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COUPLED-MODE DYNAMIC INSTABILITY OF TAINTER GATES WITH PARALLEL BENDING VIBRATION OF THE SKINPLATE

Keiko Anami
Ashikaga Institute of Technology
Ashikaga, Tochigi, Japan

Noriaki Ishii
Osaka Electro-Communication University
Neyagawa, Osaka, Japan

Takuma Tsuji
Osaka Electro-Comm. University
Neyagawa, Osaka, Japan

Tatsuya Oku
Mayekawa.Co.Ltd.
Moriya, Ibaraki, Japan

Masaru Goto
Osaka Electro-Comm. University
Neyagawa, Osaka, Japan

Kazuaki Yagi
Osaka Electro-Comm. University
Neyagawa, Osaka, Japan

Charles W. Knisely
Bucknell University
Lewisburg, PA, USA

ABSTRACT

As part of the investigation of the dynamic instability of the gate closely related to the Folsom Dam Tainter-gate failure, and in order to assure the dynamic stability of the gate, the field vibration tests on three full-scale operational Tainter-gates were conducted. From these tests, the possible existence of another coupled-mode self excited vibration mechanism, which involves the dangerous dynamic coupling of the whole gate rigid-body rotational vibration with a "parallel" bending vibration of the skinplate was suggested. This paper presents the mechanism of the suggested coupled-mode self-excited vibration, theoretical analysis for the suggested dynamic instability, and 2-dimensional laboratory model tests results. Further, the need for retrofit countermeasures for Tainter gates which are currently installed in both Japan and the USA and susceptible to this dangerous coupled-mode dynamic instability is emphasized.

INTRODUCTION

Tainter-gates (also known as radial gates) are frequently used for water-level regulation in impoundment dams. An example of a Tainter gate is shown in Figure 1. This particular gate was installed in the Folsom Dam in California. The circular-arc skinplate has a height of 15.5 m, a radius of 14.33 m, a spanwise length of 12.8 m and a gross mass of 87 tons. During operation on July 17, 1995, one of the Folsom Dam gates failed (see Ishii [1, 2] and Forensic Report [3], for details). Forced vibration tests of a remaining gate as part of the failure investigation revealed that the gate essentially possessed two typical natural vibration modes [4], also illustrated in Figure 1. One fundamental vibration mode was the rigid-body rotational lifting vibration of the whole gate about the trunnion pin, as shown by Θ in Figure 1. The second significant mode of vibration was a relatively low frequency streamwise bending of

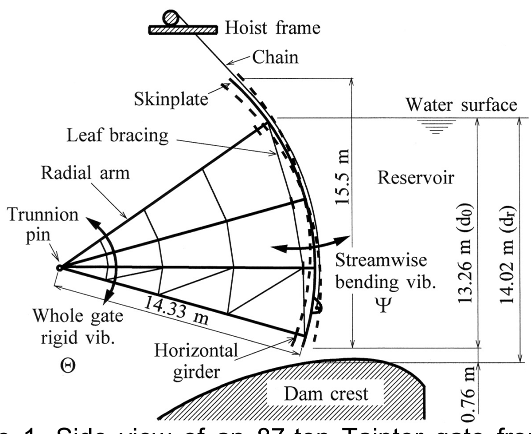


Figure 1. Side view of an 87-ton Tainter gate from the Folsom Dam in California, showing two predominant natural vibration modes.

the skinplate (see the dotted lines), as shown by Ψ in Figure 1. Since the rigid-body mode is rotation around the trunnion pin coinciding with the center of the skinplate, it does not displace water as the gate vibrates, and is therefore not significantly affected by reservoir level. However, since the streamwise bending of the skinplate must displace water with each cycle of vibration, the fundamental frequency of the skinplate bending mode decreases with increasing head on the gate, due to inertia and hydrodynamic forces. Under specific conditions, the reduced fundamental frequency of the skinplate bending mode can become coincident with that of the rigid body vibration and the two vibrations can couple [5]. The motion of one vibration mode enhances the displacement in the other mode and vice versa. This type of coupled-mode vibration is accompanied by a variation in the gate's discharge (a flow rate variation), thus potentially inducing an intense self-excited vibration. This mechanism may have caused, or contributed to, the Folsom Dam gate failure, as well as other gate incidents at other dams.

The existence of coupled-mode, self-excited vibration in Tainter-gates has been confirmed in 2D model gate tests [6, 7] and 3D model gate test [8]. Theoretical analyses were also undertaken to calculate the level of dynamic instability [9], and to establish the dynamic design criteria for Tainter gates for long-term stable operation [10-12].

