

SHOCK ABSORBER PERFORMANCE PREDICTION FOR A LARGE TUNED-MASS DAMPER APPLICATION

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EXECUTIVE SUMMARY

The predicted motion of the two tuned-mass dampers (TMDs) in a large flexible structure under worst-case storm conditions exceeds the available sway space. The TMD design agent has proposed Enidine PMXT 2100 shock absorbers to restrict the motion of the TMDs within safe limits. Dynamics analyses with a functionally-representative model of the shock absorber derived from published performance specifications indicate that the shock absorbers will successfully limit the motion of the TMDs and operate within the published energy dissipation limits. A Monte Carlo probabilistic analysis shows that the shock absorbers may experience about 96 impacts per year with an average impact velocity of 200 mm/sec. Finally, the shock absorbers will reduce the effectiveness of the base shear force mitigation provided by the TMDs from about 38% to 19%.

Two 32-ton tuned-mass dampers (TMDs) are to be integrated in a large flexible structure to provide structural load mitigation and a more comfortable environment for the occupants. Structural dynamics analyses of the wind-induced motion for extreme storm conditions show that the TMDs sway back and forth with a maximum relative displacement amplitude of 950 mm; however, only 370 mm is available where the TMDs will be installed. The TMD design agent has proposed that positive-stop shock absorbers, Enidine Model PMXT 2100, be integrated into the space to control TMD motions within the limits. Two of these shock absorbers are responsible for bringing the 32-ton (32,000 kg) moving mass to a stop before contacting structural members in the host structure. The critical energy absorption and stroke properties for the PMXT 2100 are documented in the Enidine catalog and repeated here as Figure 1.

Catalog No./ Model	(S) Stroke in. (mm)	(E _T) Max. in.-lbs./cycle (Nm/cycle)	(E _T C) Max. in.-lbs./hour (Nm/h)	(F _P) Max. Reaction Force lbs. (N)	Nominal Coil Spring Force		(F _D) Max. Propelling Force lbs. (N)	Weight (mass) lbs. (Kg)
					Extended lbs. (N)	Compressed lbs. (N)		
PMXT 1525	1.00 (25,0)	3,250 (367,0)	1,120,000 (126 000)	6,500 (29 000)	11.0 (48,0)	15.0 (68,0)	1,500 (6 700)	2.2 (1,0)
PMXT 1550	2.00 (50,0)	6,500 (735,0)	1,475,000 (167 000)	6,500 (29 000)	11.0 (29,0)	18.0 (78,0)	1,500 (6 700)	2.4 (1,1)
PMXT 1575	3.00 (75,0)	10,000 (1 130,0)	1,775,000 (201 000)	6,500 (29 000)	7.0 (31,0)	18.0 (78,0)	1,500 (6 700)	2.7 (1,3)
PMXT 2050	2.00 (50,0)	16,500 (1 865,0)	2,400,000 (271 000)	13,750 (60 500)	17.0 (80,0)	35.0 (155,0)	4,000 (17 800)	6.0 (2,7)
PMXT 2100	4.00 (100,0)	33,000 (3 729,0)	3,200,000 (362 000)	13,750 (60 500)	16.0 (69,0)	36.0 (160,0)	4,000 (17 800)	7.3 (3,3)
PMXT 2150	6.00 (150,0)	50,000 (5 650,0)	3,730,000 (421 000)	13,750 (60 500)	20.0 (87,0)	64.0 (285,0)	4,000 (17 800)	9.3 (4,2)

Figure 1 Shock Absorber PMXT 2100 Characteristics from the Enidine Catalog

The PMXT 2100 has a useful stroke of 100 mm, an energy absorption capacity of 3,729 N·m/cycle, and a maximum energy dissipation of 362,000 N·m/hour. The Engineer of Record should assume that a maximum impact force of 60.5 kN will be transmitted through each shock absorber to the supporting structure. Additional structural dynamics simulations are performed to verify that the shock absorbers will operate within their specification limits and to determine impact conditions for a worst-case storm event and for an average year of service.

A three-degree-of-freedom (3-DOF) model of the primary structural sway mode (determined from a high-fidelity structural dynamics model) and the two TMDs is used to study the system dynamics as the TMD impacts the shock absorbers. A simplified nonlinear computational model of the shock absorber is created based on the properties shown in Figure 1 and inserted into the dynamics model so that the repeated and variable impact history is properly included. The approximated force versus stroke performance of the shock absorber model (not the true PMXT 2100 device) is shown in Figure 2. The model absorbs the prescribed maximum energy within the permitted stroke of 100 mm and generates a maximum force only slightly higher than that quoted for the PMXT 2100. The actual PMXT 2100 performance curve will differ from this model; however, the critical comparison is the energy absorbed over the prescribed stroke and the maximum force generated and, by these metrics, the simplified model adopted here functions very similar to the proposed shock absorber.

