A Wireless Feedback Control System as a Base of Bio-Inspired Structure System to Mitigate Vibration in Structures

Gwanghee Heo, Geonhyeok Bang, Chunggil Kim, Chinok Lee

Abstract—This paper attempts to develop a wireless feedback control system as a primary step eventually toward a bio-inspired structure system where inanimate structure behaves like a life form autonomously. It is a standalone wireless control system which is supposed to measure externally caused structural responses, analyze structural state from acquired data, and take its own action on the basis of the analysis with an embedded logic. For an experimental examination of its effectiveness, we applied it on a model of two-span bridge and performed a wireless control test. Experimental tests have been conducted for comparison on both the wireless and the wired system under the conditions of Un-control, Passive-off, Passive-on, and Lyapunov control algorithm. By proving the congruence of the test result of the wireless feedback control system with the wired control system, its control performance was proven to be effective. Besides, it was found to be economical in energy consumption and also autonomous by means of a command algorithm embedded into it, which proves its basic capacity as a bio-inspired system.

Keywords—Structural vibration control, wireless system, MR damper, feedback control, embedded system.

I. INTRODUCTION

A bio-inspired structural system (BISS) has been here with us since human history began. Only the term is in current use. In order to apply it to bio-sensing and bio-responding, an interdisciplinary workshop was held at the University of Maryland on November 2007 although the term was not clearly defined. It attracted about forty experts in various fields such as biology, biochemistry, life science, computer-information engineering, mathematics, physics, material science, general engineering. Since then, more active attention was paid to this area of research [1]-[4].

Although researches did not reach far enough to employ bio-inspired technologies, they have developed various technologies to automatize the engineered system-maintaining structures, evaluating their safety and coping with structural crisis, all autonomously.

Monitoring is the most essential part of maintenance technologies. Initially, monitoring technologies were involved with the wired systems like wired measurement equipment and devices. However, they were found to be limited so that wireless monitoring technologies started to be developed.

Straser [5] was the first one who introduced a wireless monitoring system to the construction field. Of many researchers in this field, Lynch et al. [6] developed the MEMS based wireless acceleration sensor which was applied to a five-storied model structure, and performed an analysis and evaluation of its dynamic characteristics. Kurata et al. [7] applied the MICA system developed by Berkeley to a two-storied model structure, performing a free vibration experiment and a risk monitoring experiment. Sinozuka et al. [8] also developed Dura Node which included MEMS sensor, micro-controller, and wireless modem, successfully creating a real-time data acquisition system. In Korea, this area of researches was done by Cho et al. [9] who studied on a health monitoring system for cable-stayed bridges by means of smart wireless sensor. Heo et al. [10], [11] also studied to develop a smart wireless measurement system for bridge monitoring. Kim et al. [12] also suggested an infrastructure of sensor network which would acquire and combine all data in bridge monitoring. As well as the studies mentioned, many researchers have been studies on wireless monitoring system which makes it possible to inspect structural conditions on a regular basis and detect damage early for an effective preparation against an unexpected disaster or situation [13], [14].

Recently, researches focused not only on wireless monitoring technologies but also on a combined control system integrating different vibration control technologies. For example, Lynch et al. [15] were the representatives in this new field, creating a close-loop control system with semi-active MR damper. They just performed an experiment on a three-storied model structure by measuring responses with wireless sensors and controlling a wired feedback control system in real time. So, it is not a real wireless feedback control system.

In order to develop a wireless feedback control and wireless measurement system in real time for a creation of bio-inspired structure system where a regular inanimate structure would act like a life form. Heo and Kim [16] developed a Unified Wireless (UW) system for wireless feedback control and wireless measurement and verified its performance by means of experiments. The UW system developed by them includes the functions of a UW measurement system and a wireless feedback control system, but it uses a simple bridge seismic vibration control without considering the state-space equation of a bridge structure. They were also using the queue function in the LabVIEW. This queue function is so sensitive when error

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occurs [17]. Such a characteristic may cause problems in a wireless system such as system stoppage. The bio-inspired structure system must work under any circumstances and must know the condition of the structure itself, so the problems of the previous research must be solved. Therefore, more studies are needed for a more effective and real-time standalone wireless feedback control (WFC) system as a pre-step for the BISS.

