection was the instant that the sloshing wave passed its lowest position and the injected air bubbles reached the top position of sloshing wave in its oscillation. A small amount of air - about 1% of the water in the tank - was enough to supress the sloshing. Based on experimental results, we investigated an algorithm for controlling air-injection timing and duration to suppress earthquake-induced sloshing.

EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 is the circular test tank used, 2034 mm in diameter and 1555 mm high. A veritical partition plate was installed along the tank's center line, parallel to the excitation direction, to prevent a swirling sloshing under a large excitation. Water was filled 1000 mm deep in the tank. Two air-injection mainfolds (A and B), 180 mm in outer-diameter, 1000 mm long, and the wall thickness 10 mm, with having 20 mm air-injection holes, were installed at both ends of the tank-bottom's center line and perpendicular to the excitation direction as shown in Figure 1.

Figure 2 is a schematic diagram of the experimental system. A shaking table driven by hydraulic oil power generated a purely sinusoidal one-dimensional motion, and its oscillatory displacement was measured by a displacement meter. The sloshing of water in the circular test tank was excited by the table's sinusoidal motion at the natural period of sloshing. Sloshing-induced pressure was measured by a pressure transducer located on the side wall of the tank, 50 mm away from the bottom plate, and recorded on magnetic tape. A sinusoidal wave signal of the table motion, which had a 90-degree phase difference from sloshing pressure, was transferred to a microcomputer (PC-9801 E) through an A/D converter, and used for controlling air-injection timing.

The zero-cross point of the sinusoidal signal was identified by the computer, and then, after a specified time interval had elapsed, an electronic command signal to open a solenoid valve was transmitted from the computer to a solid-state relay through an electronic device PIO (Port of Input and Output). Air was then injected into the tank. Air, supplied from a pressurized air source, was conducted to a pressure reduction valve and was then transferred to air-injection manifolds through microcomputer-controlled solenoid valves.

Figure 3 is a schematic diagram of the control for timing the opening and closing of the solenoid valve. A sinusoidal signal of the shaking table displacement was sent to the microcomputer through an A/D converter and compared with the zero-level to find the zero-cross instance in shaking table motion. An idle-computaion routine then started to count down the time of the (n_1/10) sloshing period. A valve-opening signal was then transmitted to a solid-state relay from the computer, and again the idle-computation routine started to count down the time of the (n_2/10) sloshing period. A valve-closing signal was then sent to the relay to halt air injection. Opening and closing timings for valves 1 and 2 were thus controlled. Figure 4 is a schematic illustration of this kind of air-injection timing and duration.

We employed the following four experiments: (1) The sloshing-pressure response was measured during a sinusoidal wave sweep test to find the first natural frequency of sloshing for the test tank. (2) The test tank filled with water 1000 mm deep was sinusoidally excited and the sloshing response was fully developed. Air was then injected through air-injection manifolds A and B into the sloshing water at the timing Tm and duration To. The sloshing pressure response was measured and its Root Mean Square (RMS) for each successive interval of about 5.2 periods was evaluated. (3) For the most effective timing of air injection in experiment (2), the influence of air-injection duration To, air-injection pressure P and excitation amplitude a on sloshing suppression was experimentally examined in the same manner as that in (2). (4) At starting the sloshing motion in water, air bubbles were injected into the sloshing water at the air-injection timing Tm = 0 and duration To = 2 and 3, and the sloshing suppression characteristics were investigated for the transient response of sloshing.

The data of sloshing response pressure and excitation displacement of the shaking table were recorded on magnetic tapes and then were digitized by an A/D converter at a sampling period of 20 ms. The maximum sloshing pressure in RMS for the case of non air-injection, i.e., one at resonance, was used to normalize the sloshing response.

RESULTS

Sloshing Suppression and Air-Injection Timing

The sloshing natural frequency was found 0.652 Hz or the sloshing period T was 1.534 s for the test tank filled with water 1000 mm deep.