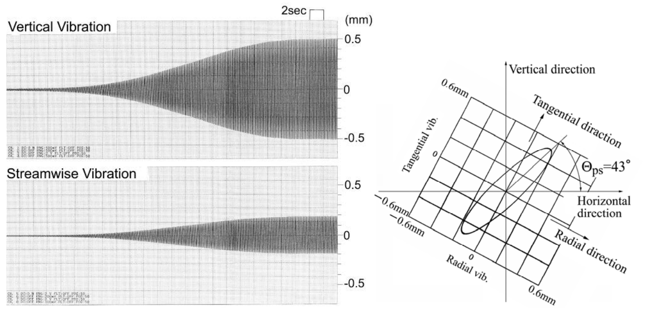
To further the understanding of this coupled-mode instability mechanism, and ultimately to assure dam safety, field vibration tests on full-scale operational Tainter gates were conducted both in Japan and in the USA [11-15].

In this paper, three of these field vibration tests results are reviewed. Their interpretation suggests the existence of another coupled-mode vibration, which involves a dangerous dynamic coupling of the whole gate rigid-body rotational vibration with a "parallel" bending vibration of the skinplate. Unlike the Folsom Dam gate in which the skinplate vibrated in a rotational bending vibration mode, these more recent full-scale tests suggests that Tainter gates may be susceptible to a dangerous coupled-mode dynamic instability, even when the skinplate vibrates in a parallel vibration mode.

In order to confirm this suggestion and the disastrous consequences of the existence of this coupled-mode self-excited instability, a theoretical vibration analysis was conducted using a similar approach to that used in the analysis of the Folsom gates. After the presentation of the analytical model in this paper, the predicted results are confirmed using a 1/30-scale laboratory model Tainter gate, along with the full-scale Tainter gate test results. Finally, it is concluded that countermeasures are absolutely needed for Tainter gates, currently installed in Japan and the USA, susceptible to this dangerous coupled-mode dynamic instability.

SIGNIFICANT VIBRATION CHARACTERISTICS OF TAINTER GATE "C"

Field vibration testing was undertaken on a 50-ton Tainter-gate (hereafter called gate "C") in Japan [13]. The skinplate is supported by two radial arms and has a radius of about 12 m, a



(a) Transient vibrations (b) Press-shut trajectory

Figure 2. Self-excited vibration waveforms at 6.79Hz and press-shut trajectory at the bottom center of the skinplate, with a gate submergence d_0 of 9.27 m.

height of about 10 m and a spanwise length of about 13 m. Tainter-gate "C" is a π-shaped gate in which the radial arms are inclined about 10° toward the center of the skinplate, which is quite similar to the Folsom Dam Tainter-gate which had an inclination angle of 13.7°. The gate is raised with 4 wire cables (two at each spanwise end of the skinplate).

In-water vibration tests were conducted with small gate openings and gate submergence depths of 9.54 m, 9.27 m and 9.00 m. The vibrational accelerations, the hydrodynamic pressure and the controlled discharge openings were measured. For the gate submergence depth of 9.54 m and 9.27 m, intense self-excited vibrations were clearly observed.

For both submergence depths, self-excited vibration waveforms were recorded showing initial exponential growth which subsequently asymptotically approaches a fixed amplitude. Representative vibration waveforms at the bottom center of the skinplate with the gate submergence depth of 9.27 m are shown in Figure 2. Figure 2(a) shows clear exponential growth of the vibration amplitude which then asymptotes to a fixed value limit cycle vibration, while Figure 2(b) shows the so-called characteristic press-shut vibration trajectory (i.e., the downstream motion of the gate is accompanied by a concurrent downward motion of the gate resulting in a simultaneous reduction in flow rate as the gate moves in the downstream direction), at the bottom center of the skinplate.

When the skinplate vibrates with this press-shut trajectory, the vibration-induced hydrodynamic pressure feeds energy back to the streamwise vibration of the skinplate, thus inducing the violent, self-excited vibration. The press-shut angle was 43°, which is very close to the optimal 45° angle for most efficient energy feedback.

The press-shut vibration trajectory, shown in Figure 2(b), resulted from the phase difference between the vertical and streamwise vibrations. This press-shut behavior is indicative of the coupling of the whole gate rigid body rotational vibration around the trunnion pin with the skinplate streamwise vibration and is accompanied by variation in the flow rate under the gate.

This behavior is fundamental to the coupled-mode, self-excited vibration mechanism.

Significant parameters, such as in-water natural vibration frequencies, excitation ratios, vibration amplitudes and vibration modes were obtained by analyzing the self-excited vibration waveforms. The steady vibration was analyzed with an FFT analyzer to obtain the frequency spectrum, where a sharp peak appeared at 6.79 Hz, at the gate submergence depth of 9.27 m. An excitation ratio of 0.0034 was determined from the exponentially growing waveforms with small initial amplitude. For a gate submergence depth of 9.54 m, the corresponding vibration frequency was 6.71 Hz and the excitation ratio was 0.0052.

