Experimental Study on Active Suppression by Gas Bubble Injection for Earthquake Induced Sloshing in Tanks*

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This research aims to develop a technique to suppress liquid sloshing vibration in a tank by injecting air bubbles in a microcomputer-controlled manner. Using a rectangular tank 800 mm long, 150 mm wide, and 500 mm high, installed on an oil-hydraulically controlled shaking table, sloshing was excited by a sinusoidal motion of the table and air was injected at each end of the test-tank bottom. The timing and duration of air injection were controlled by a microcomputer using the pressure signal caused by sloshing. Experiments showed that the most effective timing of air injection was the instant that the sloshing wave was ascending from the lowest position to the equilibrium one, and a small amount of air, equivalent to 1 to 3% of the water contained in the tank, was sufficient to suppress sloshing. A scaled-up test showed a similar effectiveness in reducing sloshing. An algorithm for controlling air-injection timing and duration was developed using knowledge obtained from the experiments.

Key Words: Sloshing, Liquid Storage Tank, Suppression, Air Bubble Injection, Microcomputer Control

1. Introduction

Many reports on earthquake hazards describe the occurrence of sloshing vibration of petroleum contained in large tanks during earthquakes--an occurrence of sloshing causes the petroleum to overflow and damages the tanks containing it. During the Niigata Earthquake in 1964, such sloshing caused fires at a large petroleum tank. During the 1978 Miyagi-ken-oki Earthquake, crude oil overflowed from 400 000 kl tanks. In the 1983 Nihonkai-chubu Earthquake, a petroleum tank 70 m in diameter underwent heavy sloshing that raised 4 m waves.

The urgent need to develop techniques to suppress earthquake-induced sloshing in such tanks cannot be overemphasized. Hayama⁽¹⁾ studied the absorption 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 concentrate in the U tube. Others, in Japanese industry, have applied for several patents⁽²⁾⁻⁽⁴⁾ for sloshing-reduction devices. There has, however, been no study of the active control of sloshing.

This paper deals with the development of a technique that suppresses liquid sloshing vibration in a tank through the microcomputer-controlled injection of gas bubbles. A rectangular tank 800 mm long, 150 mm wide, and 500 mm high was installed on a pneumatically-controlled shaking table and sloshing was excited by a sinusoidal motion of the table; air was then injected into the sloshing water. The two air injectors used were located at each end in the bottom of the test tank. A microcomputer controlled the air-injection timing and duration using sloshing pressure signals. Two types of air-injection mode were examined to investigate the effects of air bubble injection on sloshing suppression; one was alternate air injection, in which air was alternately injected by each injector during each sloshing cycle, and the other was simultaneous air injection, in which air was simultaneously injected by both injectors twice during each sloshing cycle.

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Experiments showed that the most effective air-injection timing for alternate air injection was when the sloshing wave approached the equilibrium position from below, and small amounts of air—about 2 % of the water in the tank—were enough to suppress sloshing. A scaled-up tank test showed the same effectiveness in reducing sloshing as that obtained in small-scale tank experiments.

Based on experimental results, we investigated an algorithm for controlling air-injection timing and duration to suppress earthquake-induced sloshing.

2. Experimental System and Procedure

Figure 1 is a schematic diagram of the experimental system. A shaking table driven by hydraulic oil power generated a purely sinusoidal one-dimensional motion. The table's oscillatory displacement was electronically controlled and measured by a displacement meter (B). The sloshing motion of water in a rectangular tank 800 mm long, 150 mm wide, and 500 mm high, installed on the shaking table, was excited by the table's sinusoidal motion at its natural period. Sloshing-induced pressure oscillation was measured by a pressure transducer (C) located on the bottom plate of the tank and 200 mm away from the side wall,

Fig. 1 Experimental system

and recorded on magnetic tape. A sinusoidal wave signal used for controlling the table's motion, which had a 90-degree phase difference from sloshing-induced pressure oscillation, was transferred to a microcomputer (PC-9801 E) through an A/D converter. This sinusoidal signal was used for controlling air-injection timing.

The zero-cross point of the sinusoidal signal was identified by the computer and, 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. A small air compressor supplied pressurized air to a surge tank, from which air was transferred to air injectors through microcomputer-controlled solenoid valves. The two air injectors were 50 mm in diameter, 140 mm long, and had 5 holes 5 mm in diameter at a 25-mm pitch. They were installed at both ends of the tank bottom plate.

Figure 2 is a schematic diagram of the control for timing the opening and closing of the solenoid valve. A sinusoidal analog wave signal was sent to the microcomputer through an A/D converter and compared with the zero-level value to find the zero-cross instance in shaking table motion. An idle-computation routine then started to count down the time of the $(n_1/10)$ sloshing period. A valve-opening signal was then transmitted to a solidstate 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. Air was thereby injected into the water for the $(n_2/10)$ sloshing period. Opening and closing timings for valves 1 and 2 were thus controlled. Changing the values n_1 , n_2 , n_3 , and n_4 provided a variety of air-injection timings and durations. Figure 3 is a schematic illustration of air-injection timing and duration.

