Noriaki Hiwatashi
Sumitomo Construction Co. Ltd.
1-3-1 Minato Chuoku
Fukuoka, 810 Japan

Yoji Mizuta
Yatsushiro National College of Technology
2627 Hirayama Shinmachi
Yatsushiro, Kumamoto-ken 866
Japan

Yutaka Ishihara
Itio Hirai
Department of Civil and Environmental Engineering
Kumamoto University
2-39-1 Kurokami, Kumamoto-shi
860, Japan

Excitation of Arch and Suspension Bridges by Subwires

A force generation method using a subwire for arch and suspension bridges is proposed. The subwire is connected to the arch or the cable of the bridge through rollers. The uniform force produced by pulling and releasing the pretensioned subwires acts on the bridge as an external force. A new device called "the resonance force generator" is also developed to excite the bridges by applying a small force. To verify the proposed concept, a stress ribbon bridge was excited with the resonance force generator. © *1993 John Wiley & Sons, Inc.*

INTRODUCTION

This article proposes an approach to generate a uniform force by the use of a subwire for full-scale vibration tests of long-span arch and suspension bridges. The pretensioned subwire with many rollers placed along the parabolic main cable (or arch) of a suspension (or arch) bridge produces a uniform force by the action of pulling or releasing the pretensioned subwire. The uniform force acts on the bridge as an external force.

The resonance force generator is adopted to efficiently produce the pulling and releasing external force to be applied to the subwire. The subwire itself is elastic and has an equivalent spring constant. In case a mass is attached to the subwire, a vibration system with one degree of freedom is composed of the mass and the subwire. The change in mass enables the synchronization of the vibration system with the natural frequency of the bridge under consideration. The frequency of the driving force is kept very close to the lowest natural frequency of the bridge. The synchronization is experimentally performed by adjusting the parameter associated with the mass.

The change in the subwire pretension force is implemented by a hydraulic forcer. Therefore, the characteristics of the dynamic force generated by the subwire is subjected to the required capacity of the hydraulic forcer. The servocontrolled hydraulic actuator permits straightfor-

Shock and Vibration, Vol. 1, No. 1, pp. 59–64 (1993)

CCC 1070-9622/93/01059-06

ward programming of the force level and arbitrary periodic waveforms using a desktop. This means that the proposed approach shows the feasibility of active control for reducing the oscillations caused by the action of dynamic external forces, like gusting winds, earthquakes, etc. .

Many articles concerning active control have been published. The vibration of some beams and buildings is controlled by means of a tendon mechanism [e.g. Camotim and Roorda, 1991; Chung, Reinhorn, and Soong, 1988; Roorda, 1975; Yang and Giannopoulos, 1979]. However, it seems that this kind of uniform load produced by a parabolic subwire on many rollers, which is continuous over the elastic main cable (or arch) of a suspension (or arch) bridge, has not been developed.

Usual counter-rotating eccentric mass force generators driven by a variable speed motor have been used for many years to excite vibration in these type of bridges and are quite simple to apply. The disadvantage of using such generators is the poor force generation (proportional to the square of the frequency) for very low frequency zones, which correspond to the lowest natural frequencies of large-span bridges. In addition, these large-span bridges need larger exciting energy for full-scale vibration tests. The above-mentioned hydraulic actuator furnished with high pressure oil is able to easily generate dynamic forces of the order of 500×10^3 kN. It should be mentioned that only low frequency control is needed for large-span bridges.

For the validation of the proposed concept, a stress ribbon pedestrian bridge instead of a suspension bridge was oscillated at resonance by pulling and releasing the subwire connected to the slab surface of the bridge through rollers.

CONCEPT

Structures such as arch and suspension bridges are treated as beams stiffened with parabolic axial force members. The configuration of the axial force member is represented by

$$Y = \frac{4f(L-x)x}{L^2} \tag{1}$$

where f is the rise (or sag) of the arch (or cable) and L is the span.