A pressure wave pattern decaying from a fully developed sloshing state at each air injection is shown in Figure 4, where the air-injection timing Tm was 0, the air-injection duration To was 3, i.e., 3/10 of the sloshing period T, and the air-injection pressure 50 kPa. The air-injection timing Tm = 0 showed that injected air bubbles effectively suppressed the sloshing even when the tank continued to be excited at the sloshing resonance frequency. This sloshing suppression by air-bubble injection was also reported by Hara and Shibata(5) for a amall-scale rectangular test tank.

Figures 5 shows typical timewise histories of sloshing oscillation in terms of RMS Ratio of sloshing pressure to the fully developed one obtained under the sloshing resonance for the air-injection duration To = 1 and excitation amplitude of 2 mm. In Figure 5, for Tm = 0, the sloshing was almost monotonously decreased, and at 90 seconds its magnitude was suppressed down to about 15% of that for the initial state. For Tm = 4, this air-injection timing was ineffective on suppressing the sloshing. For Tm = 7, the sloshing was gradually decreased with time, and reduced by 40% of the original magnitude.

The minimum value of the RMS ratio over the 90 second interval of sloshing suppression was plotted against the air-injection timing Tm for To = 1 and 2, and the result is shown in Figure 6, where the vertical axis is the minimum RMS ratio and the horizontal one air-injection timing Tm. The symbols ● and □ designate To =1 and 2, respectively. This figure clearly shows that 1) the timing Tm = 0 and 1 are very effective on suppressing the sloshing, but the timing Tm = 4 to 7 are not, and 2) the air-injection duration To = 2 is more effective on the sloshing suppression than To = 1.

Effect of Air-Injection Duration

The minimum RMS ratio of sloshing pressure was examined for air-injection duration To = 1, 2, 3 and 4 under the air-injection pressure P = 50 kPa, and the result is shown in Table 1. The most effective interval of air injection was found To = 2, at which the sloshing was suppressed down to about 9% of the original magnitude in 39 cycles of sloshing period. This table implies that a certain amount of air injected into sloshing water per 1 cycle is essentially needed to suppress the sloshing effectively.

Effect of Air-Injection Pressure

For Tm = 0 and To = 2, we examined the effectiveness of air-injection pressure on suppressing the sloshing . The result is shown in Table 2, where the minimum RMS ratio of sloshing pressure and their appearance time in terms of sloshing period are shown for each air-injection pressure. When air-injection pressure was large, e.g., 210 kPa, the minimum RMS ratio reached the value of

26%, but for a small pressure of air injection, the sloshing was effectively suppressed. Among these results, sloshng was quickly and effectively suppressed for Tm = 0, To = 2, and P = 70 kPa.

Effect of Excitation Level

For Tm = 0, To = 2, and P = 50 kPa, the excitation level was changed from a = 1 mm, 2 mm, 3 mm, to 4 mm and the time history of RMS ratio of sloshing pressure was evaluated. The minimum and maximum RMS ratio, normalized for the excitation level of 2 mm, are shown in Table 3, showing that, when the excitation level was high, the air-injection condition such as Tm = 0, To = 2 and P = 70 kPa, effective for the medium excitation level i.e., a = 2mm, was not sufficient to suppress the sloshing effectively. This implies that we need an appropriately sufficient amount of air bubbles to suppress the sloshing generated by a large excitation level.

Transient Characteristics of Sloshing Suppression

Figure 7 shows the transient time history of the RMS ratio of sloshing pressure when air injection started simultaneously with the sinusoidal wave excitation at the sloshing natural frequency and amplitude of 2 mm, where Tm was 0 and P 50 kPa. The air injection with To = 3 prevented the sloshing from growing fully to the resonance state. However, the air injection with a small duration, e.g., To = 2, could invited a full growth of sloshing, but even so, the sloshing was gradually suppressed by this air injection mode after the sloshing reached the maximum.

We estimated the amount of air bubbles per one air-injection for To = 2 and P = 50 kPa, and obtained the result that it was about 1% to the total volume of water contained in the test tank.

CONTROL ALGORITHM FOR SLOSHING SUPPRESSION

We used the knowledge obtained in experiments to construct a sloshing control algorithm: (a) Air-injection timing is the most important parameter and should be the instant that air bubbles reach the top position of sloshing wave when it takes the highest position in its oscillation. (b) The air-injection duration is also essential for reducing sloshing oscillation, meaning that the appropriately long duration is most effective on sloshing suppression. (c) The fundamental sloshing period is precisely estimated in advance using the tank diameter and liquid height.