Figure 3 presents the vertical distribution of streamwise vibration amplitudes of the skinplate at its spanwise center. Several instantaneous vibration-mode shapes with differing amplitudes from the incipient small amplitude to steady state are presented. As the vibration amplitude grows, the amplitude in the lower half of skinplate becomes larger than the amplitude in the top half. However, it is quite significant to find that the skinplate clearly undergoes uniform parallel vibration for small amplitudes at the beginning of the self-excited vibration.

For the gate submergence depth of 9.00 m, intense self-excited vibrations were not observed, but small beating vibrations were measured. The measured frequency of the whole gate vibration around the trunnion pin was 7.18 Hz. The frequency of the skinplate streamwise parallel vibration was 11.3 Hz. Since the gate submergence depth d_0 was decreased to 9.00 m, the water added mass effect was reduced, and reduction in the skinplate streamwise vibration frequency was to only 11.3 Hz, a significantly smaller frequency reduction than was measured for $d_0 = 9.27$ m and for $d_0 = 9.54$ m. As a result, this skinplate streamwise natural vibration at a frequency of 11.3 Hz was higher than the whole gate natural vibration frequency of 7.18 Hz, and thus no coupled, self-excited vibration could occur.

SIGNIFICANT VIBRATION CHARACTERISTICS OF TAINTER GATE "T"

Field vibration test was undertaken on a 24-ton Tainter-gate (hereafter called gate "T") in USA [14]. The skinplate is supported by two radial arms and has a radius of about 9 m, a height of about 7 m and a spanwise length of about 12 m. The

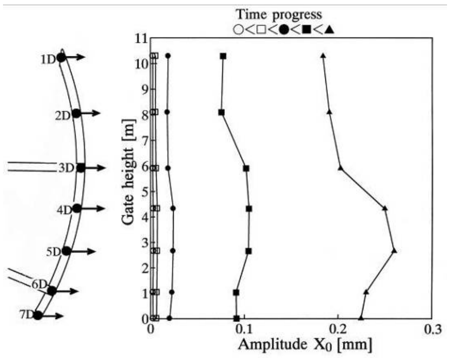
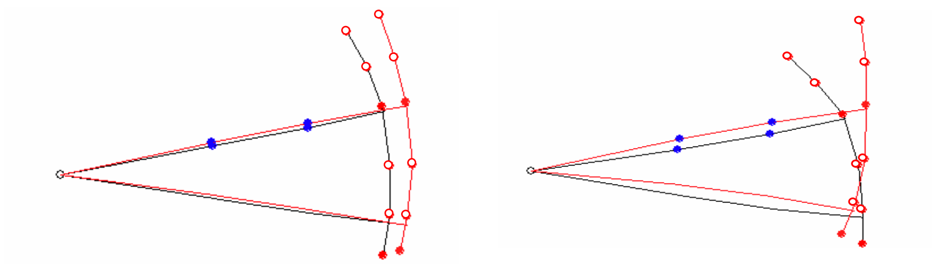


Figure 3. Streamwise parallel vibration mode of skinplate, at d_0=9.27 m.

skinplate is uniquely reinforced to reduce bending deformation with 8 tension rods installed just behind the skinplate. The gate is raised with 4 wire cables (two at each spanwise end of the skinplate).

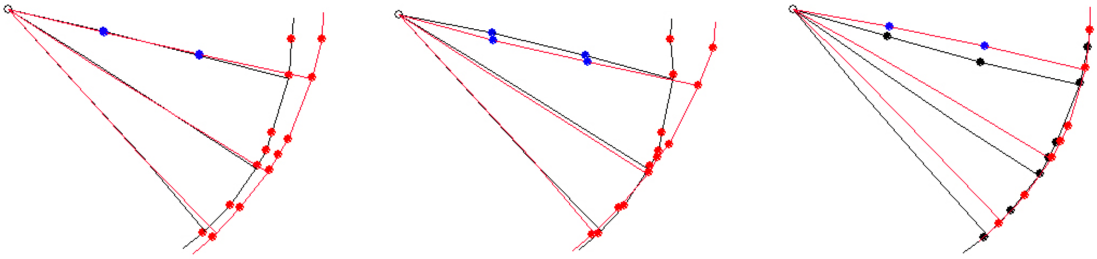
The field vibration testing was undertaken by the steel rod breaking excitation method [14]. A machined steel rod with a very small diameter (much like a tensile test specimen) was installed between the bottom center of the skinplate and the spillway concrete. The gate was gradually raised in a step-wise fashion until the steel-rod was loaded past its capacity and broke suddenly. The sudden rod breaking provided an initial excitation to induce a damped vibration. The gate was stable at all times. The clear exponentially damping waveforms initiated by the steel-rod breaking excitation were measured.

