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THE EFFECT OF IMPULSIVE MOTIONS ON OPTIMUM TUNED MASS DAMPER PARAMETERS

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Abstract. *Strong ground motions recorded in near-fault regions contain impulsive motions with long period and large amplitude. These motions are directivity pulses and flint steps. Directivity pulses, which occur in the direction perpendicular to fault, are distinctive with their peak ground velocity and long period. In the direction parallel to fault, flint steps occur and these steps are permanent ground displacements. These distinctive impulsive motions in near-fault earthquake data are effective on seismic behaviour of structures. Since performance of structural control systems are related to seismic behaviour of structures, the optimum design of structural control systems must be performed by considering impulsive motions for the best vibration stability and damping in near fault regions. In this study, optimum tuned mass damper (TMD) parameters such as mass, stiffness and damping variables were investigated by using a metaheuristic algorithm called Harmony Search (HS). Harmony search is inspired from musical performances. In the optimization process, impulsive motions with various characteristics were used singly or together. Thus, in addition to the specific optimum values, general optimums were provided by using motions with different periods. In the analyses, impulsive motions were modelled as simplified pulse-type ground motions which were obtained by trigonometric functions called cycloidal fronts. Since the maximum seismic effects occur when the periods of the structure and external excitation are equal to each other, the optimum TMD parameters were searched for single degree of freedom (SDOF) structures with different periods. The developed method was also performed for a 10-storey multiple degree of freedom (MDOF) structure. The optimum values of TMD were investigated for several cases with different maximum TMD damping ratio limits. The method is feasible for practical use because of implementability of specific solution ranges considering physical and economic conditions of TMD parameters. The optimum TMDs are effective on reducing peak responses and obtaining a rapid steady state response.*

1 INTRODUCTION

Near fault ground motions contain two types of impulsive motions such as directivity pulse and flint step. Directivity pulses occur in the direction perpendicular to fault and these pulses are distinctive with their peak ground velocity and long period. Forward directivity occurs when the fault rapture propagates towards the site at a velocity close to the shear wave velocity. Forward directivity causes most of the seismic energy to arrive at the site within a short time [1]. Directivity pulses has caused significant damages on civil structures during major earthquakes such as Northridge, California, USA (1994), Kobe, Japan (1995), Chi Chi, Taiwan (1999), Kocaeli, Turkey (1999) and Duzce, Turkey (1999). Flint steps occur in the direction parallel to fault and these steps represent permanent ground displacements. The motion and directions of impulsive motions can be seen in Figure 1.

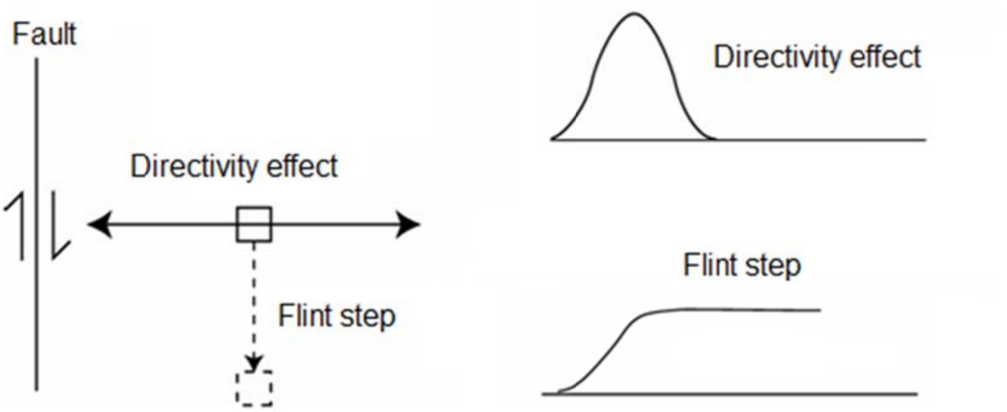

Figure 1: Impulsive motions.