The subwire (the dotted line in Fig. 1) for arch and suspension bridges is placed on the rollers set along the parabolic axial member. The pre-

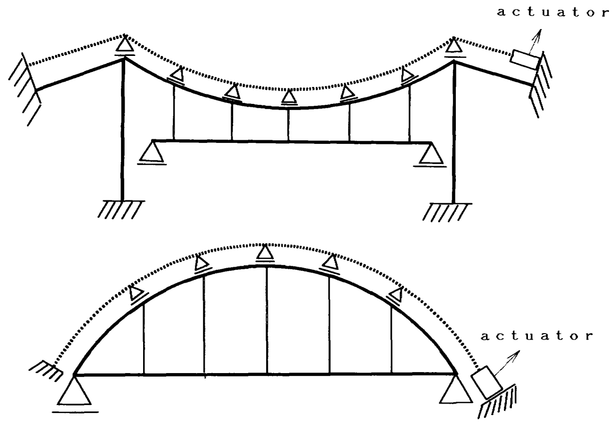


FIGURE 1 (a) A suspension bridge with a subwire; (b) an arch bridge with a subwire.

tention force H_0 is initially applied to the subwire. The change ΔH in H_0 by the actuator generates the external uniform force given by

$$p = \Delta H \frac{d^2Y}{dx^2} = \Delta H \frac{8f}{L^2}. \tag{2}$$

Because the ΔH is changeable with time, t, by the action of the actuator and the subwire elongation, Δl, is proportion to ΔH, Eq. (2) is expressible as

$$p(t) = \frac{8f}{L^2} \Delta H(t) = \alpha \Delta l(t) \tag{3}$$

where α is a constant determined by the subwire stiffness and by the configuration of the parabolic axial force member.

Once the external force has been generated, arbitrary bridge vibration may be caused by the actuator. But asymmetrical mode components are not excited for this actuator position due to the symmetrical mode components force.

Asymmetric mode component vibration may be produced by the actuator set at the midspan of a suspension bridge (Fig. 2). In this scheme, the actuator generates upward (or downward) uniform force on the left (or right) side from the midspan. It is noted that the actuator in this position can be directly connected to the cable and the stiffening girder of the bridge without the use of the subwire [Hirai, 1968].

So far the force generation with one subwire is developed. In general, an arch (or suspension) bridge has two arches (and two cables) on both sides. Combining the independent forces generated by the two subwires set on the two arches

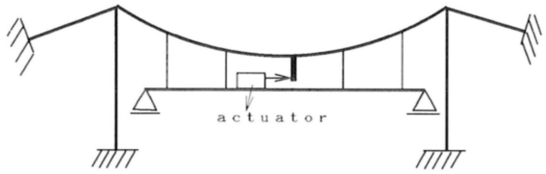


FIGURE 2 A suspension bridge with an actuator placed at midspan.

(or two cables) is able to cause torsional vibration for these bridges.

RESONANCE FORCE GENERATOR

The subwire stiffness, k, is determined from the elongation, Δl_s, due to a force, P, as follows:

$$k = \frac{P}{\Delta l_s} \tag{4a}$$

or

$$k = \frac{AE}{l} \tag{4b}$$

where A is the cross-sectional area of the subwire, l is the length of the wire, and E is Young's modulus.

The stiffness, k is theoretically determined from Eq. (4b) for the subwire with uniform cross-section. But the stiffness for the subwire composed of some twisted wires must be determined from Eq. (4a), after repeating the pretension operation several times.

The equation of motion of the subwire with masses M and m (Fig. 3), is given by

$$\left(\frac{I}{r^2} + M\right) \ddot{y} + ky = 0 \tag{5}$$

and its natural frequency ω_e is

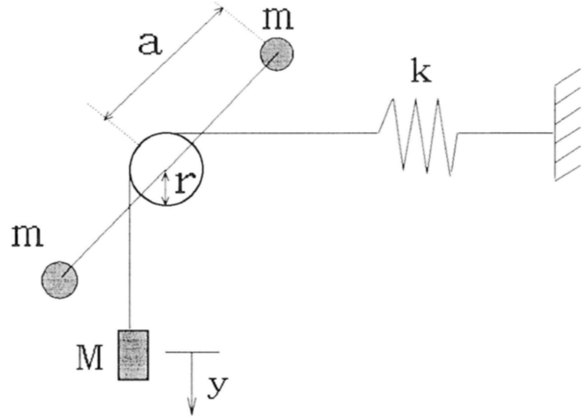
$$\omega_e = \sqrt{\frac{k}{M_{eq}}} \tag{6}$$

where

$$M_{eq} = \frac{I}{r^2} + M \tag{7}$$

$$I = 2a^2m \tag{8}$$

and m is the mass for rotational inertia, M is the mass for subwire pretension, a is the eccentricity of m, r is the radius of the wheel, y is the elongation of the subwire.