In this study, an appropriate WFC system for BISS has been developed as a standalone system, and experimental tests were carried out. The WFC system has been embedded with all appropriate feedback control logic and measurement functions. And also some extra virtual memory space has been utilized to prevent acquired data from being lost. The developed system has been verified by the seismic response test conducted on the two-span bridge.

II. DESIGN OF WFC SYSTEM AS A PART OF BISS

A BISS is supposed to function like a biological organism sensing (perception), transmitting (nerve), and responding to external stimulation (muscle). Accordingly, it is essential for the WFC system as a part of BISS to correctly measure responses of structure, evaluate its safety, and control its behavior. To do this, it should be not only a standalone system but it also should be embedded with function for measurement, decision, and control. Therefore, as shown in Fig. 1, it is composed of a decision making system, a responding system, and a sensing and data communication system in order to control harmful vibration inflicted to structure. Therefore it works real-time like a living organism, perceiving/judging/responding to any injurious external vibration. It is thus supposed to measure and analyze external stimulation with a programmed algorithm, and then to respond properly on the basis of the analysis. First of all, a wireless measurement and feedback control system, a bidirectional communication system, and finally a central control system managing the whole are developed to constitute the WFC system.

III. DEVELOPMENT OF THE WHC SYSTEM

A. Configuration of the WFC System

The WFC system was developed as a basis of BISS. The WFC system is composed of four parts: a wireless measurement system and a wireless communication system both of which measure and transmit structural responses, a control system that controls structural vibration responding to the control order, and finally a control algorithm embedded into the system as shown Fig. 2. It is particularly based on a wireless system to measure data and control the structure system since it is required to be a standalone system.
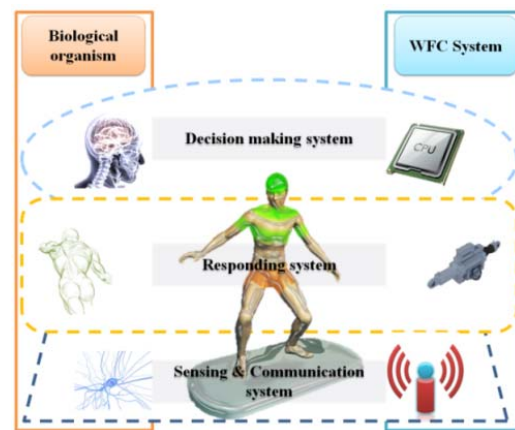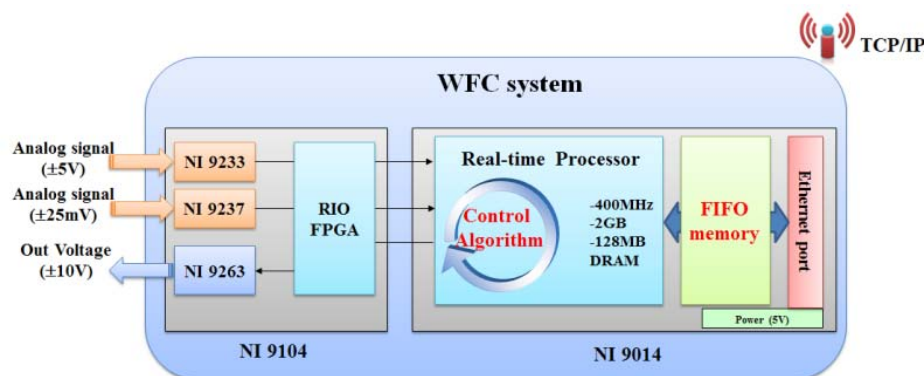

Fig. 1 WFC system for BISS

Fig. 2 Wireless feedback control system

As shown in Fig. 2, the WFC system consists of three different modules: a unified measurement module, a system control module and a wireless communication module. As a measurement module, cRIO-9104 has a built-in FPGA Chip, which can speed up acquisition of data from NI 9233, and NI 9237, which can accept various types of sensors attached to the structure. As a control module, cRIO-9014 is working to measure data and perform a feedback control algorithm embedded in the system in real-time. The wireless bridge of RFLink-500M(RF Vision) between WFC system and data acquisition system is also employed with TCP/IP, and to solve the problem of wireless data transmission and data loss, a

function is applied to prepare a virtual saving space, what is called "Real-Time FIFO(First in First out)" instead of LabVIEW queues for the UW system [16]. The logic of the WFC system was programmed using LabVIEW. In particular, by embedding control logic into the cRIO-9014, the WFC system can be standalone.