These two types of impulsive motions in near-fault earthquake data are effective on seismic behaviour of structures and the effect of these motions must be taken into account during dynamic analyses and design of structural control systems. Since the design parameters of structural control systems are depended to the seismic behaviour of the main structure, these effects and motions must be investigated during the optimization of structural control systems.

Because of the long period of impulsive motions, their effects are significant on the structures with long vibration period like high-rise structures and seismic isolated structures. The effect of near fault and impulsive motions has been widely investigated for seismic isolated structures and several proposals have been developed in order to prevent the failure of seismic isolation systems [2-8].

The tuned mass damper (TMD) is a passive vibration control device consisting of mass, dampers and stiffness members. This device has been used for several mechanical systems including civil buildings in order to surpass harmful vibrations resulting from wind and earthquake forces. The properties of the mechanical components of TMD must be tuned according to the seismic behaviour of the main structure.

Several closed form expressions have been proposed for the frequency and damping ratio of TMD [9-14]. These expressions were generally obtained for single degree of freedom (SDOF) structures and mass ratio of TMD is a predefined value. In order to use these expressions on multiple degree of freedom (MDOF) structures, the structure must be idealised to a SDOF structure. By this idealization, only the critical frequency of the structure can be taken into account and reaction of the TMD can be directed only to a single mass although TMDs are generally implemented on the top of the structures. For a realistic design and optimization, the TMD parameters can be numerically searched [11, 15-16].

The optimization of TMD parameters can be conducted by using metaheuristic algorithms inspired from several natural happenings. Metaheuristic algorithms such as Genetic Algorithm (GA) [17-21], Particle Swarm Optimization (PSO) [14,22], Bionic Algorithm [23] and Harmony Search [24-35] have been employed for the optimization of TMDs.

The aim of the paper is to find optimum tuned mass damper properties under the excitation of impulsive motions. Harmony search algorithm was employed in the optimization process. The optimization was conducted under directivity pulses and flint steps, singly and together. Impulsive motions with different periods were modelled as simplified pulse-type ground motions which were obtained by trigonometric functions called cycloidal fronts [36]. The optimum TMD parameters were searched for single degree of freedom (SDOF) structures with different periods and 10-storey multiple degree of freedom (MDOF) structure. Different TMD parameter ranges for TMD damping ratio were used for different cases.

2 SIMPLIFIED PULSE-TYPE IMPULSIVE MOTIONS

In several academic research papers, simplified pulse-type ground motions were defined with forward motion only and forward and backward motion by using linear variables for velocity and acceleration [37, 38]. Alavi and Krawinkler used linear variable simplified pulses for velocity and acceleration, but triangle-shaped velocity pulses were modified with parabolic curves in order to study the effect of rise time on response parameter [39]. Simplified pulse-type ground motions were modelled with trigonometric variables in several academic papers [2-3, 40].

Makris [2] proposed pulse-type A with forward motion and pulse-type B with forward and back motion with simple trigonometric functions called cycloidal fronts [36]. Equations of the type A and B motions are given in Eqs. (1-3) and Eqs. (4-6), respectively. In these equations, $\ddot{x}_g(t)$, $\dot{x}_g(t)$, $x_g(t)$, ω_p, V_p, t and T_p describe ground acceleration, ground velocity, ground displacement, pulse frequency, peak ground velocity (PGV), time and pulse period, respectively.

$$\ddot{x}_g(t)=\omega_p \frac{V_p}{2}\sin(\omega_p t) \qquad 0 \le t \le T_p \tag{1}$$

$$\dot{x}_g(t)=\frac{V_p}{2}-\frac{V_p}{2}\cos(\omega_p t) \qquad 0 \le t \le T_p \tag{2}$$

$$x_g(t)=\frac{V_p}{2}t-\frac{V_p}{2\omega_p}\sin(\omega_p t) \qquad 0 \le t \le T_p \tag{3}$$

$$\ddot{x}_g(t)=\omega_p V_p \cos(\omega_p t) \qquad 0 \le t \le T_p \tag{4}$$

$$\dot{x}_g(t)=V_p \sin(\omega_p t) \qquad 0 \le t \le T_p \tag{5}$$

$$x_g(t)=\frac{V_p}{\omega_p}-\frac{V_p}{\omega_p}\cos(\omega_p t) \qquad 0 \le t \le T_p \tag{6}$$

