MR감쇠기가 설치된 지진격리 건물의 스마트 진동제어

Application of Some Semiactive Control Algorithms to a Smart Base Isolated Building Employing MR Dampers

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ABSTRACT

This paper investigates the effectiveness of the MR damper-based control systems for seismic protection of base isolated building sturcutres employing some semiactive control algorithms, such as the modified clipped-optimal control, the maximum energy dissipation, and the modulated homogeneous friction, by examining the Phase I smart base isolated benchmark building problem. The results of the numerical simulations showed that most of the control systems considered herein could be beneficial in reducing seismic responses, especially base displacement or isolator deformation, of base isolated building structures. It is also verified that another version of the modified clipped-optimal control algorithm proposed in this study and the modulated homogeneous friction algorithm are more effective than other semiactive control algorithms.

1. Introduction

Base isolation systems, such as elastomeric, friction and lead-rubber bearing systems, have been accepted as an effective means for seismic protection of building structures, and also widely applied in numerous full-scale structures (Skinner et al., 1993; Soong and Constantinou, 1994). Those systems can reduce the responses of super-structure, especially inter-story drifts and floor accelerations. On the other hand, the base displacements in those systems under near-fault ground motions may be increased, resulting in expensive loss of space for the seismic gap. To mitigate these problems, base isolation systems have been augmented with supplemental control devices. Several hybrid-type base isolation systems employing additional active control devices have been analytically and experimentally studied with the goal of supplementing passive-type base isolation with active devices to limit base drift of the structure (Yang et al., 1996; Ramallo et al., 2002). Active control devices, however, have yet to be fully embraced by engineers, in large part due to the challenges of large power supplies, concerns about stability, and so on. Because semiactive control devices such as MR (magnetorheological) dampers have the potential to achieve the majority of the performance of fully active systems as well as offer the adaptability of active devices without requiring the associated large power sources, it is expected that the hybrid-type base isolation system employing additional semiactive control devices could solve the large base drift problem of the passive-type base isolation.

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To systematically compare the effectiveness of control systems for base isolated buildings, the benchmark study have been developed by Narasimhan et al. (2003, 2004a,b) based on input from the ASCE structural control committee. In the benchmark problem, three different kinds of base isolation systems, such as linear elastomeric systems with low damping, frictional systems, and bilinear or nonlinear elastomeric systems, are considered.

In this study, the effectiveness of the MR damper-based control systems for seismic protection of base isolated building structures is verified when some semiactive control algorithms, such as the modified clipped-optimal control, the maximum energy dissipation, and the modulated homogeneous fiction, are used to mitigate the base displacements of the building structure. Among three kinds of base isolation systems provided in the problem definition paper, a linear elastomeric system with low damping is considered herein.

2. Benchmark Base Isolated Building Structure

The benchmark structure considered is an eight-story base isolated building similar to existing buildings in Los Angeles, California. The base isolation system includes both linear elastomeric bearings with low damping and nonlinear friction bearings representing friction pendulum system. The super-structure is considered to be a linear elastic system with lateral-torsional behavior. Linear elastomeric isolation system consists of 92 low damping elastomeric bearings, and the fundamental period and the damping ratio of the system are T_b=3 sec and 3%, respectively. On the other hand, nonlinear friction isolation system consists of 61 friction pendulum bearings and 31 linear elastomeric bearings, and the fundamental period and the friction coefficient of the system are T_b=3 sec and μ=0.06, respectively. In the case of nonlinear system, the damping ratio of the linear elastomeric bearings is the same as that of the linear system. In all cases, total of 16 active/semiactive control devices (i.e., actuators/MR dampers), 8 in the X- and 8 in the Y-direction, are placed at the isolation level. More detailed information on the model can be found in Narasimhan et al. (2003, 2004a,b) and Nagarajaiah and Narasimhan (2003, 2004a,b).

3. MR Damper-based Control System

In this paper, an MR damper is considered as a supplemental control device, which is the same as the sample semiactive controller for linear isolation system (Nagarajaiah and Narasimhan, 2004a,b). The capacity, total number and configuration of MR dampers are also the same as those of the sample semiactive control system (i.e., 2,200kN, 16, 8 in the X- and 8 in the Y-direction at the isolation level, respectively). The difference between the sample controller and the controllers considered in this study is only the control algorithm used for calculating the desired command signal. While the original clipped-optimal control strategy is adopted as the control algorithm in the sample controller, several different control strategies are considered to find the appropriate control algorithm for a base isolated building structure in this study.