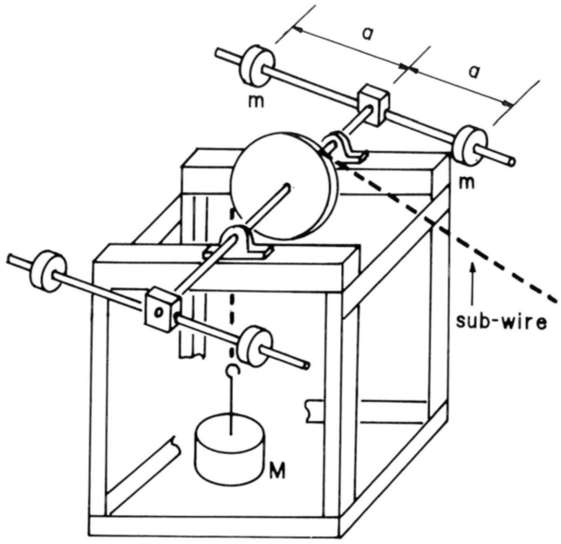


FIGURE 3 (a) Schematic model of the resonance force generator; (b) the resonance force generator.

The value of ω_e can be made equal to the lowest natural frequency ω_1 of the bridge under consideration by adjusting the parameter a. The vibration system adjusted in this way is the proposed "resonance force generator" and can easily efficiently produce larger driving uniform force with the lowest natural frequency of the bridge. This resonance force generator is a powerful tool to excite the actual bridge with a small applied force, although the driving force is confined to a sinusoidal force.

FIELD TESTS OF A STRESS RIBBON BRIDGE

The purpose of these field tests is to verify the proposed concept and to find out how a small

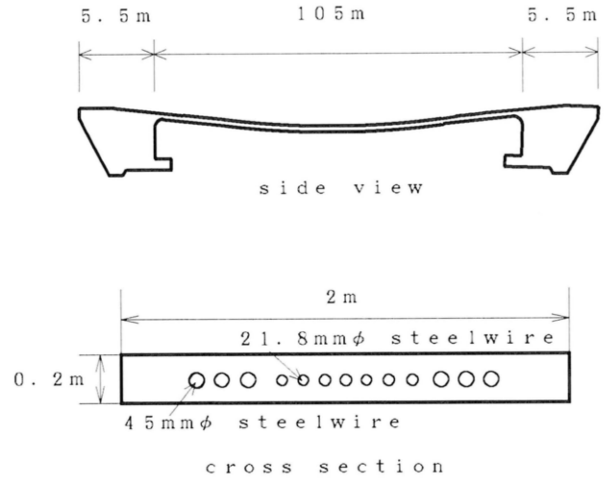


FIGURE 4 The Umenoki Bridge (a stress ribbon pedestrian bridge).

force to drive the resonance force generator may cause large bridge vibration. The proposed force generation is theoretically simple, but application to actual arch and suspension bridges is not easily implemented. This could be attributed to the fact that the preparation to install the subwire and the rollers to be placed on arch (or cable) must be taken into account previous to when the bridge is being designed.

In this sense a stress ribbon bridge (Fig. 4) is an appropriate structure to demonstrate the force generation with the subwire. The configuration of this bridge is of a parabolic shape and the rollers for the subwire are directly set on the pavement. To prevent the upward motion of the rollers due to the upward force produced by the initial and incremental tensions of the subwire, a certain weight is placed on each roller.

The Umenoki bridge (Fig. 5) as a test bridge is a stress ribbon pedestrian bridge with the specifi-

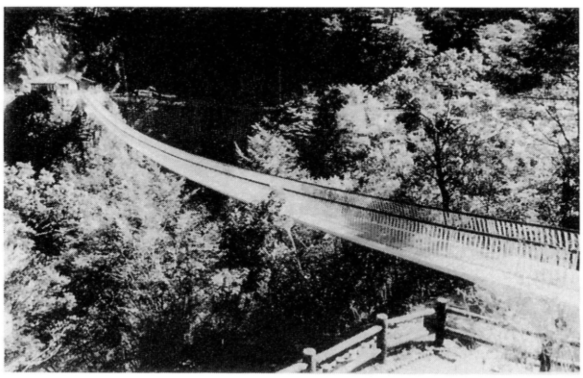


FIGURE 5 The Umenoki Bridge.

Table 1. Specifications of the Umenoki Bridge

$L(m)$	$EI(MNm^2)$	$T_0(MN)$	$\rho(tm^{-1})$	$f(m)$	$f_1(Hz)$
105	45	4.45	1061	3.10	0.95

L: span; EI: flexural rigidity; T_0: initial tension due to dead load; ρ: mass per unit length; f: sag; f_1: lowest natural frequency of bridge.

cations in Table 1 and Fig. 4. As can be seen from these dimensions, the bridge is a very flexible structure that can be excited easily.