Cox and Ashford proposed an empirical expression for PGV of near fault ground motions by conducting a regression analysis of several recorded near-fault ground motions [41]. This equation can be seen as Eq. (7). In this equation, M_w and ϕ are described as the moment magnitude of the earthquake and the directivity angle in degrees, respectively.

$$\text{Log(PGV)}= 6.444-0.01870\phi-5.022\text{Log}(M_w) \tag{7}$$

Somerville developed expressions for the period of pulse-type ground motions in seconds by conducting regression analysis of earthquake data recorded on soil and rock sites [42]. Respectively, for soil and rock sites, Eq. (8) and Eq. (9) are given.

$$\mathrm{Log}T_p = -2.02+0.346M_w \tag{8}$$

$$\mathrm{Log}T_p = -3.17+0.5M_w \tag{9}$$

3 HARMONY SEARCH AND METHODOLOGY

Harmony search (HS) is a nature inspired metaheuristic algorithm which imitates musical performances in solving optimization problems. For the optimization of TMDs with HS, a computer code is generated for the dynamic analyses of structure and optimization process.

The dynamic analysis of structure is done for all iterations inside a loop. The objective function is related with the results of dynamic analyses. The methodology can be explained in five steps.

i. At the beginning of the optimization process, structural data, external excitations, HS parameters and a possible solution range must be entered. Also, the solution range for the possible TMD properties must be defined by considering physical and economical restrictions in design.

ii. Then, the dynamic analysis of the uncontrolled structure must be done for the future comparison of TMD controlled structure because the main objective of the optimization is to reduce displacement of the structure.

iii. Essentially, the optimization starts in this step. The initial harmony memory matrix is generalized with harmony vectors as many as harmony memory size (HMS). Harmony vectors contain randomly assigned values for optimum parameters of TMD including mass, period and damping ratio. For each set of vectors, the dynamic analyses of the TMD controlled structure are conducted.

iv. After the generation of initial harmony memory matrix, stopping criterion must be checked. The ratio of the peak first storey displacements of the structure with and without TMD must be less than a user defined ratio value. The program has ability to increase this value after several iterations if a solution cannot be found within the solution range.

v. If the criterion is not satisfied, a new harmony vector is formed by using the special rules of the HS. A new vector can be generated in two ways. It can be generated from the elements of an existing harmony vector in harmony memory (HM) or randomly from the whole solution range. If a vector in the HM was chosen for the source of generation, elements of the new vector are assigned within a smaller range around an existing harmony vector. The ratio between the smaller range and whole range can be defined by the parameter called Pitch Adjusting Rate (PAR). Harmony Memory Considering Rate (HMCR) is the possibility to generate a new vector from the existing ones in HM. The program randomly chooses an existing vector but optimization process will be shorter if the best vector has more possibility than others. When generating a new vector from the HM, the probability to select the best vector can be defined with a parameter. This parameter is named with Best Harmony Memory Considering Rate (BHMCR).

If this new vector is better than the existing worst ones, it is replaced with the worst one. The best vector is selected according to a parameter called Best Solution (BS). BS is the sum of the ratios of first storey peak displacements and peak values of first storey acceleration transfer function at the first natural frequency. By this elimination, first storey acceleration transfer function is also taken into consideration in the optimization process. Until the stopping criterion is satisfied, the process continue from step iv.