4. Control Algorithms

A variety of semiactive control algorithms have been proposed for control of MR dampers (Jansen and Dyke, 2000). In this paper, four different control algorithms are considered. They are model-based control algorithms such as the two modified clipped-optimal control algorithms, the maximum energy dissipation algorithm and the modulated homogeneous friction algorithm. In this chapter, each algorithm is briefly explained, and further details can be found in Jansen and Dyke (2000), Yoshida and Dyke (2004), and Choi et al. (2004).

4.1 Modified Clipped-optimal Control Algorithms

Dyke et al. (1996) proposed a clipped-optimal control strategy based on acceleration feedback for controlling an MR damper. Because the force generated in the MR damper is dependent on the local responses of the structural system, the desired optimal control force, f_c, cannot always be produced by the device. Only the control voltage, v, can be directly controlled to increase or decrease the force produced by the device. The algorithm for selecting the command signal for the MR damper can be stated as

$$v = V_{\max} H(\{f_c - f_{MR}\} f_{MR}) \quad (1)$$

where $V_{\max}$ is the maximum voltage, and $H(\cdot)$ is the Heaviside step function. Fig. 1 represents the original clipped-optimal control algorithm graphically.

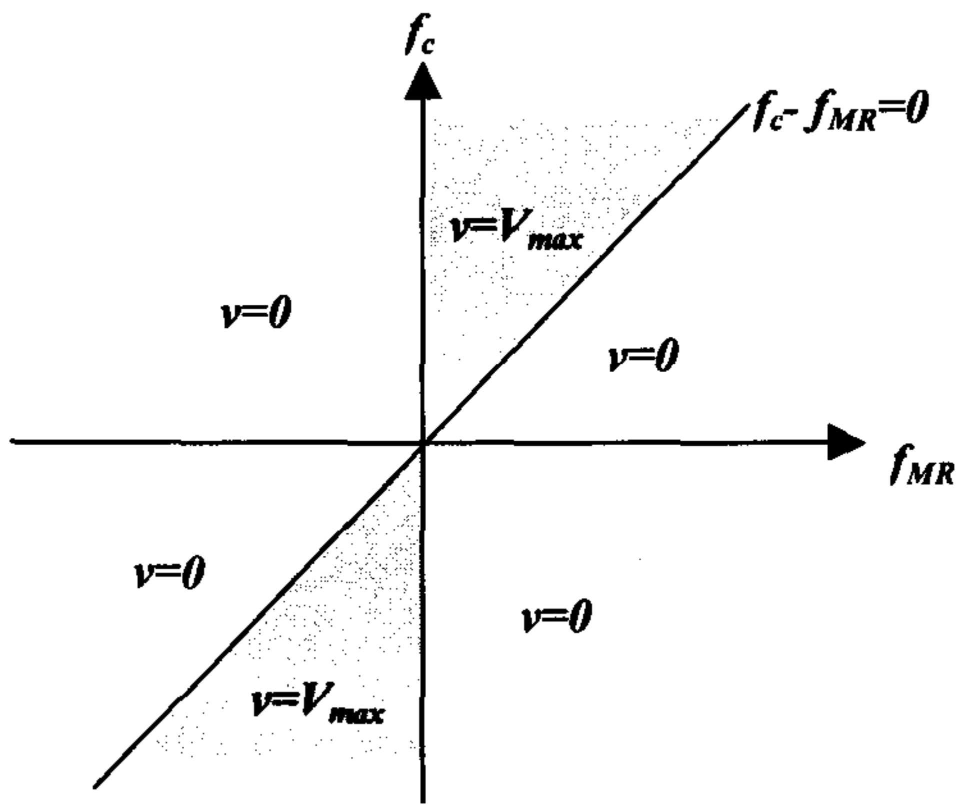

Fig. 1. Graphical representation of the original clipped-optimal control algorithm