The dimensions of the resonance force generator used in the tests are $m = 3$ kg; $M = 150$ kg, $a = 40$ cm; $r = 14$ cm, $k = 100$N/cm. The fine adjustment of the resonance force generator is implemented experimentally by changing the eccentricity a to make the bridge vibration amplitude larger. The driving force to be applied to the mass m is introduced manually in a resonance force generator that is synchronized with a metronome tuned to the lowest natural frequency of the bridge.

A schematic set-up of the tests for the arrangement of the rollers placed on the slab, subwire, load cell, and resonance force generator is shown in Fig. 6. A load cell inserted between the subwire and the resonance force generator accurately measures the initial tension force H_0 and its change ΔH. The subwire is made of 5-mm diameter stainless steel composed of seven twisted wires and its stiffness k is determined from the relationship in Fig. 7 to be $k = 100$ N/cm. The bridge vibration due to a sinusoidal force is measured by accelerometers placed at midspan and at quarter-span. The acceleration response at the midspan of the bridge due to the excitation of the resonance force generator is presented in Fig. 8. The maximum acceleration amplitude is 6.9 gal and the displacement amplitude is numerically calculated as 0.19 cm.

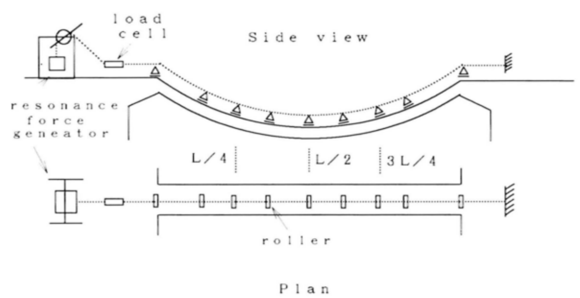


FIGURE 6 Field tests set-up.

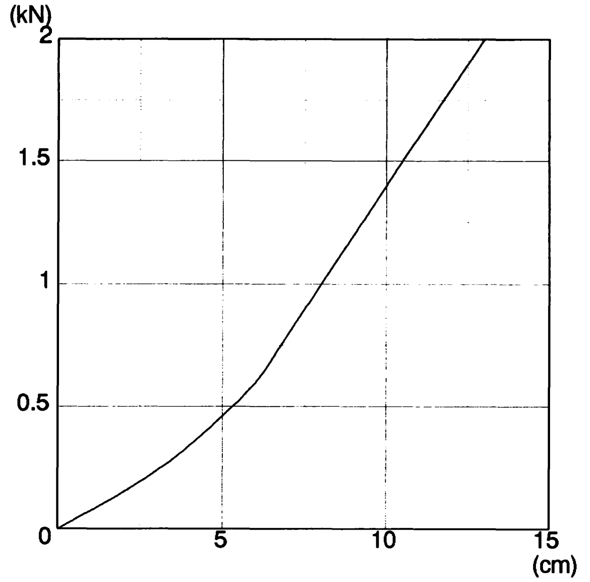


FIGURE 7 Force–elongation diagram of a 50-m long subwire.

Despite the fact that the exciting force applied to the mass m in the resonance force generator due to the manual movement is in the small value range of 20–30 N, the maximum change ΔH produced in the vibration tension force H of the subwire, measured with a loadcell, is $\Delta H = 609$ N. Because the speed of the driving force produced manually in the resonance force generator is adjusted by observing the needle movement of the metronome, the manually introduced force applied to the mass m changes with the time.

To eliminate the transverse vibration resulting from a large elongation, rollers are placed in two specified locations along the subwire length. These specified locations correspond to those with negative value in the lowest symmetric natural mode of vibration, $\Phi_1(x)$, shown in Fig. 9. According to the modal analysis theory, the induced bridge vibration with the mode component under consideration due to a uniform force is proportional to the area resulting from subtracting the negative areas from the positive ones in the mode function. Therefore, the elevations of the rollers set in the specified locations are adjusted such that the subwire may be stretched on a straight line to avoid generating forces in these rollers.

