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ACTIVE CONTROL OF TRAFFIC-INDUCED VIBRATIONS IN ELEVATED HIGHWAY BRIDGES

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1. INTRODUCTION

Elevated highway bridges are subjected to moving vehicles which generate loads that vary in both time and location. From the dynamics point of view, this forms a complex time-varying system which is difficult to be controlled. Following is an effort that seeks for an appropriate control which can effectively and practically suppress the bridge vibrations. As the first step, this paper attempts to understand the vehicle-bridge-control characteristics, focusing on the vehicle's effects on control performance, through the applications of the AMD and ATMD control mechanisms.

2. VEHICLE-BRIDGE-CONTROL SYSTEM

The system used in this study consists of a simply supported bridge, a vehicle and a control unit, as shown in Fig. 1. The state-space representation of the vehicle-bridge-control interaction equation is

$$\dot{\mathbf{x}} = \mathbf{A}(t)\mathbf{x} + \mathbf{B}\mathbf{u}(t) + \mathbf{F}(t)$$

where $\mathbf{x}$ is the system state consisting of vehicle, bridge modal and auxiliary mass state. $\mathbf{A}(t)$ is the system matrix. $\mathbf{B}$ is the control location matrix. $\mathbf{u}(t)$ is the control and $\mathbf{F}(t)$ is the disturbance matrix.

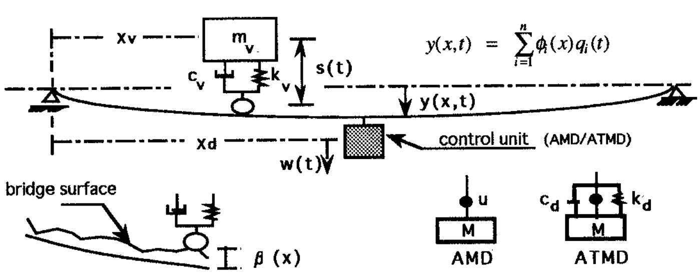

Figure 1. Vehicle-Bridge-Control Model

3. CONTROL ALGORITHMS

All controls are designed to minimize the performance index, $J = \int_0^{t_f} [\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u}]dt$ where $\mathbf{Q}$ and $\mathbf{R}$ are weight matrices. In order to obtain the minimal J, three different control algorithms are employed.

(1) full-state feedback: $\mathbf{u}(t) = \mathbf{G}(t)\mathbf{x}(t)$; $\mathbf{G}(t)$ is the optimal time-varying gain.

(2) output feedback: $\mathbf{u}(t) = \mathbf{G}(t)\mathbf{y}(t)$; $\mathbf{y}(t)$ is the output (excluding the vehicle state).

(3) constant gain feedback: $\mathbf{u}(t) = \mathbf{G}\,\mathbf{y}(t)$; $\mathbf{G}$ is the optimal time-invariant gain.

It is noted that (i) the full-state feedback needs to know all vehicle information: vehicle properties, location and its motion, (ii) the output feedback needs only the vehicle properties and location, while (iii) the constant gain feedback requires no vehicle information. The optimal gains, in case (1) and (3), are obtained from the standard linear regulator[1] whereas the output feedback optimal gain in (2) can be computed by solving the two-point boundary value problem[2].

4. SIMULATION RESULTS

Model properties are as follow: (i) bridge: m = 3.306 ton/m, L = 40 m, EI =3.09×10^6 kN-m^2, and damping ratio = 0.02 (ii) vehicle: m_v = 19.47 ton, k_v = 6.91×10^3 kN-m^2, ξ_v = 0.0018, and speed = 20 m/s (iii) ATMD: m_d = 1.98 ton, k_d = 0.665 kN-m^2, ξ_d = 0.12, and mass ratio = 0.03. The natural frequency of the vehicle is intentionally made equal to that of the bridge's first mode natural frequency (=3.0 Hz), and the ATMD is also optimally tuned to the same frequency.

4.1) Active Mass Driver (AMD): Fig. 2 reveals that the full-state feedback performance is always superior to both output and constant gain feedbacks. The improvement increases as the control force becomes larger. The comparison between output and constant gain feedback indicates that the former is slightly better. Table 1 lists the control force contributions. In all controls, the bridge velocity feedback component governs the total control force. The feedback of vehicle motion, in full-state feedback, is comparable and it improves the control performance as shown in Fig. 2. However, that improvement is very small.