In the original clipped-optimal control algorithm, the command voltage takes on the value of either zero or the maximum as shown in Eq. (1). In some situations when the dominant frequencies of the system under control are row, large changes in the forces applied to the structure may result in high local acceleration values. Yoshida and Dyke (2004) proposed a modification to the original clipped-optimal control algorithm to reduce this effect. In the modified version of the algorithm, the control voltage can be any value between **0** and $V_{\max}$. The control voltage is determined using a linear relationship between the applied voltage and the maximum force of MR damper. When the desired force is larger than the maximum force that the device can produce, the maximum voltage is applied. This modified clipped-optimal control algorithm is graphically represented in Fig. 2, and can be given as follows:

$$v = V_c H(\{f_c - f_{MR}\} f_{MR}), \text{ in which } V_c = \begin{cases} (V_{\max}/f_{\max}) f_c, & \text{for } f_c \le f_{\max} \\ 0, & \text{for } f_c > f_{\max} \end{cases} \quad (2, 3)$$

where $f_{\max}$ is the maximum force of the MR damper (i.e., 2200 kN in this study).

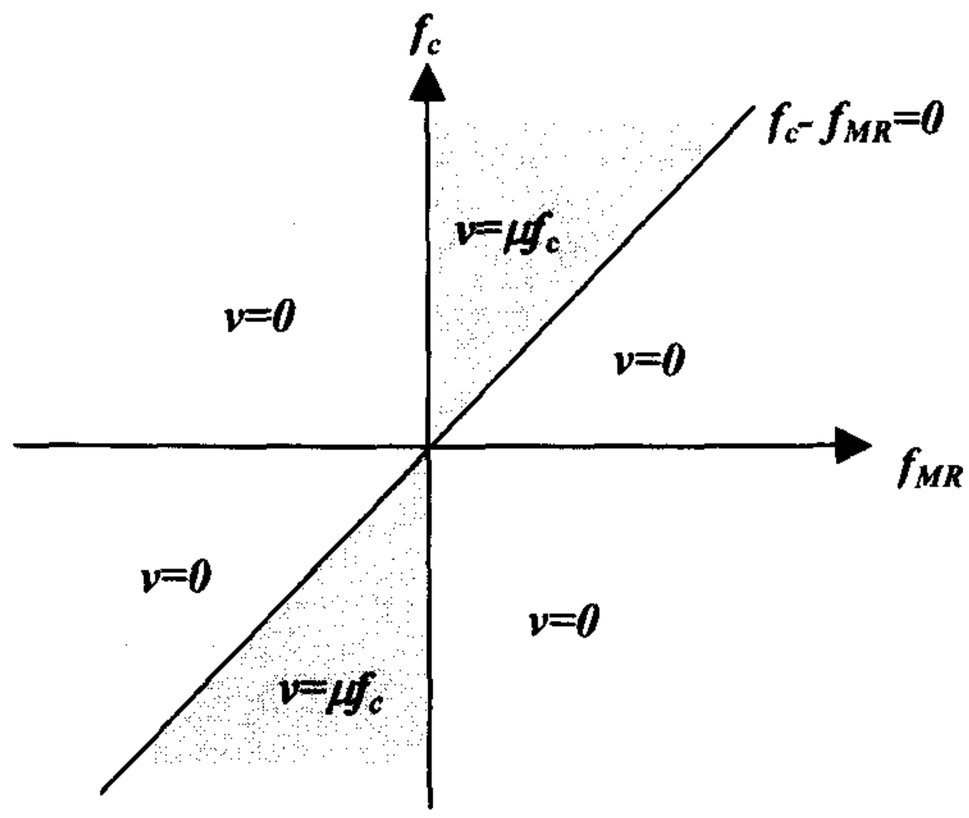

Fig. 2. Graphical representation of the modified clipped-optimal control algorithm

They showed that the modified clipped-optimal control algorithm is typically able to achieve a significant reduction in the peak accelerations over that of the original clipped-optimal control algorithm (Yoshida and Dyke, 2004).

4.2 Another Modified Version of Clipped-optimal Control Algorithms

Although the modified clipped-optimal control algorithm could reduce the peak accelerations significantly, the modification of the original clipped optimal control algorithm might increase the peak drifts slightly (Yoshida and Dyke 2004). In this study, another modified version is proposed to solve the problem of an increase in the peak drifts. To do this, the region of $f_c \le f_{\max}$ in Eq. (3) is subdivided as follows:

$$V_c' = \begin{cases} \mu f_c & for \;\; f_{MR} \le f_c < \alpha f_{MR} \\ V_{\max} & for \;\; f_c \ge \alpha f_{MR} \end{cases} \tag{4}$$

where $\mu = V_{\max} / f_{\max}$ and $\alpha > 1$ is the coefficient to be properly selected.