The NI 9263 module was used to send the output signal to the control system, which resists the external force of the WFC system. The NI 9263 is a module capable of outputting a $\pm 10V$ 16-bit analog voltage signal, which is adapted to the semi-active control device to be used in this study.

B. Embedded Control Algorithm of the WFC System

As control algorithm, Luapunov direct approach and Lyapunov function has been developed for this specific study. Lyapunov's direct approach was employed by Leitmann [18] for the design of semi-active controller. It is applicable for a variety of systems such as a linear, a nonlinear, a time-variant, and a time-invariant system. Lyapunov function for its application is as in equation:

$$V(z) = 1/2 \|z\|_p^2 \tag{1}$$

Here, $\|z\|_p = \left[z^T P z\right]^{1/2}$ refers to P-norm. After deriving $\|z\|_p$ using Lyapunov equation ($A^T P + P A = -Q_p$), an equation expressed as controllable is as follows:

$$V_i = V_{max} \, H((-z^T) P B_i f_i) \tag{2}$$

Equation (2) shows a control theory in which Lyapunov control algorithm is applied. Here, V_i refers to the final input voltage supplied into a power device of MR damper. V_{max} expresses the input voltage of power device allowed at maximum. $H(\cdot)$ refers to Heaviside step function, $\dot{z}$ to an equation of state in the system, derived from that of motion, P to positive confirmation matrix found by Lyapunov equation, B_i to a row of i in B matric, and f_i to the control capacity of MR damper for the same row i.

IV. EXPERIMENTAL SETUP AND DEVICES

In this study, a two-span bridge was constructed with each span made of difference size and mass as seen in Fig. 3 to evaluate the performance of the WFC system in comparison to the wired control system.

As seen in Fig. 3, the bridge is composed of superstructure, substructure, and abutment. Its superstructure is made of RC slab and I-type beam to raise its mass, while its substructure is made up of short columns of I-type beam to minimize the effect of pier stiffness on structural behavior. A rubber bearing is fitted into each contact area of the superstructure with the substructure. Abutments are added on both ends of the bridge for the purpose of incurring clash against each span as well as

preventing the superstructure from falling down. For a control of lateral vibration of two spans, a MR damper is installed between two spans right beneath them. Both of the two spans and a MR damper together constitute a MR damping system which would be able to control the lateral vibration of the whole bridge structure.
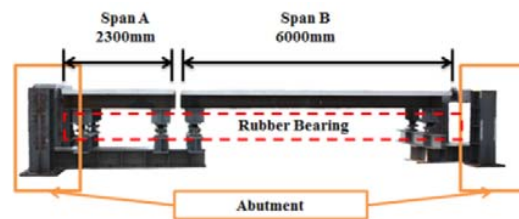

Fig. 3 Two span model bridge

As seen in Fig. 3, a shorter span (span A) and its columns were placed on a shaking table on the left of the picture below; meanwhile, a longer span (span B) and its columns on another table. The span A is made 1476 kg in weight, 2300 mm in length, and span B one 3492 kg, 6000 mm. Then, 50% of Kobe earthquake load (PGA 0.821 g measured at the KJMA Observatory station in 1995) was inflicted equally on both tables by connecting them on an axis (longitudinal direction).

The MR damper in this study was designed to have a maximum control capacity of 30 kN. Its control performance was verified by a spring testing machine, a dynamic experiment device, manufactured by Shalom Engineering Co., that the Korea Railroad Research Institute now maintains. Its basic design specifications are listed in Table I.

TABLE I
DESIGN SPECIFICATION OF MR DAMPER

Items	Condition	
Piston Stroke (pick to Pick)	140 mm ($\pm$ 70 mm)	
Maximum damping force (nominal)	30 KN	
magnetic field length	58 mm	
Orifice difference	1.0 mm	Control Device: 30kN MR Damper
MR fluid	BASF MRF	

Two shaking tables (60 ton each, available for the three degrees of freedom experiment under the 30-ton payload condition) at the seismic simulation test center (Pusan University, Korea) were employed to evaluate its control performance in comparison to the wired control system.