The exponentially damped natural streamwise vibration of the skinplate had frequencies of 5.5 Hz and 6.5 Hz, which are quite significant when considering "movement-induced self-excitation." The natural vibration mode shapes were analyzed using spatial distributions of the amplitude and phase-lag of the damped vibratory response to the impulsive input provided by the breaking of the steel rod. A simulated mode shape for the 5.5 Hz vibration is shown in Figure 4(a). When the skinplate moves in the downstream direction, the whole gate also moves downward, exhibiting known characteristics of a press-shut device which has a higher likelihood of susceptibility to "movement-induced self-excitation." Based on the amplitude and phase modal analysis, the whole skinplate performs a streamwise "parallel vibration" in the press-shut direction. A



(a) for 5.5 Hz vibration (b) for 6.5 Hz vibration

Figure 4. In-water vibration mode shapes of gate "T".



(a) for 4.6 Hz vibration (b) for 6.3 Hz vibration (c) for 8.3 Hz vibration

Figure 5. In-water vibration mode shapes of gate "P".

simulated mode shape for the 6.5 Hz vibration is shown in Figure 4(b). The mode shape suggests a streamwise rotational vibration coupled with a vertical vibration. Based on the mode shapes determined in this analysis, it was concluded that the frequency of the skinplate streamwise rotational vibration and that of the whole gate vibration around the trunnion pin are coincident and result in the 6.5 Hz vibration.

SIGNIFICANT VIBRATION CHARACTERISTICS OF TAINTER GATE "P"

Field vibration test with steel-rod breaking excitation was undertaken on a 77-ton Tainter-gate (hereafter called gate "P") in USA [15]. The skinplate is supported by two radial arms and has a radius of about 15 m, a height of about 12.5 m and a spanwise length of about 15 m. Tainter-gate "P" is a π-shaped gate in which the radial arms are inclined about 16° toward the span center, toward the skinplate from trunnion pin. The gate is raised with 2 massive chains attached at each spanwise end of the skinplate.

The gate was stable at all times. The clear exponentially damping waveforms initiated by the steel-rod breaking excitation were measured. The exponentially damped natural vibration frequencies are 4.6 Hz, 6.3Hz and 8.3 Hz. From the amplitude and phase modal analysis, the vibration mode shapes were obtained, as shown in Figure 5. The mode shape of the 4.6 Hz vibration is a whole skinplate streamwise parallel vibration, the 6.3 Hz vibration is a whole skinplate streamwise rotational vibration, and 8.3 Hz vibration is the whole gate vibration around the trunnion pin. In the case of the 4.6 Hz vibration of Figure 5(a), when the skinplate moves in the downstream direction, the whole gate moves upward, exhibiting known characteristics of a press-open device which has very little likelihood of susceptibility to "movement-induced self-excitation."

MECHANISMS AND DYNAMIC STABILITY ANALYSIS OF COUPLED-MODE SELF-EXCITED VIBRATION

The test results for each of the gates "C", "T" and "P" indicate two fundamental vibration modes. One is the streamwise parallel vibration of the skinplate, and the other is the whole gate rigid-body rotational vibration around the trunnion pin. It is postulated that the coupling between these two vibration modes through hydrodynamic and inertial forces produced the press-shut trajectory shown in Figure 2, indicative of the coupled-mode, self-excited vibration mechanism.

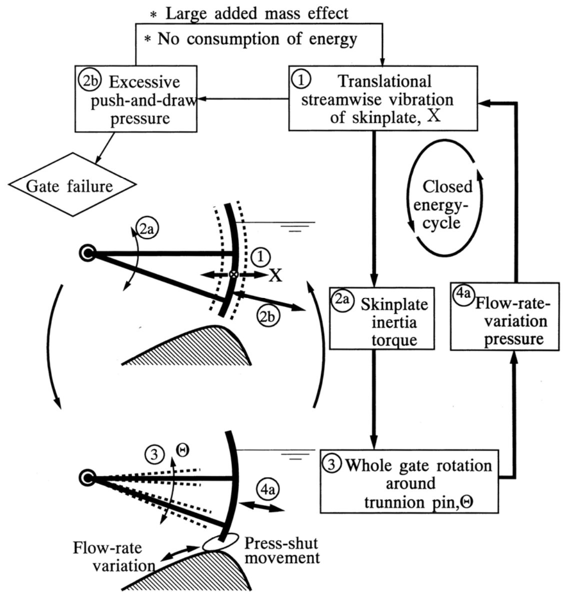


Figure 6. Closed energy cycle of coupled-mode self-excited vibration with skinplate streamwise parallel vibration.

In the case of skinplate streamwise parallel vibrations, the line of motion of the center of gravity position "G" is very important. If the line of motion of the center of gravity is eccentric to the trunnion pin, then vibratory motion of the produces a significant inertial torque around the trunnion pin. This inertial torque, in turn, drives the whole gate vibration around the trunnion pin. With an eccentric line of motion of the skinplate center of gravity, necessary conditions exist for the onset of coupled-mode vibration. The coupling of these two modes denoted as "1" and "2a" in the closed energy cycle shown in Figure 6 can result in self-excitation through the pressure forces resulting from discharge variation if their frequencies coalesce.