4.2) Active Tuned Mass Damper (ATMD): Unlike the AMD case, the output and constant gain feedback performances are better than that of the full-state feedback even though the full vehicle information is utilized in the full-state feedback. This is because the excitation resulted from surface roughness acts on only the vehicle and, in this case, the vehicle feedback gain is very large. Therefore, the full-state feedback needs to supply a large control force to move the system poles to the optimal locations as shown in Table 2.

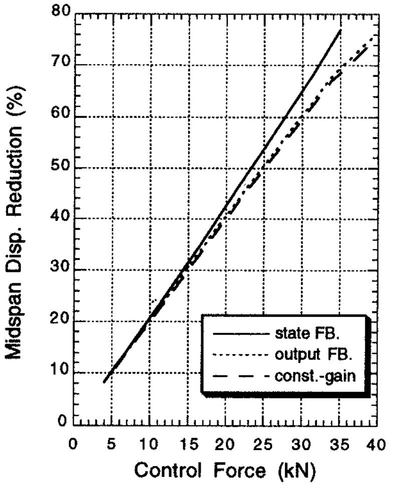

Figure 2. AMD Performance

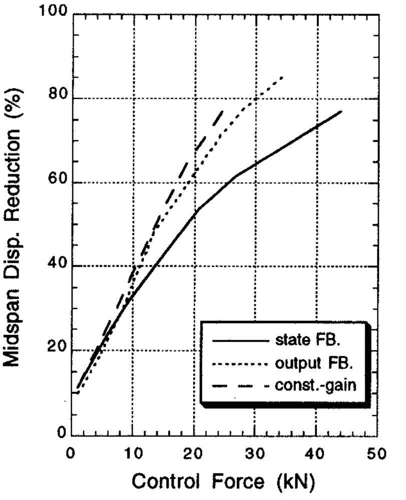

Figure 3. ATMD Performance

Table 1. Control Force Contribution (AMD)

control algorithm	control force (kN)					displacement reduction (%)
	$\dot{q}_1$	q_1	$\dot{s}$	s	total	
full-state FB.	22.36	0.78	8.82	5.41		45.40
output FB.	22.50	0.63	-	-	22.48	45.59
const-gain FB.	22.64	1.06	-	-	22.63	45.17

Table 2. Control Force Contribution (ATMD)

control algorithm	control force (kN)							displacement reduction (%)
	$\dot{q}_1$	q_1	$\dot{w}$	w	$\dot{s}$	s	total	
full-state FB.	2.33	7.72	9.93	1.49	23.11	4.72	20.66	53.60
const-gain FB.	5.74	22.60	16.31	0.00	-	-	19.14	65.79

note.- definitions of " q, s and w ", see Fig.1

5. CONCLUSION

Beside the difficulties in getting vehicle information on-line, it was found that incorporating the vehicle information in control design may not lead to significant improvement of the bridge vibration control. Moreover, if such control is not properly designed, it may degrade the control performance. The effective control can be constructed by the feedback of the bridge motion alone. It is interesting to note that the ATMD requires less control force comparing to the AMD for the same level of vibration reduction. To control the actual bridges subjected to multi-vehicle, the authors are developing a semi-active damper in which its control objective is to keep maximizing the correlation of the damper reaction and the bridge velocity. This damper offers an inexpensive mean and it is believed to have adequate effectiveness. It should be noted that there is a small mistake in the selection of the system coordinates used for the control design in ref.[3]. In which, the reported results are different from those obtained by this study.

6. REFERENCES

[1] Kailath, T., "Linear Systems", Prentice-Hall, 1980.
[2] Levine, W.S., Johnson, T.L., and Athans M., (1971), "Optimal Limited State Variable Feedback Controllers for Linear Systems ", IEEE Trans. Auto. **Control, vol. AC-16, no 6.**
[3] Kasahara, S., Fujino, Y. and Bhartia, B., (1994) "Active Control of Traffic-Induced Vibrations in Highway Bridges", Proc. of 49th Annual Conf. of JSCE, I-636 (in Japanese).