Based on the above knowledge is the algorithm constructed and shown in Figure 8 and reads mainly as follows:

(1) Sample the sloshing pressure for one period T and calculate the mean and RMS values.

(2) Find the zero-cross point (0_-) to identify the initiation instance for control.

(3) Set the most effective air-injection timing, for example (Nt/10) T, and start the idle-computation for this time interval.

(4) Transmit a command signal to a relay to open solenoid valve 1.

(5) Start the idle-computation for counting down the time interval, for example, (Nt + Nd/10)T - (Nt/10)T = (Nd/10)T.

(6) Transmit a command signal to the relay to close the valve.

(7) Do same as in (3) to (6) for valve 2.

(8) Repeat procedures (3) to (7) three times.

(9) Sample the sloshing pressure oscillation for one sloshing period and calculate mean and RMS values.

(10) If the sloshing is enough small, then cease air injection.

(11) If the sloshing is growing, increase the air-injection duration by an increment and repeat procedures (2) to (7).

(12) If the sloshing is decreasing, repeat procedures (2) to (7).

CONCLUSION

We conclude the followings about active control of sloshing oscillation by injecting air bubbles into sloshing liquid from the tank bottom:
(a) Injecting air bubbles at a proper timing and duration into liquid effectively suppresses the sloshing oscillation.
(b) A small amount of air - for instance, 1% of the liquid volume contained in a tank per one air-injection is sufficient to suppress the sloshing.
(c) There exists an optimum for air-injection timing, that is, the air should be injected so that air bubbles rise up to the top position of sloshing wave when it takes the highest position in its oscillation.
(d) A micro-computer control algorithm can be constructed using the knowledge obtained from our experiments.

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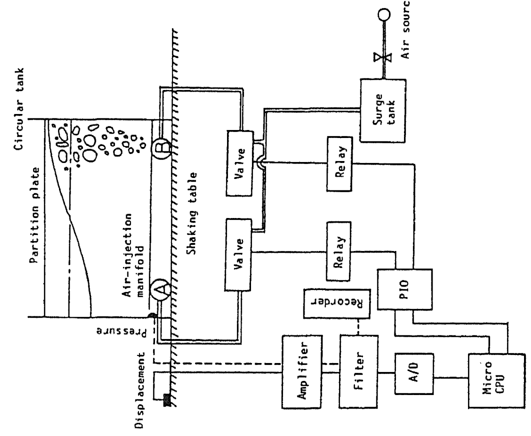

Fig. 2 Schematic diagram of experimental system

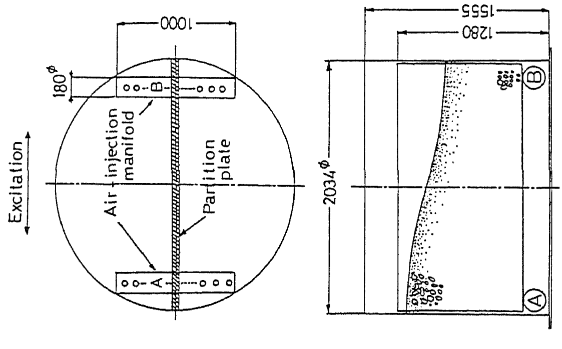

Fig. 1 Major dimensions of a circular tank used in experiments

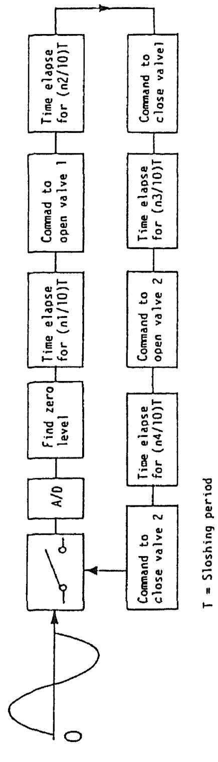

Fig. 3 Control flow diagram of timing to open and close solenoid valves for air injection