When the whole gate undergoes vibration around the trunnion pin due to the inertial torque, the discharge opening will naturally change, thus inducing a flow-rate variation pressure. If the bottom end of the skinplate has the vibration trajectory of a press-shut device, the flow-rate variation pressure supplies energy to the skinplate parallel vibration. The closed energy cycle results in the effective coupling of the skinplate parallel vibration and the whole gate vibration around the trunnion pin, producing the coupled-mode self-excited vibration [10].

Since the center of circular-arc skinplate aligns with the trunnion pin, the whole gate rotational vibration around the trunnion pin is independent of the hydrodynamic load, and is excited by the inertial torque caused by the skinplate parallel vibration. On the other hand, the skinplate streamwise parallel vibration is excited by both the hydrodynamic load and the secondary torque of inertia, and is excited by the inertial torque caused by the skinplate parallel vibration. On the other hand, the skinplate streamwise parallel vibration is excited by both the hydrodynamic load and the secondary torque of inertia. Therefore, the equations of motion for this coupled-mode-vibration can be written as follows:

$$y_c'' + 2\zeta_{a\theta} y_c' + y_c + \frac{2}{\pi}\frac{\alpha_I}{l_G \cdot \alpha_{co}} x_c'' = 0\,, \tag{1}$$

$$\begin{aligned}&(1+\delta_p \alpha_m \Delta m_x + \frac{2}{\pi}\sqrt{2}\,c_f k \alpha_m \Delta m_\theta) x_c'' \\ &+ 2\gamma_{x\theta}\left(\zeta_{ax} + \zeta_{fx} - \frac{\frac{2}{\pi}\sqrt{2}\,c_f k \alpha_m \Delta c_\theta}{2\gamma_{x\theta} F_{a\theta}}\right) x_c' + \gamma_{x\theta}^2 x_c \\ &= \sqrt{2}\,c_f \alpha_{co}\left(\frac{\alpha_m \Delta c_\theta}{F_{a\theta}} y_c' - \alpha_m \Delta m_\theta y_c''\right)\end{aligned} \tag{2}$$

where, x_c and y_c represent the reduced vibration amplitude of the skinplate center and the whole gate around the trunnion pin, respectively. $\zeta_{a\theta}$ and ζ_{ax} are the in-air damping ratios of the whole gate vibration and the skinplate streamwise vibration, respectively, heavily governing the dynamic stability of the gate. α_m represents the water to skinplate mass ratio, α_I represents the moment-of-inertia ratio and $\gamma_{x\theta}$ is the in-air frequency ratio. Δc_θ and Δm_θ represent the reduced fluid-excitation coefficient and the added mass, caused by the flow-rate-variation pressure, and Δm_x represents the added mass of the push-and-draw pressure. This study assumes small-amplitude vibrations, thus neglecting the hydrodynamic pressure torque due to the small shift of the skinplate center from the trunnion center. In Equation (2), the first term on the right-hand side represents the energy source for excitation of the streamwise vibration due to flow-rate variation under the gate.

Coupled-mode vibration occurs when the two vibrational frequencies become synchronized, with one of the two natural vibration modes serving as the driving excitation for the other mode. Through the feedback of one mode driving the other, the coupled-mode self-excited vibration is built up. With this understanding the physical state, the equations of motions of the coupled-mode vibration can be solved approximately. The dynamic stability criterion diagram for the gate can be ascertained through the simultaneous solution of Equations (1) and (2), using a numerical computer-simulation to obtain the approximate solution.

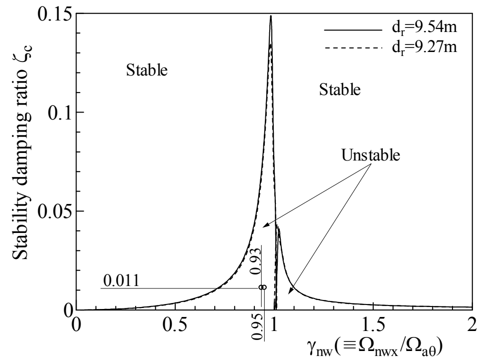


Figure 7. Dynamic stability criterion curve for Tainter-gate "C".

Figure 7 shows the calculated dynamic stability diagram for Tainter-gate "C". The vertical axis is the critical damping ratio ζ_c required for the stability. The abscissa is the in-water natural vibration frequency ratio γ_{nw}, defined by

$$\gamma_{nw} \equiv \Omega_{nwx} / \Omega_{a\theta} \tag{3}$$

where Ω_{nwx} is the in-water natural vibration frequency of the streamwise vibration, and $\Omega_{a\theta}$ is the natural vibration frequency of the whole gate vibration around the trunnion pin. The region under the curve is the region of instability, while the region above the curve is the region of stability. It is of significance to note the intense dynamic instability that appears in the region where the frequency ratio is just slightly smaller than 1.0.