We used two types of air injection modes—alter-

T = sloshing period

Fig. 2 Control of timing to open and close solenoid valves

Fig. 3 Air-injection timing and sloshing pressure

nate (AL mode) and simultaneous (SI mode)—to investigate air-bubble influence on sloshing vibrations. In the AL mode, air was alternately injected once per sloshing cycle by each injector. In the SI mode, air was injected simultaneously twice per sloshing cycle from both injectors. The air-supply pressure was kept constant at 2 atm to reduce the number of experimental cases.

Sloshing-induced pressure data and valve open-close signals were simultaneously recorded on magnetic tape. Data was digitized by a 2-channel A/D converter at a sampling rate of 10 ms; RMS (Root Mean Square) values of pressure amplitude were evaluated by a microcomputer.

A large-scale rectangular tank 1600 mm long, 300 mm wide, and 900 mm high was used for scaled-up tests. Two air injectors with 27 holes (9 holes in three lines) 6 mm in diameter were installed at each end of the test-tank bottom. The test tank, which was filled with water 500 mm deep, was fixed on a large hydraulic oil shaking table (50 kN). The experimental system was essentially like that aforementioned. The AL mode was used in the scaled-up test, and the experimental procedures were the same as those described above.

3. Results

3.1 Alternate air injection

The small scale tank filled with water 300 mm deep continued to be excited by the shaking table at a resonance period of sloshing $T = 1.13$ s, and the excitational acceleration was about 20 Gal. When the sloshing became fully developed, we started injecting air bubbles into the water in a microcomputer-controlled manner.

A pressure wave pattern decaying from a fully developed sloshing state at each air injection is shown in Fig. 4 for the AL mode experiment, where the air-injection interval was $(2/10)T$; meaning air was

Fig. 4 Sloshing pressure wave pattern for timing $(7/10)T$

Fig. 5 RMS ratio and air-injection timing for air injection duration $(2/10)T$

injected for 20% of sloshing period T , and air-injection timing was $(7/10)T$. When air was injected the instant that sloshing-induced pressure reached its maximum, that is, the sloshing wave was at the top position, air injection little influenced sloshing suppression. However, as seen in Fig. 4, air-injection timing $(7/10)T$ showed that injected air bubbles effectively suppressed sloshing even when the tank continued to be excited by the shaking table's sinusoidal motion at the sloshing resonance frequency.

The ratio of the RMS value of sloshing pressure under air injection for the first 10, 20 and 30 seconds to that of the original or fully developed sloshing pressure was evaluated for each combination of air-injection timing and duration. Figure 5 shows one of the results with respect to air-injection timing for an air-injection duration of $(2/10)T$.

Figure 6 shows the RMS value of sloshing pressure for a 30 second air injection with respect to air-injection timing, where the parameter is air-injection duration in terms of sloshing period T . This figure

Fig. 6 RMS ratio for 30-second pressure data and air-injection timing with respect to air injection duration

Fig. 7 RMS ratio for pressure data of 30 sloshing cycles and air-injection timing with respect to air-injection duration

indicates that sloshing was almost completely suppressed for air-injection timings of $(7/10)T$ or $(8/10)T$ with an air-injection interval of 20% to 30% of the sloshing period.

These figures suggest that the most effective air-injection timing is the instance when the sloshing wave starts moving upward and approaches its equilibrium. A longer duration of air injection suppresses sloshing more effectively, but air injection for a 40% sloshing period has little significance in suppressing sloshing compared with the cases of $(3/10)T$ air-injection duration.

3.2 Simultaneous air injection

For simultaneous air injection, the RMS ratio of sloshing pressure for air injection and no air injection is shown in Fig. 7 with respect to the timing of air injection, where RMS values were evaluated for 30-second sloshing pressure data. This shows that for an air-injection duration of $(2/10)T$, $(0/10)T$ and $(4/10)T$ timings were effective in suppressing sloshing. Other timings were less effective, but still reduced sloshing. This characteristic appeared for $(1/10)T$ to

Fig. 8 AL vs. SI mode sloshing suppression

$(3/10)T$ air-injection durations, but not for the $(4/10)T$ duration.

We conclude from the figure that simultaneous air injection effectively suppresses sloshing when air is injected at the instant the sloshing wave takes a bottom position at one (left or right) antinode-position of the sloshing wave. Note that simultaneous air injection consumed almost twice as much air as alternate air injection.