A dynamics simulation is performed for the worst-case storm event (3-second gust wind speed of 43.8 m/sec) using a wind force time history generated by Cermak, Peterka, Petersen Wind Engineering and Air Quality Consultants (CPP). The TMDs are permitted to sway back and forth within ±270 mm before they contact the shock absorbers. The shock absorbers will permit another 100 mm of travel before bringing the mass to a relative

stop with the maximum sway space limit of 370 mm. The predicted relative motion of the TMD mass for an hour-long storm event is plotted in the upper plot in Figure 3 and the impact force time-history is provided in the lower plot. The proposed shock absorbers successfully control the maximum motion of the TMDs within the available sway space and generate peak impact forces less than 50 kN.

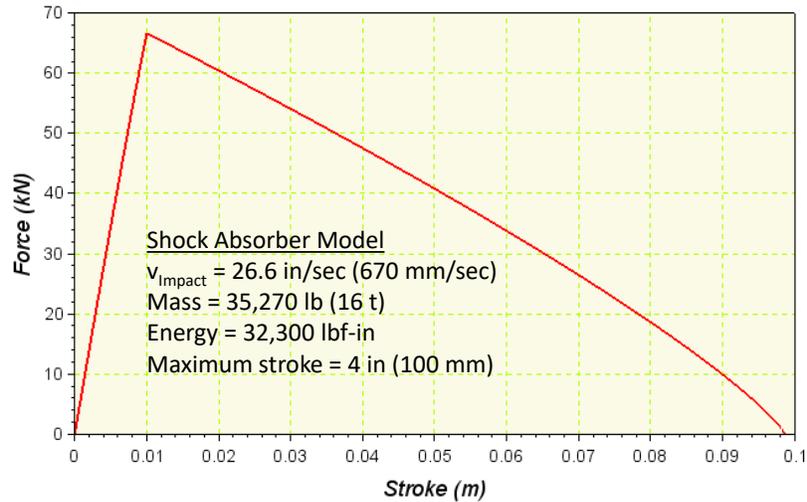


Figure 2 Shock Absorber Model Performance Curve

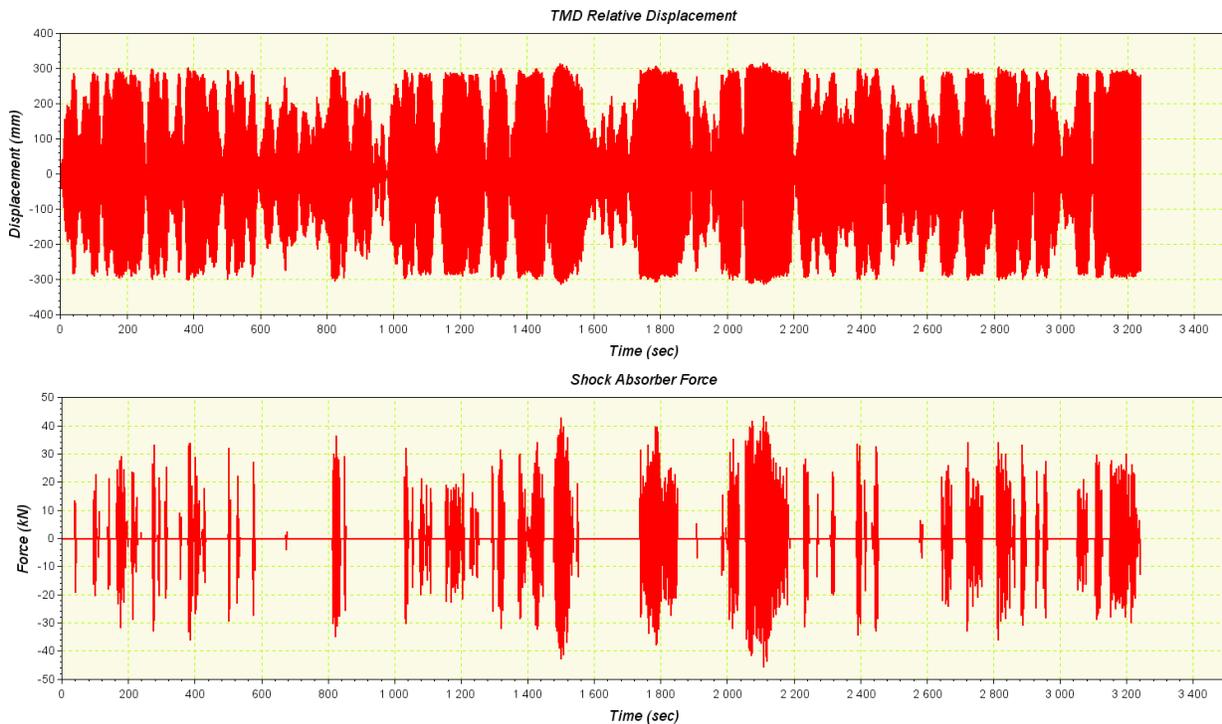


Figure 3 Relative TMD Displacement (Above) and Shock Absorber Impact History (Below)

Each shock absorber is exposed to about 370 discrete impacts during the 1-hour period with a minimum time between successive impacts of 3.2 seconds. The impact velocity for each impact varies based on the dynamics of the system as shown in Figure 4 where each impact is identified with its impact velocity and maximum impact