4 NUMERICAL EXMAPLES

The approach was applied to SDOF structure with 1.5 s, 2 s and 2.5 s periods. Also, a ten-storey structure with 2 s period was investigated. Flint steps were generated by using Type A equations given in Eqs. (1-3). Type B equations (Eqs. (4-6)) were used for directivity pulses. According to the Eqs. (7-9), possible PGV and period values were chosen. Three different directivity pulses and flint steps with periods 1.5 s, 2 s and 2.5 s was used in the optimization. The optimization was conducted under three different directivity pulses and three different flint steps. Also, the optimization was separately performed for directivity pulses (DP) and flint steps (FS). The PGV of pulses were taken as 200 cm/s. HS parameters were taken as 5, 0.5, 0.5 and 0.1 for HMS, HMCR, BHMCR and PAR, respectively. The solution range for the period of the TMD is between 0.8 and 1.2 times of the natural period of the main structure. The mass ratio range was taken between 1% and 5%. Three different damping ratio ranges were used. The lower limit of the damping ratio is 5% and the upper limits are 20%, 30% and 40%.

4.1 Single degree of freedom structures

In the analyses of SDOF structures, the inherent damping of the main structure was taken as 5% and unit mass (1 kg) is used. Thus, the mass of the TMD is equal to the mass ratio. The optimum results of TMD properties (μ= mass ratio, T_{TMD}= TMD period, ξ_{TMD}= TMD damping ratio), ratio of the maximum first storey displacements of TMD controlled and uncontrolled structures (DR), peak value of first storey acceleration transfer function in dB at the first natural frequency for uncontrolled (TF_{w/o_cont}) and TMD controlled (TF_{w_cont}) structure for different damping ratio limits, excitation cases and SDOF structure periods (T_{st}) are given in Table 1.

For the SDOF structure with 1.5 s period, the peak displacement was reduced with 12%, 13% and 15% for the cases with maximum damping ratio limits 20%, 30% and %40, respectively in the optimization process conducted by using two types of impulsive motions. For this structure, the effect of directivity pulses can be reduced more than effect of flint steps. The peak displacement of SDOF structure with 2 s period was reduced between 16% and 22%. The effects of impulsive motions on the peak displacement of structure with 2.5 s period were reduced between 13% and 36%.

As seen from the results given in Table 1, the increase of damping ratio has negative effect on the acceleration transfer function. Thus, the optimum damping ratios of the TMD are generally below 20% although the limits of the damping ratio ranges are higher than 20% for several cases.

4.2 10-storey structure

The application of a TMD was investigated for a 10-storey structure. The properties of the structure can be seen in Table 2. The critical period of 10-storey structure is 2 s. A TMD is implements on the top of structure and the optimum parameters of it were optimized by using HS approach for impulsive motions. The optimum TMD parameters (m_{TMD}= TMD mass, T_{TMD}= TMD period, ξ_{TMD}= TMD damping ratio) and reduction can be seen in Table 3.

For the cases conducted under the effect of two types of impulsive motions, the reduction percentage of peak first storey displacements are between 27% and 39%. Under the effect of directivity pulse, these reductions are lower than other excitation cases (36%-46%). In Figure 2, the time history plots of first storey displacements comparing the response of uncontrolled structure and TMD controlled structure optimized under the effect of two types of impulsive motions can be seen for the case with 20% maximum TMD damping ratio.