3.3 Comparison of AL and SI modes

The effectiveness of air injection in suppressing sloshing was compared for AL and SI modes under the condition of equal air consumption per sloshing cycle. That is, the timing was $(7/10)T$ and the duration was $(4/10)T$ for the AL mode, and the timing $(4/10)T$ and the duration $(2/10)T$ for the SI mode. The result is given in Fig. 8, where H_0 = the original or fully developed sloshing pressure amplitude and H_m = the sloshing amplitude decaying at each cycle due to air injection. This shows that the AL mode is more effective than the SI mode.

For the AL mode, the air consumed per sloshing cycle was estimated as 800 cm^3 at a 2 atm surge pressure for a $(2/10)T$ air injection, which corresponded to 2.2% of the sloshing water in volume.

3.4 Results of scaled-up test

We calculated the ratio of RMS values of sloshing pressure oscillation between no-air injection and air injection for intervals of 20, 40, 60, and 80 seconds. The result is given in Fig. 9, in which the RMS ratio takes a minimum value at air-injection timings $(5/10)T$ or $(6/10)T$, where T = sloshing period of 1.656 s. This indicates that the most effective timing for air injection is when the sloshing wave starts moving upward and gaining velocity. When air is injected the instant that the sloshing wave reaches the top position, air bubbles can no longer suppress sloshing.

The amount of air consumed per air injection was evaluated as about 2.4% of the water in the scaled-up

Fig. 9 RMS ratio and air-injection timing for air injection duration $(2/10) T$

test tank for a $(2/10) T$ duration of air injection.

4. Control Algorithm for Sloshing Suppression

We used the knowledge obtained in experiments to construct a sloshing control algorithm:

(1) Air-injection timing is the most important parameter and should occur at the instant that the sloshing wave approaches equilibrium while rising.

(2) The air-injection duration is also essential for reducing sloshing vibration, meaning the longer the duration, the more effective the sloshing suppression.

(3) The fundamental sloshing period is precisely estimated in advance using the tank diameter and liquid height.

The algorithm constructed based on the above knowledge is shown in Fig. 10 and reads mainly as follows:

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

(2) Find the zero-cross point (0-), meaning the point where the pressure crosses the zero level from below, of sloshing pressure oscillation to identify the initiation instance for control.

(3) Set the most effective air-injection timing, for example $(3/10) T$, from the zero-cross point (0-) and start the idle-computation for this time interval to count down actual time.

(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, $(5/10) T - (3/10) T = (2/10) T$.

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

(7) Start the idle-computation for another time

Fig. 10 Microcomputer-control algorithm for suppressing sloshing by air-bubble injection

interval, for example, $(3/10) T$.

(8) Send a command signal to another relay to open valve 2.

(9) Start the idle-computation for a time interval, $(2/10) T$.

(10) Send a command signal to the relay to close the valve.

(11) Repeat procedures (2) to (10) three times.

(12) Sample the sloshing pressure oscillation for one sloshing period.

(13) Calculate mean and RMS values.

(14) Calculate the ratio of these successive RMS values to determine whether sloshing is increasing.

(15) Calculate the ratio of the original RMS value to the last value and, if this is small enough, cease air injection.

(16) If the ratio in (14) is larger than 1, increase the air-injection duration by an increment, for example, $(1/10) T$ and repeat procedures (2) to (11).

(17) If the ratio in (14) is smaller than 1, repeat procedures (2) to (11).

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

(19) Calculate the ratio of two successive RMS values, and the ratio of these two successive ratios to see whether sloshing is increasing and how its rate is changing.

Fig. 11 Microcomputer-controlled sloshing oscillation

(20) If the former ratio is larger than 1, increase the air-injection duration by an increment, say, $(1/10)T$, and repeat procedures (2) to (11).

(21) If the latter ratio is larger than 1 and the former smaller than 1, decrease the air-injection duration by a decrement, for example, $(1/10)T$.

(22) If both ratios are smaller than 1, decrease the duration by, for example, $(2/10)T$.

(23) After (20) or (22), repeat procedures (2) to (11).

Figure 11 is an example of the test results we

obtained, and shows that sloshing was suppressed by injecting air bubbles using a microcomputer that controlled the timing of air injection and duration based on sloshing-state data.

5. Conclusions

We concluded the following about active control of sloshing vibration by injecting air bubbles into the sloshing liquid: (a) Injecting air bubbles into water effectively suppresses sloshing vibration. (b) A small amount of air—for instance, 2% of the volume concerned—is sufficient to suppress sloshing. (c) There is an optimum for air-injection timing, that is, the timing when the sloshing wave starts moving upward and approaches the equilibrium position, but sloshing suppression is not so sensitive to the precision of this timing. (d) Scaled-up model tests support the usefulness of air injection to suppress sloshing. (e) A microcomputer control algorithm can be constructed based on the knowledge obtained from our experiments. (f) Air-bubble injection to suppress or control earthquake-induced sloshing can be considered effective technologically, but further study is needed to apply this method to actual cases.

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