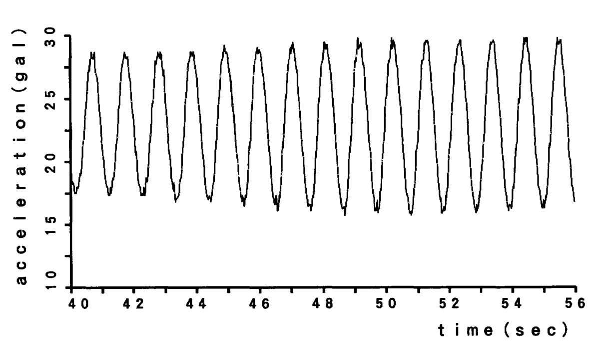


FIGURE 8 Acceleration response at the midspan of the bridge.

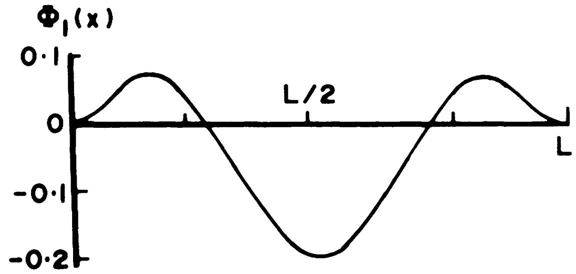


FIGURE 9 The lowest natural mode of vibration of the Umenoki Bridge.

DISCUSSION

As can be seen from Eq. (3), the induced uniform force by the change in a subwire tension force increases with the increase of rise (or sag)–span ratio. Hence, arch and suspension bridges with large rise (or sag)–span ratios will be excited more effectively compared with a stress ribbon bridge with a very small sag–span ratio by the use of a subwire.

The field test data demonstrate the capability of the resonance force generator to effectively change the subwire pretension force with a minimum applied force. However, it should be mentioned that its effectiveness is influenced by a

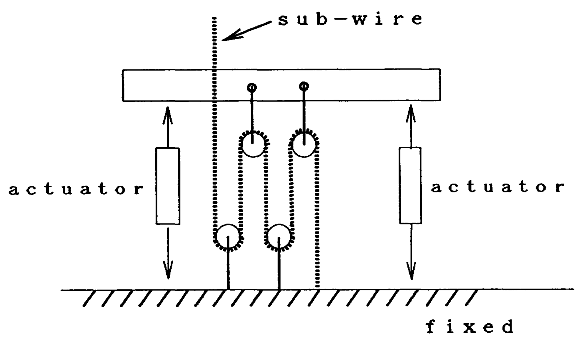


FIGURE 10 Arrangement of running blocks and actuators.

variety of complicated damping factors existing in the total vibration system composed of the extra elements such as subwires, rollers, and bridges, and the resonance force generator itself.

As one of the predictable disadvantages to the proposed approach, a large subwire elongation problem for a very large span bridge needs to be discussed. The subwire used in the above-mentioned field tests of a stress ribbon bridge exhibits a little shortage of stiffness. Therefore, larger vibration is not easily induced. Increase of the subwire stiffness determined from Eq. (4b) is obviously an efficient and simple approach. The use of running blocks and actuators (Fig. 10) may be a powerful device to drastically decrease the ram displacement of an actuator, although the actuator force needed to change the subwire tension force also drastically increases.

CONCLUSIONS

An approach for exciting arch and suspension bridges by the use of subwires is proposed and its concept is verified by oscillating an actual stress ribbon bridge. Both the stress ribbon bridge and arch and suspension bridges are equivalent structures in that their flexural members are stiffened with the arch action of the parabolic members. Therefore, the field test results for a stress ribbon bridge will be valid for this kind of bridge, as far as the proposed concept is concerned.

REFERENCES

Camotim, D. and Roorda, J., August 1981, "Active Vibration Control of a Simple Beam," Solid Mechanics Division, University of Waterloo, Paper No. 166.

Chung, L. L., Reinhorn, A. M., and Soong, T. T., 1988, "Experiments on Active Control of Seismic Structures," *Journal of Engineering Mechanics Division, ASCE,* Vol. 114, No. EM2, pp. 241–256.

Hirai, I., 1968, "Analysis of Eigenvalue Problems by the Use of External Forces," Research Report, ST-1-68, Faculty of Engineering Science, the University of Western Ontario, London, Canada.

Roorda, J., 1975, "Tendon Control in Tall Structures," *Journal of Structural Division, ASCE,* Vol. 101, No. ST3, pp. 505–521.

Yang, J. N. and Giannopoulos, F., 1979, "Active Control of Two Cable-Stayed Bridges," *Journal of Engineering Mechanics Division, ASCE,* Vol. 105, No. EM5, pp. 795–810.