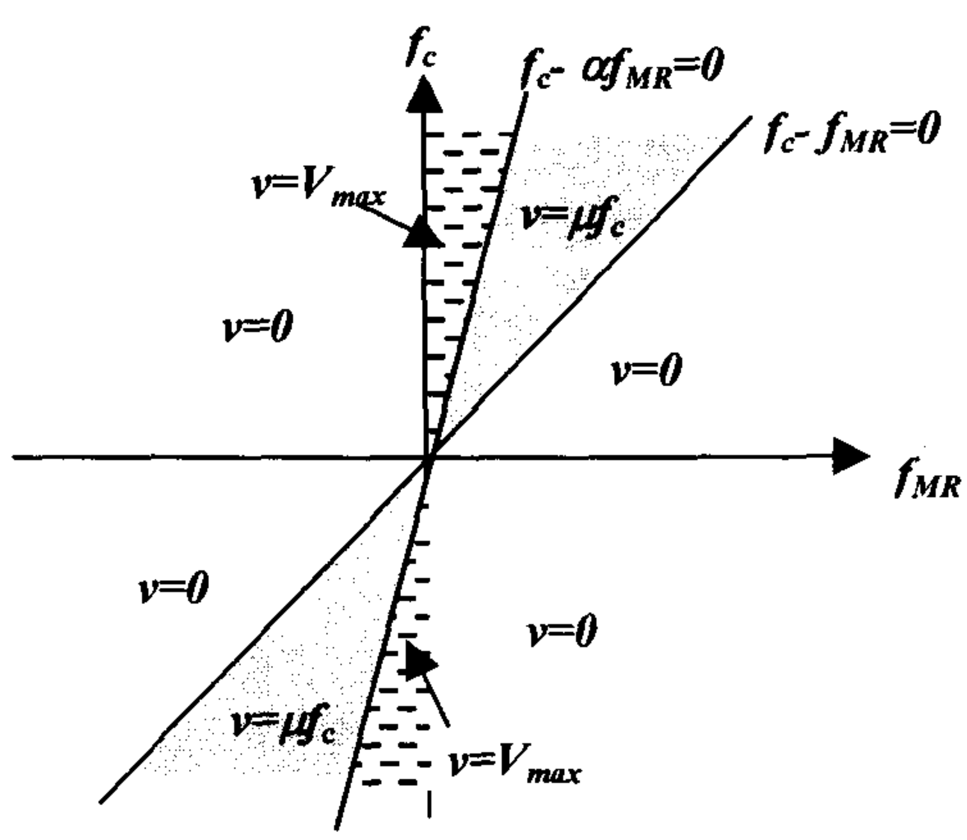

Fig. 3. Graphical representation of another modified version of the clipped-optimal control algorithm

As shown in the equation and the figure, the command voltage input to the MR damper should be the maximum value (i.e., $V_{\max}$) inside the region where the difference between the desired control force (f_c) and the actual control force (f_{MR}) is quite large. Otherwise, the command signal should be calculated according to the modified algorithm. That is, this revised version proposed in this study represents a compromise between the original and the modified clipped-optimal control algorithms.

4.3 Maximum Energy Dissipation Algorithm

The maximum energy dissipation algorithm is presented as a variation of the decentralized bang-bang approach proposed by McClamroch and Gavin (1995). This algorithm considers a Lyapunov function that represents the relative vibratory energy in the structure (i.e., without including the velocity of the ground in the kinetic energy term) (Jansen and Dyke, 2000). This control algorithm commands the maximum control voltage when the relative velocity at damper location and the measured damper force dissipate energy. The control law for the abovementioned algorithm is as follows:

$$v = V_{\max} H\left(-\dot{x}_b \cdot f_{MR}\right) \tag{5}$$

One of the main advantages of the maximum energy dissipation algorithm is that the control law requires only local measurements. Hence, this algorithm does not need any design parameter to decide. This algorithm has quite a simple design procedure compared with other control algorithms considered herein.