T_{st} (s)	Excitation	max(ξ_{TMD})	μ	T_{TMD} (s)	ξ_{TMD}	DR	$TF_{w\ cont}$	$TF_{w/o\ cont}$
1.5	DP+FS	20	0.0492	1.7884	0.1644	0.8798	4.5816	10.0125
		30	0.0498	1.5992	0.2092	0.8685	4.7186	
		40	0.0491	1.7890	0.2003	0.8521	4.8743	
	DP	20	0.0499	1.5826	0.1882	0.8314	4.4772	
		30	0.0498	1.5873	0.2135	0.8081	4.7433	
		40	0.0492	1.5768	0.2168	0.8071	4.7971	
	FS	20	0.0493	1.7856	0.1883	0.8608	4.7567	
		30	0.0499	1.6388	0.2228	0.8457	4.9467	
		40	0.0500	1.7864	0.2969	0.7870	5.5450	
2	DP+FS	20	0.0492	2.0768	0.1829	0.8391	4.4085	9.5578
		30	0.0500	2.0790	0.1893	0.8334	4.4453	
		40	0.0498	2.0823	0.2013	0.8237	4.5999	
	DP	20	0.0498	2.0791	0.1827	0.8390	4.3720	
		30	0.0495	2.1009	0.1866	0.8366	4.4531	
		40	0.0486	2.0756	0.1869	0.8361	4.4820	
	FS	20	0.0496	2.0767	0.1795	0.8307	4.3501	
		30	0.0498	2.1194	0.2075	0.7965	4.6802	
		40	0.0498	2.1356	0.2262	0.7773	4.8711	
2.5	DP+FS	20	0.0487	2.5923	0.1660	0.8746	4.2435	9.8919
		30	0.0499	2.6034	0.1699	0.8712	4.2323	
		40	0.0494	2.5900	0.1752	0.8671	4.3250	
	DP	20	0.0495	2.6003	0.1710	0.8705	4.2514	
		30	0.0487	2.6019	0.1793	0.8648	4.3618	
		40	0.0492	2.6021	0.1824	0.8623	4.3814	
	FS	20	0.0494	2.6079	0.1666	0.8167	4.2395	
		30	0.0500	2.6792	0.2270	0.7538	4.8942	
		40	0.0497	2.6594	0.3579	0.6436	5.9666	

Table 1: SDOF structures – Optimum results.

Storey	1	2	3	4	5	6	7	8	9	10
m (t)	179	170	161	152	143	134	125	116	107	98
k (MN/m)	62.47	52.26	56.14	53.14	49.91	46.91	43.67	40.55	37.43	34.31
c (kNs/m)	805.9	674.2	724.2	684	643.8	603.6	563.6	523.1	482.8	442.6

Table 2: 10-storey structure – Properties [11].

Excitation	max(ξ_{TMD})	m_{TMD}	T_{TMD} (s)	ξ_{TMD}	DR	$TF_{w\ cont}$	$TF_{w/o\ cont}$
DP+FS	20	67620	2.2624	0.1951	0.7265	0.5542	4.2685
	30	67886	2.2889	0.2938	0.6578	0.7445	
	40	68718	2.3067	0.3827	0.6053	0.8876	
DP	20	67263	2.1930	0.1933	0.6370	0.5707	
	30	68065	2.1009	0.2887	0.5763	0.7634	
	40	68363	2.1566	0.3684	0.5374	0.8790	
FS	20	68779	2.3011	0.1997	0.7228	0.5702	
	30	67530	2.2065	0.2960	0.6572	0.7393	
	40	69145	2.2479	0.3967	0.5957	0.9008	

Table 3: 10-storey structure – Optimum results.