As shown Fig. 4, RFLINK 500M wireless antenna, MR damper and Standalone WFC system are set up around the two span bridge. The wireless distance between left RFLINK 500M and right RFLINK 500M is 60 m. C shows the MR damper, while B is the stand-alone WFC system.
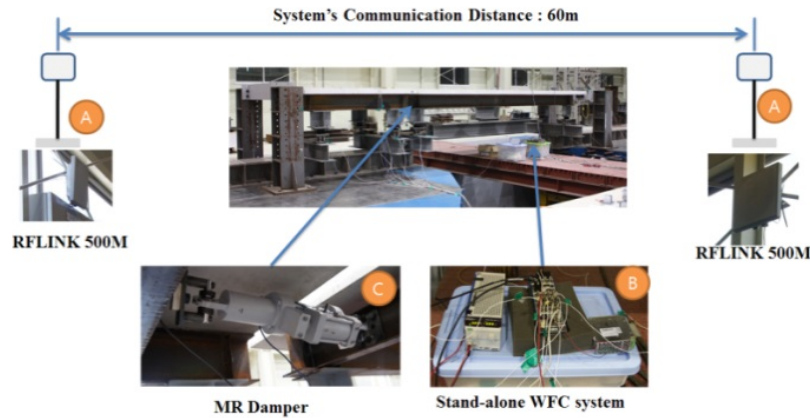
Fig. 4 Test devices and wireless distance of RFLINK 500M

V. EXPERIMENTAL TEST FOR WFC SYSTEM

The shaking table tests were aimed to examine whether the WFC system is effective in mitigating responses of the two-span bridge under seismic load and to compare it to the wired control system. In order to measure structural responses and analyze the measured data for control of the MR damping system, a DS 1103 PPC controller manufactured by dSpace Co. was employed. Electricity needs to be supplied to the MR damper according to each voltage output from the controller, and for the purpose a PMC 18-3A DC Power Supply made by KIKUSUI Co. is employed. Table II shows the experimental condition of both the WFC system and the wired control system. As shown in Table II, the WFC system is found to spend less current than the wired control system does.

TABLE II
MEASUREMENT DEVICES OF THE WIRE AND WFC SYSTEMS

Devices		Wired System	WFC System	
Main Device		DS1103 PPC Controller	cRIO-9014	Real-time OS
			cRIO-9104	FPGA
			NI-9233	
			NI-9237	Module
			NI 9263	
			RFLink-500M	Antenna
Cable length/Ch		About 12 m	About 3m	
Sampling Rate		1000 Hz	2000 Hz	
Input Voltage		220 V	5V	
Sensor	Acceleration		3134D (5ch)	
	Displacement		CDP-50 (3ch)	
	Force		DBBP-5t (1ch)	

First, it is necessary to verify its performance so that an experiment was carried out to measure the responses on span A wirelessly. The validity of the measured data here was verified by comparing them to those measured by wired sensors installed at span A.

As seen in Fig. 5, the amplitude value of acceleration response in the wired system was found to be 7% bigger than in the WFC system because of some noise of the shaking table whose movement was precise though.
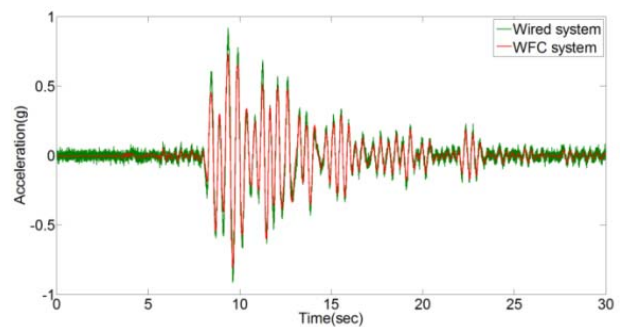

Fig. 5 Comparison of data of wired system and WFC system (time domain)