In the case of Tainter-gate "C", the in-water streamwise natural vibration frequency Ω_{nwx} is 6.79 Hz for d_0 = 9.27 m, and 6.71 Hz for d_0 = 9.54 m, respectively. The natural vibration frequency of the whole gate vibration around the trunnion pin, $\Omega_{a\theta}$, takes a value of 7.18 Hz from in-water test with submergence depths of 9.00 m. Therefore, the in-water natural vibration frequency ratio γ_{nw} takes on values of 0.95 and 0.93, just less than 1.0.

The damping ratio of Tainter-gate "C", measured from in-water impact tests, was determined to be 0.011 for the skinplate streamwise vibration, which is considered to be the possible maximum value of in-air damping ratio. This value is plotted at the vibration frequency ratios of 0.95 and 0.93, as shown in Figure 7. The plotted data are precisely in the most intensely unstable region.

The observed intense self-excited vibration of Tainter-gate "C" can clearly be explained by the theoretical dynamic stability analysis, developed by Anami [10]. Therefore, one may conclude that the violent, self-excited vibration of Tainter-gate "C" resulted from the coupling of the skinplate streamwise parallel vibration with the whole gate vibration around the trunnion pin through the hydrodynamic and inertial forces.

Similar calculations were undertaken for Tainter-gate "T", as shown in Figure 8. The location of the measured data point undergoing coupled vibration of the parallel streamwise vibration mode with the whole gate rotation mode indicates a narrow escape from the unstable region, as shown in Figure 8 [14]. Therefore, Tainter-gate "T" barely maintained its dynamic stability for the coupling of the skinplate streamwise parallel vibration and whole gate rotational vibration around the trunnion pin at the tested condition. When decreasing the submergence depth, the condition point is expected to move to the right along the abscissa of the dynamic stability curve, *i.e.*, just into the region of intense dynamic instability. The reasoning is that as the submergence level decreases, the effect of the water added mass on the skinplate streamwise vibrations also decreases, yielding an increase in the in-water natural vibration frequency Ω_{nwx} and a correspondingly higher frequency ratio, γ_{nw}, moving the condition point to the right along the abscissa. The gate stability is estimated under various upstream submergence conditions based on the stability theory presented. As a result, the coupled-mode self-excited vibration can appear when the gate submergence depths decreases below that of the experimental condition, and it will appear until the upstream submergence depth becomes about 70% of that of the experiment.

Similar calculations were made for the Tainter-gate "P", also, as shown in Figure 9. Due to the installation angle of the gate and the direction of the skinplate vibration, the instability level is far smaller than the other gates. The location of the measured data point indicates no susceptibility to coupled-mode instability [15]. Therefore, Tainter-gate "P" is dynamically stable and not susceptible to coupling of the skinplate streamwise parallel vibration and whole gate rotational vibration around the trunnion pin.

MODEL INVESTIGATIONS FOR NEW MECHANISM OF COUPLED-MODE VIBRATION

In order to confirm the self-excited vibration mechanism predicted in the previous section, model gate test for the coupled-mode vibration with the skinplate parallel vibration and the whole gate rotation was conducted.

The two-dimensional 1/30-scaled model gate of Tainter-gate "C" is shown in Figure 10. The rigid skinplate is supported by a horizontal coiled spring (B) just behind the skinplate, which represents the skinplate streamwise bending flexibility of the full-scale gate. The skinplate is also supported by two rods with slide bearing for each side, thus performing the streamwise parallel vibration represented by X. The whole gate is suspended by a vertical coiled spring (A), which represents the wire ropes' flexibility in the full-scale gate. Thus, the gate performs the rotating vibration around the trunnion pin, represented by Θ. The position of both the springs can be adjusted, thus permitting a fine adjustment of each natural vibration frequency. The model gate was so adjusted at static equilibrium with all upstream heads that the skinplate center coincides exactly to the trunnion center, that is, it is non-eccentric. Therefore, without parallel skinplate motion and sliding of the support rods through the slide bearings, self-excited vibration cannot occur. With parallel skinplate motion, a torque is generated due to the eccentricity between the line of motion of the center of gravity of skinplate and trunnion pin, which leads to self-excited vibration of the gate.

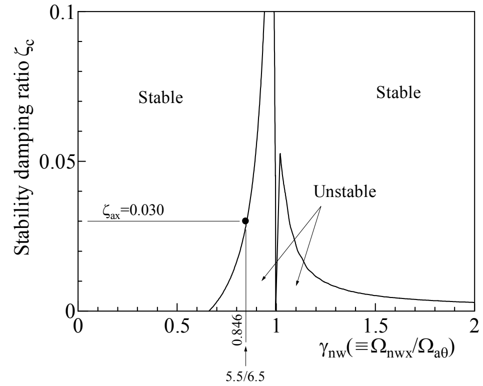


Figure 8. Dynamic stability criterion curve for gate "T".