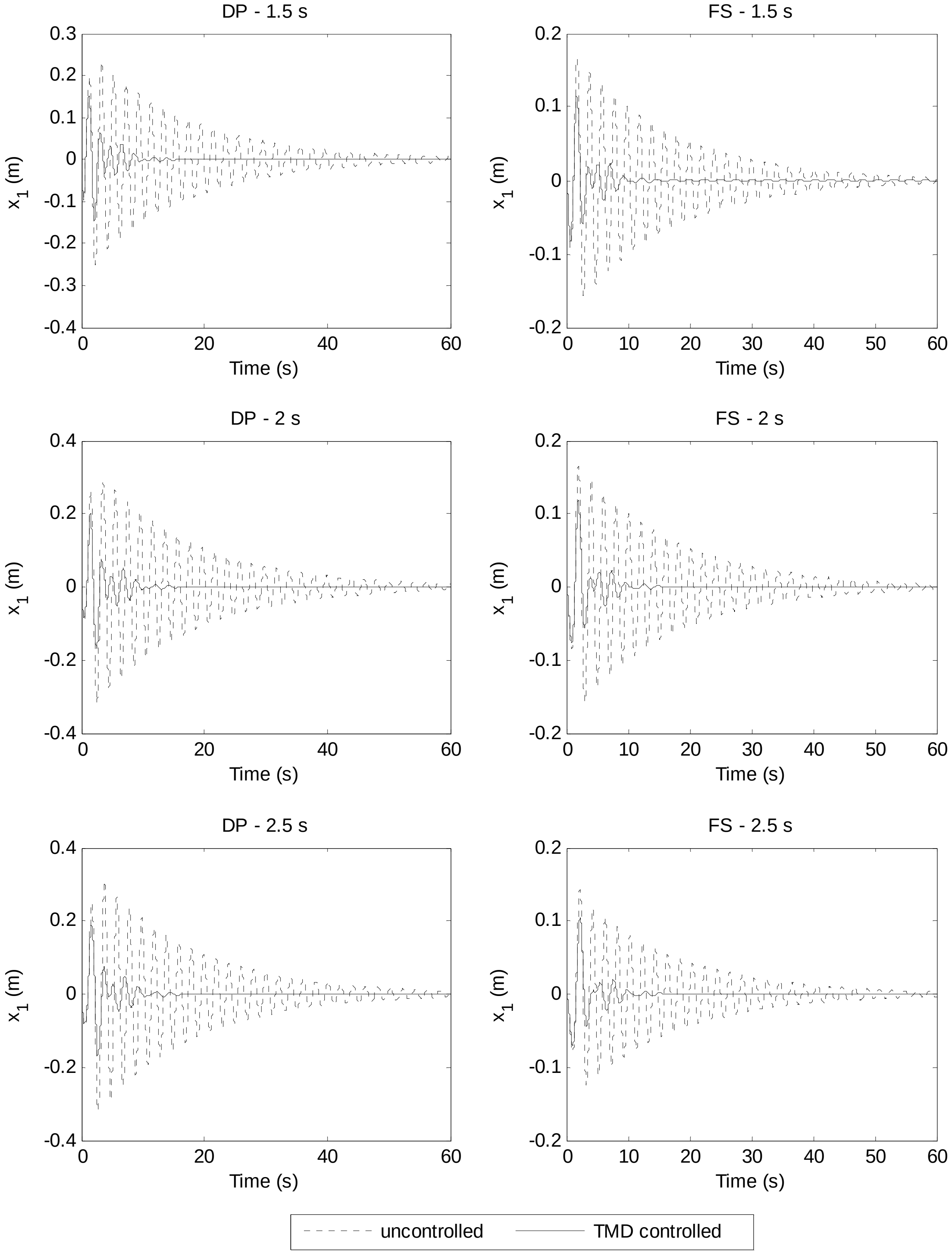

Figure 2: Time-history plots of first storey displacements for the case DP+FS with 20% maximum TMD damping ratio.

The approach is effective on reducing the peak displacements and also, the real benefit of TMD can be seen on obtaining a rapid steady state response. The most critical excitation effective on optimization is the flint step with 2 s period for the case given in Figure 2.

5 CONCLUSIONS

In structural control system used in seismic protection of the structure, the increase of the damping is generally effective on the reduction of structural displacements but it can negatively affect the acceleration of the structure. In this study, a multi objective approach is applied for the elimination of the worst results. Thus, a balance between the reduction of the first storey displacement and acceleration transfer function were found. By using this option, the unnecessary increase of the damping ratio is prevented and optimum solutions were obtained. The approach is effective on reduction of seismic responses under impulsive motions. Since the transfer function values are considered during the optimization, the optimum TMD parameters can sustain its robustness under different types of excitations.

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