The dynamic control test on the WFC system was carried out under the four conditions: 1) the Un control (a basic structure without any control device) 2) passive-off (with a control device but without electric current input) 3) passive-on (with a control device with 3A) 4) Lyapunov control (with a control device input with the current allowed by a control algorithm Lyapunov). Its performance was measured by means of relative displacement responses acquired between spans as in Fig. 6.
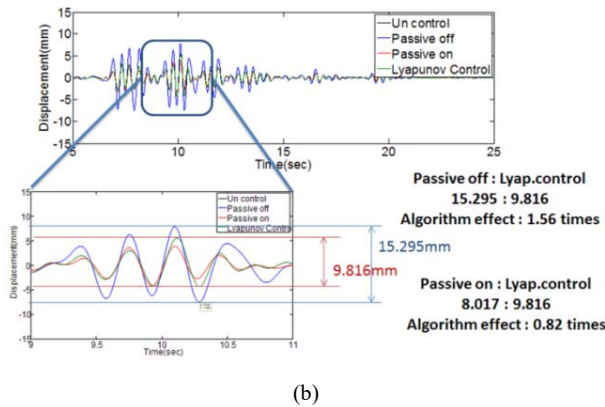

(a)

(b)
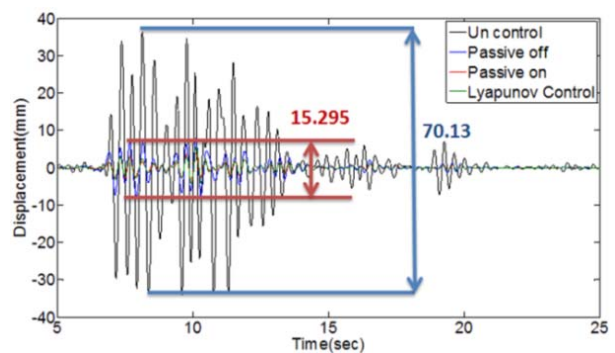
Fig. 6 Response comparisons by control condition of WFC system: (a) Relative displacement (all conditions); (b) Relative displacement (MR Damper condition)

As seen in Fig. 6 (a), the relative displacement between two spans decreased by 80 % because of the MR damper installed in the WFC system. As also seen in (b), it decreased again by 35% in comparison to the passive off without current input. To express mathematically, maximum response (MR), the performance index (PI), and the control effect (CE) according to each response data, are as in Table III.

TABLE III
MEASUREMENT DEVICES OF THE WIRE AND WFC SYSTEMS

Estimation Results	Relative Displacement					
	MR	RMS	PI (%)		CE	
Control Case	mm	mm	*MR*	*RMS*	*MR*	*RMS*
Un damping	36.3597	6.5231	100	100	0	0
Current off	7.7920	1.2760	21.43	19.56	78.57	80.44
Current on	3.8223	0.5752	10.51	8.82	89.49	91.18
Lyapunov	5.4942	0.6411	15.11	9.83	84.89	90.17

In Fig. 6 and Table III, it is found that the responses under each different conditioning verify that the control performance gradually improves in an order of Un control, passive off, Lyapunov, and finally passive on. The result of the dynamic control test shows that it performed the best under the condition of passive on as far as relative displacement is concerned. Now, in order to verify its dynamic control performance with Lyapunov control algorithm applied, the acceleration responses of each span are compared to the clash responses between each span and its adjacent abutment as in Fig. 7.
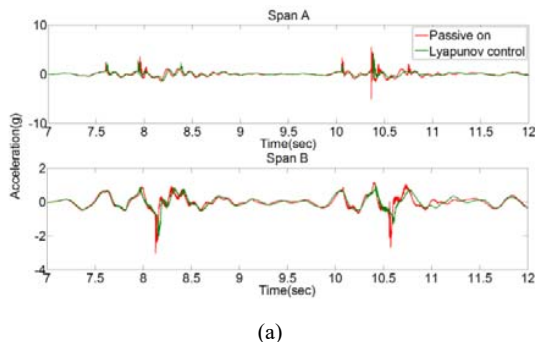
(a)
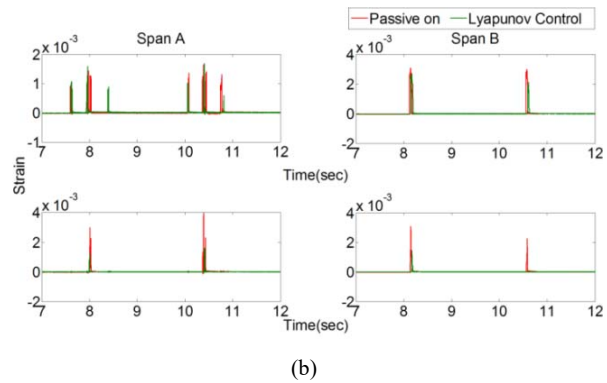
(b)