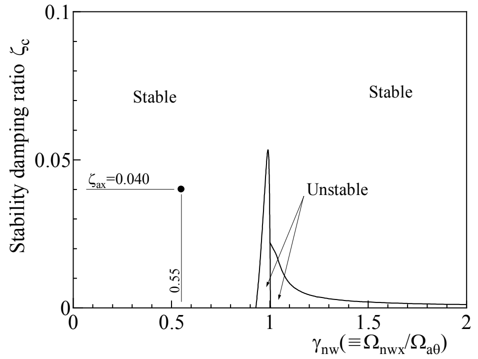


Figure 9. Dynamic stability criterion curve for gate "P".

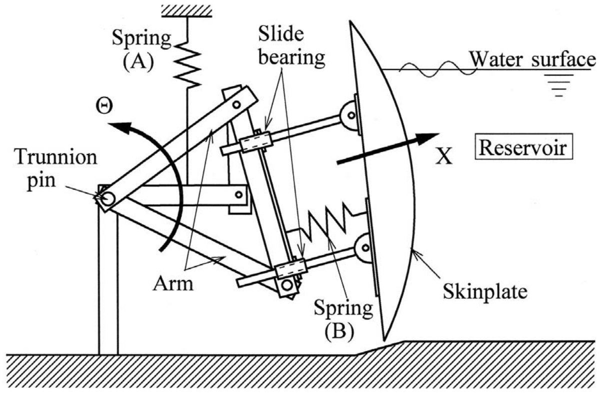


Figure 10. Cross-sectional view of a 1/30-scaled parallel coupled-mode vibration model of Tainter-gate "C".

The skinplate has a radius R_a of 455 mm and a mass of 11.2 kg. The skinplate has a spanwise length W_0 of 316 mm, and is inserted into a 320 mm-wide channel, with a gap of about 2 mm from the channel wall on each side of the skinplate. The whole gate has a mass of 18.7 kg. The moment of inertia of the whole gate around trunnion pin, I_θ, takes a value of 2.324 kgm^2.

The flow-rate variation pressure and the push-and-draw pressure are participating in this kind of coupled-mode self-excited vibration. The push-and-draw pressure induces a very large added mass effect, and the flow-rate variation pressure will supply energy to the gate vibration and will cause the dangerous coupled-mode self-excited vibration. Dynamic similarity of the hydrodynamic pressure scales with the Froude number. However, since the variation of flow-rate under the gate has a strong dependence on the vibration frequency, a constant value of Froude number does not serve to scale this flow. If the vibration frequency increases according to Froude number scaling, dynamic similarity will not be maintained. Therefore, in this model tests the in-water streamwise vibration frequency of the skinplate was adjusted to be near the same value as in the full-scale Tainter-gates. From the field vibration tests of the Tainter-gates, the in-water streamwise skinplate vibration frequency was found to be 5.5 Hz to 6.8 Hz. In the present model tests, the in-water streamwise vibration frequency of the model skinplate, Ω_{wx}, was set at 5.1 Hz.

As shown in Figure 10, the direction of the support rods of the skinplate is inclined downward at 17°. One of the major purposes of the present model gate tests is to demonstrate the self-excited vibration due to the coupling between two inherent modes of vibration. For this reason, the channel floor just beneath the gate is also inclined at the same angle of 17°, such that the press-shut angle becomes zero, thus eliminating the press-shut hydrodynamic pressure component. With such a simplification of the model test setup, an easy physical understanding of the test results can be obtained.

The model gate was exposed to a water flow under the gate with an upstream submergence depth d_0 of 400 mm. The mean gate opening height was adjusted to 5 mm, which is 1.2% of the gate submergence depth d_0. The outflow is not submerged.

In the present model gate tests, the in-air whole gate vibration frequency $\Omega_{a\theta}$ was varied from 4.0 Hz to 6.0 Hz, so as to include the in-water natural streamwise vibration frequency of the skinplate of 5.1 Hz.

Figure 11 shows typical records of the self-excited vibration waveforms for an $\Omega_{a\theta}$ of 5.61 Hz and an in-air damping ratio $\zeta_{a\theta}$ of 0.0133, which were measured at the lower end of the gate. The upper waveform shows the up-and-downward vibration Θ, and the lower shows the streamwise parallel vibration X. The model gate clearly undergoes spontaneous vibrations, exponentially increases in amplitude, and approaches a steady vibration with constant amplitude. The excitation ratios ξ_θ and ξ_x, measured from the exponentially increasing vibration-waveforms, were 0.0109 and 0.0123, respectively. These test results clearly demonstrate that Tainter gates possess a surprising inherent dynamic instability, even if the skinplate undergoes "parallel" vibration.