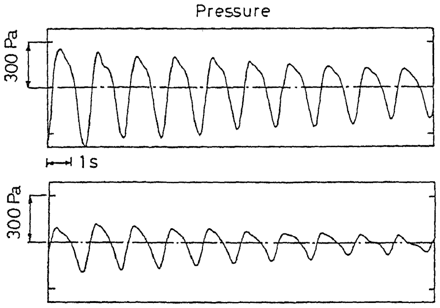

Fig. 4 Time history of sloshing oscillation decaying by injecting air bubbles at the timing Tm = 0 and duration To = 3

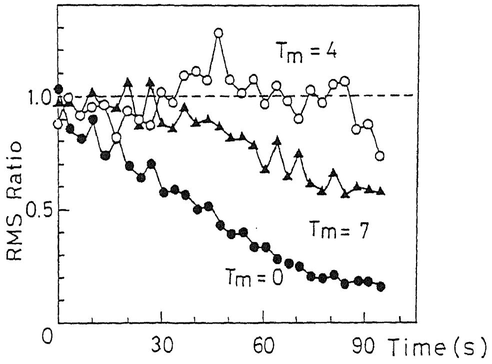

Fig. 5 Typical timewise history of sloshing oscillation in terms of RMS ratio of sloshing pressure for To = 1

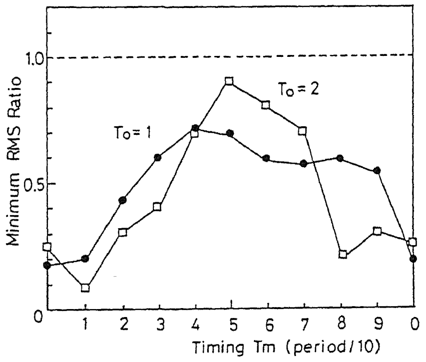

Fig. 6 Minimum RMS ratio of sloshing pressure plotted against air-injection timing Tm

Table 1 Minimum RMS ratio and its appearance time in relation to air-injection duration To

To	Minimum RMS ratio (%)	Appearance time (in period)
1	19.7	44
2	8.8	39
3	9.1	42
4	25.4	44

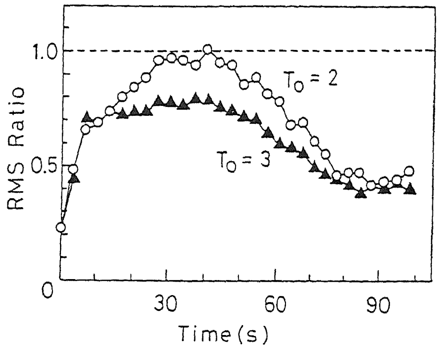

Fig. 7 Time history of the RMS ratio of sloshing pressure for transient sloshing response to the sinusoidal excitation at the natural sloshing frequency

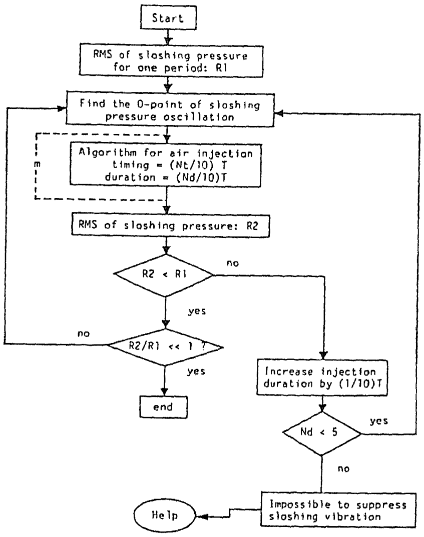

Fig. 8 Micro-computer control algorithm for suppressing sloshing oscillation by air-bubble injection

Table 2 Minimum RMS ratio and its appearance time in relation to air-injection pressure P

P (kPa)	Minimum RMS ratio (%)	Appearance time (in period)
210	25.8	30
150	20.0	37
110	14.0	37
70	12.0	30
50	10.0	39

Table 3 Minimum and maximum RMS ratios in relation to excitation level a

a (mm)	Minimum RMS ratio (%)	Maximum RMS Ratio (%)
1	40.0	75.0
2	20.0	100.0
3	25.0	120.0
4	70.0	160.0