4.4 Maximum Energy Dissipation Algorithm

The modulated homogeneous friction algorithm was originally proposed for the controller using a variable fiction damper (Inaudi 1997), but there are strong similarities between the behavior of a variable friction device and the MR damper. This algorithm commends more slip force with damper deformation larger by increasing the damping coefficient through feedback of the damper deformation to improve the energy dissipation process of semiactive dampers (Inaudi 1997). This algorithm was modified for MR dampers by Jansen and Dyke (2000). The control law is

$$v = V_{\max} H\left(f_n - |f_{MR}|\right) \qquad \text{where } f_n = g_n|\Delta(t-s)| \tag{6, 7}$$

defining $\Delta(t-s)$, in which $s = \{\min x \geq 0 : \Delta(t-x) = 0\}$, as the most recent local extrema in the deformation of the MR damper. The proportionality constant g_n has units of stiffness (kN/m), and its optimal value is dependent on the amplitude of the ground excitation.

5. Numerical Simulation Results

In numerical simulation, the five control algorithms are considered for the MR damper-based system. The first controller is designed by using the modified clipped-optimal algorithm proposed by Yoshida and Dyke (MCO-1). The second controller is designed by adopting another modified clipped-optimal control algorithm with α=2 proposed in this paper (MCO-2). The third and fourth controllers are designed by using the maximum energy dissipation algorithm (MED) and the modulated homogeneous friction algorithm with g_n=200 kN/m (MHF), respectively.

A total of seven historical earthquake records are considered (Nagarajaiah et al., 2004a,b): the fault-normal (FN) and fault-parallel (FP) components of Newhall, Sylmar, El Centro, Rinaldi, Kobe, Jiji and Erzinkan records. All the excitations are used at the full intensity for the evaluation of the performance indices.

To systematically evaluate the control performance of each controller, the nine evaluation criteria defined in the benchmark problem statement as follows (Narasimhan et al., 2004a,b): normalized peak base shear (J_1), normalized peak structure shear (J_2), normalized peak base displacement or isolator deformation (J_3), normalized peak inter-story drift (J_4), normalized peak absolute floor acceleration (J_5), normalized peak force generated by all control devices (J_6), normalized RMS base displacement (J_7), normalized RMS absolute floor acceleration (J_8), and normalized total energy absorbed by all control devices (J_9). To more easily verify the effectiveness of each control algorithm, the results of each algorithm are compared with those of the original clipped-optimal control algorithm (OCO) (Nagarajaiah and Narasimhan, 2004b).

The results of evaluation criteria for the five different control designs in the linear elastomeric case are presented in Tables 1 to 2. Table 1 shows the control performance of MCO-1 compared with OCO. As shown in the table, all the peak floor accelerations (J_5) are reduced up to 63% except of the Sylmar and the Jiji cases while maintaining the similar level of the peak inter-story drifts (J_4) (a 28% increase ~ a 10% decrease). It is demonstrated that the slightly more space at the isolation level is needed in this case, because all the peak isolator deformations (J_3) in MCO-1 are larger than those in OCO (a 4%~140% increases) except of the Rinaldi case (a 2% decrease). In the El Centro case, MCO-1 significantly reduces the peak floor acceleration (J_5), whereas it drastically increases the peak isolator deformation (J_3).

Table 2 represents the effectiveness of MCO-2 proposed herein. The overall performance of MCO-2 is similar to that of MCO-1. All the peak floor accelerations (J_5) are reduced up to 27% except of the El Centro and the Rinaldi cases. However, increases in J_5 of MCO-2 are not large compared with those of MCO-1 (e.g., an 18% increase under El Centro in MCO-2, a 140% increase under Sylmar in MCO-1). It is verified that MCO-2 is the more reliable control algorithm under various ground motions.

6. Conclusions

Some control algorithms, such as the modified clipped-optimal control, the maximum energy dissipation, and the modulated homogeneous friction algorithms are considered to verify the effectiveness of the MR damper-based control systems for seismic protection of the base isolation system by investigating the benchmark base isolated building problem. The numerical simulation results demonstrate that most of the control systems considered could be beneficial in reducing seismic responses of base isolated building structures. Among them, the modulated homogeneous friction algorithm could be considered one promising candidate for the nonlinear as well as linear benchmark base isolated systems.