Fig. 7 Response comparisons under each control conditions: (a) Acceleration; (b) Pounding strain

Fig. 7 (a) shows a graph where acceleration responses of each span are compared under the conditions of passive-on and Lyapunov control, while (b) shows a graph of clash responses between each span and its abutment, measured at the strain gage installed at the abutment. As seen in Fig. 7 (a), acceleration responses of both spans decreased under Lyapunov control, which is caused by the mitigation of clash between each span and its adjacent abutment as seen in Fig. 7 (b). The dynamic control performance of the WFC system needs to be compared to that of the wired system so that their comparison result are graphed through tests carried out under the same control algorithm applied and the same structural condition, as in Fig. 8.

As seen in Fig. 8, the result of the WFC system was found to well match with those of the wired system carried out on the two-span bridge under the same condition with only 5% error of RMS. Finally, the voltage uses of both systems are compared in Table IV.
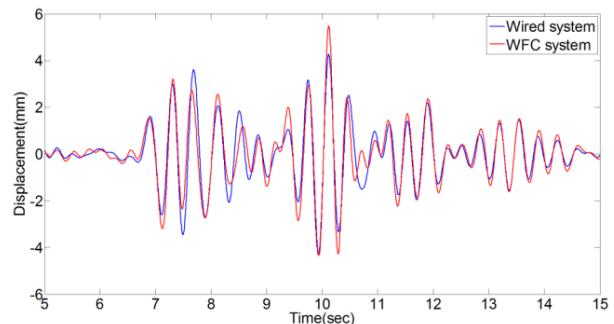

Fig. 8 Response comparisons with wired system and WFC system

As seen in Table IV, the wired system was found to save around 30% of control voltage when algorithm was applied, while the WFC system saved more than 90%. Therefore, the WFC system is proven effective in dynamic control by performing as well as the wired one and saving control voltage at the same time.

TABLE IV
MEASUREMENT DEVICES OF THE WIRE AND WFC SYSTEMS

Estimation Results	Voltage			
	Total Voltage		CE (%)	
Control Case	WFC System	Wired System	WFC System	Wired System
Passive off	0	0	-	-
Passive on	180003	90003	0	0
Lyapunov	1293	65772	99.28	26.92

VI. CONCLUSIONS

In this study, a WFC system was developed as a primary requisite to a bio-inspired structure system where a regular inanimate structure would act like a life form. For a bio-inspired structure system, a standalone WFC system has been developed to include all logics that can be used in the WFC system. And all results of the experimental test on the WFC system have been compared to those of the wired communication system. Therefore, the following conclusions were made.

1) A stand-alone WFC system that requires constant measurement has been developed using RT FIFO (Real time first-in first out) that can drive the system without problems in measurement even if I / O error occurs.

2) In this paper, we used the Lyapunov control algorithm based on state-space equation to enhance the feedback function in order to realize "self-judgment and corresponding capability" in the WFC system.

3) The stand-alone WFC system as a BISS successfully solved the problems caused by time delay and transmission error due to analogue data transmission.

4) Our wireless system has some advantages of saving 75% of cables and reducing noise. It also solved the problem of data loss by making a virtual storage based on RT FIFO for wireless data *transmission.* When compared to the wired system, its performance turned out to be almost equal.

5) The WFC system effectively output control signals to mitigate structural vibration according to the system's judgment. It also performed effectively compared to a wired system. Specially, electric current consumption for controlling the structure was much less than the wired control system needed

From the conclusions above, the stand-alone WFC system developed in this study is proven to be capable of effective performance primarily as a bio-inspired structure system by making autonomous wireless feedback possible.

AUTHOR CONTRIBUTIONS

All authors discussed and agreed upon the idea, and made scientific contributions. Gwanghee Heo conceived and designed the wireless feedback control system; Chunggil Kim performed the experimental study and theoretical analysis, drafting the paper; Seunggon Jeon collected the experimental and analyzed the data. All authors approve the final version to be published and have agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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