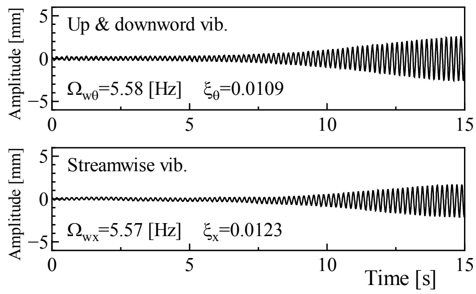


Figure 11. Measured coupled-mode self-excited vibration waveforms of 1/30-scaled model of Tainter-gate "C" (d_0 = 400mm, $\Omega_{a\theta}$ = 5.61 Hz).

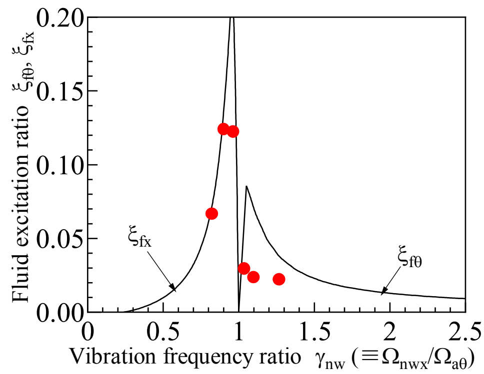


Figure 12. Model test results for vibration frequency ratio and fluid-excitation ratio.

The exponentially increasing or decreasing vibration wave-forms suggest a significant characteristic of the self-excitation due to fluid motion called the "fluid-excitation ratio." If the in-air damping ratios $\zeta_{a\theta}$ and ζ_{ax}, due to mechanical and additional damping, were measured, one may calculate from any spontaneous vibration wave-forms, the fluid-excitation ratio for the whole gate vibration, $\xi_{f\theta}$, and that for the streamwise vibration, ξ_{fx}, by the following expressions, respectively:

$$\xi_{f\theta} = \frac{\xi_\theta}{\gamma_{w\theta\theta}} + \zeta_{a\theta} \quad , \tag{4}$$

$$\xi_{fx} = \frac{\xi_x}{\gamma_{wxx}} + \zeta_{ax} \tag{5}$$

where ξ_θ and ξ_x are the resultant excitation ratios for the streamwise and whole gate vibrations. In other words, the magnitude of the fluid-excitation ratio $\xi_{f\theta}$, is the critical damping ratio ζ_c required for the stability.

In the present model gate, the mean value of $\zeta_{a\theta}$ was 0.016 from in-air free vibration tests of the whole gate around the trunnion. In the case of model experiments, a fairly large damping effect appears for the skinplate streamwise vibration, due to leakage flows from comparatively large clearances kept at both sides of the skinplate. This kind of additional damping is intrinsic to a model experiment and cannot be avoided. Then, in-water free vibration tests of the skinplate were made in detail to measure the damping ratio including this additional damping effect. As a result, the damping ratio of the skinplate streamwise vibration, ζ_{ax}, was found to be 0.058.

Calculated values of the fluid-excitation ratios based on experimental data are plotted in Figure 12. The results of theoretical calculations are also shown in Figure 12 by the solid line. As clearly shown in Figure 12, the model gate test results are in good agreement with the theoretical calculations. As a result, the existence of the flow-induced coupled-mode self-excited vibration with skinplate streamwise parallel vibration and whole gate vibration is clearly confirmed.

CONCLUSIONS

Field vibration testing was conducted on three operational full-scale Tainter-gates in Japan and in the USA. These tests results suggest the existence of another coupled-mode vibration, which involves the dynamic coupling of the whole gate rigid-body rotational vibration with the skinplate streamwise parallel vibration.

The closed energy cycle of the coupled-mode self-excited vibration with the skinplate streamwise parallel vibration was presented, using a similar approach to that used in the analysis of the Folsom gates. The mechanism of this coupled-mode self-excited vibration is identical with that found for the Folsom Tainter-gate. The only difference is that the skinplate vibrates in a rotational vibration mode for the Folsom Tainter-gate, whereas the skinplate vibration is in a parallel streamwise mode for tested Tainter gates. In addition, the existence of this dynamic instability was clearly demonstrated by a two-dimensional 1/30-scaled model of the Tainter-gate “C”.

Operational Tainter-gates susceptible to this dangerous intense dynamic instability should be identified, as soon as possible. Retrofit countermeasures should be implemented for any dynamically unstable Tainter-gate, in order to prevent a failure similar to that of the Folsom Dam Tainter-Gate in 1995. Establishment of a design criterion that guarantees the dynamic stability of Tainter gates is needed for new gate constructions as well. Our field testing method and the theoretical analyses established in Anami [10] can provide the framework and basic concepts needed for a safe dynamic design.

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