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TABLE 1. Evaluation criteria for various control algorithms (FP-X and FN-Y)

Earthquakes		J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9
Newhall	OCO	0.97	1.02	0.56	1.04	1.49	0.30	0.33	0.89	0.79
	MCO-1	0.93	0.91	0.80	0.96	1.02	0.14	0.68	0.85	0.44
	MCO-2	0.91	0.91	0.73	0.94	0.97	0.15	0.55	0.80	0.55
	MED	0.90	0.88	0.78	0.88	0.89	0.21	0.66	0.85	0.47
	MHF	0.92	0.91	0.79	0.92	0.94	0.05	0.63	0.83	0.49
Sylmar	OCO	0.90	0.91	0.73	0.87	1.16	0.24	0.45	0.74	0.81
	MCO-1	0.95	0.96	0.90	0.93	1.00	0.13	0.71	0.86	0.50
	MCO-2	0.93	0.94	0.88	0.90	0.95	0.13	0.67	0.82	0.56
	MED	0.97	0.97	0.92	0.93	0.96	0.14	0.78	0.90	0.39
	MHF	0.93	0.94	0.92	0.94	0.97	0.05	0.75	0.85	0.42
El Centro	OCO	1.25	1.24	0.54	1.26	1.61	0.38	0.42	0.76	0.65
	MCO-1	0.95	0.93	0.78	0.83	0.85	0.08	0.70	0.74	0.49
	MCO-2	0.94	0.93	0.64	0.84	0.87	0.12	0.55	0.65	0.59
	MED	0.89	0.86	0.64	0.76	2.21	0.44	0.53	0.97	0.59
	MHF	0.95	0.93	0.67	0.82	0.86	0.08	0.59	0.64	0.58
Rinaldi	OCO	1.04	1.02	0.60	0.96	1.01	0.27	0.38	0.71	0.77
	MCO-1	1.01	1.01	0.91	0.99	1.01	0.15	0.71	0.81	0.46
	MCO-2	1.00	0.99	0.86	0.97	0.99	0.15	0.64	0.76	0.53
	MED	0.97	0.97	0.90	0.98	1.00	0.14	0.79	0.83	0.37
	MHF	1.00	1.00	0.92	0.98	1.01	0.05	0.77	0.79	0.42
Kobe	OCO	1.04	1.03	0.52	1.00	1.63	0.28	0.26	0.73	0.73
	MCO-1	0.86	0.86	0.78	0.89	0.97	0.15	0.73	0.80	0.44
	MCO-2	0.82	0.81	0.69	0.80	0.97	0.14	0.62	0.81	0.47
	MED	0.88	0.86	0.69	0.86	1.54	0.25	0.65	0.93	0.51
	MHF	0.83	0.82	0.76	0.83	0.97	0.06	0.71	0.75	0.48
Jiji	OCO	0.84	0.84	0.65	0.86	0.87	0.17	0.46	0.72	0.64
	MCO-1	0.92	0.92	0.84	0.93	0.93	0.10	0.69	0.83	0.43
	MCO-2	0.92	0.91	0.83	0.91	0.93	0.10	0.62	0.81	0.47
	MED	0.96	0.96	0.92	0.95	0.95	0.08	0.79	1.12	0.33
	MHF	0.93	0.93	0.90	0.93	0.94	0.03	0.79	0.87	0.32
Erzinkan	OCO	0.93	0.93	0.47	0.86	1.23	0.25	0.34	0.63	0.80
	MCO-1	1.01	1.02	0.74	0.86	1.02	0.13	0.72	0.83	0.48
	MCO-2	0.99	1.02	0.65	0.88	1.05	0.13	0.65	0.78	0.55
	MED	0.97	1.00	0.86	0.94	1.04	0.15	0.86	0.89	0.34
	MHF	0.96	0.98	0.83	0.88	0.97	0.04	0.82	0.84	0.39

TABLE 2. Maximum evaluation criteria related to structural responses for seven earthquakes (FP – X and FN – Y)

	OCO	MCO-1	MCO-2	MED	MHF
J_1	**1.25**	**1.01**	1.00	0.97	1.00
J_2	**1.24**	**1.02**	**1.02**	1.00	1.00
J_3	0.73	0.91	0.88	0.92	0.92
J_4	**1.26**	0.99	0.97	0.94	0.98
J_5	**1.63**	**1.02**	**1.05**	**2.21**	**1.01**
J_6	0.38	0.15	0.15	0.44	0.08
J_7	0.46	0.73	0.67	0.86	0.82
J_8	0.89	0.86	0.82	**1.12**	0.87
J_9	0.81	0.50	0.59	0.59	0.58

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