force, as shown in the left-hand-side of the figure. A histogram of the impact velocities is provided in the right-hand-side of the figure. The majority of the impacts fall within the 200 mm/sec to 300 mm/sec range. There is only one impact between 450 mm/sec and 500 mm/sec. The total energy absorbed over the hour-long worst-case storm is 185,400 N·m, which is within the PMXT 2100 limit of 362,000 N·m/Hr. The shock absorber selected by TES successfully constrains the motion of the TMD mass within the available sway space and operates within the performance specifications defined by Enidine for the PMXT 2100.

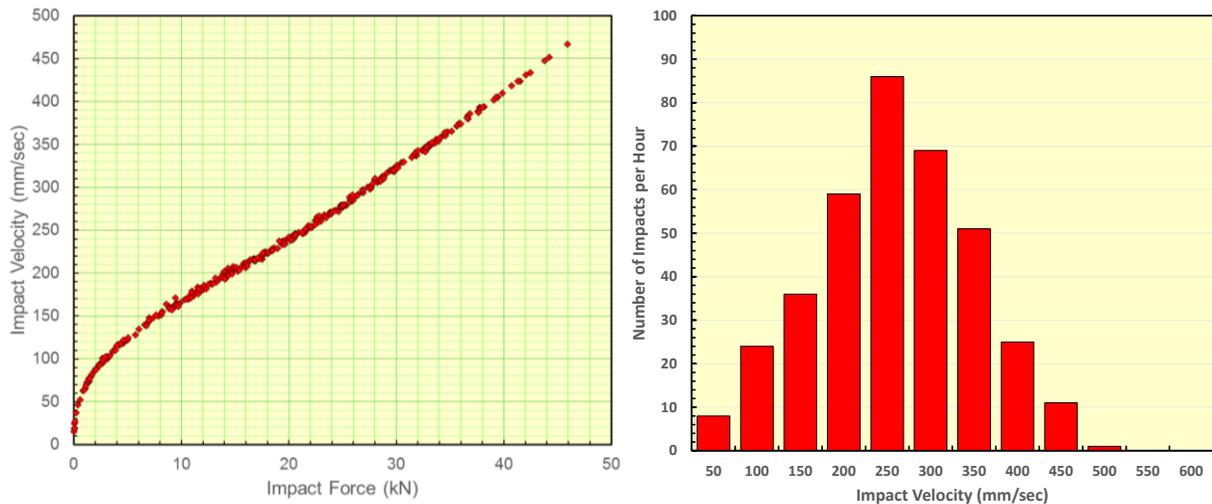


Figure 4 Storm-Level Impact Conditions (Left) and Impact Velocity Histogram (Right)

The worst-case storm event is exceedingly rare so the impact conditions shown in Figure 4 are an extreme case that may not happen within the operating lifetime of the structure. A statistically representative impact analysis is needed to assess the expected lifetime and possible maintenance/inspection requirements of the shock absorbers based on the expected impact events. A Gumbel Type 1 correlation model for the 3-second gust wind speed as a function return period, T , in years is provided by CPP. The Gumbel cumulative probability distribution function and parameters are given by:

$$P = 1 - \frac{1}{T \cdot 365} = e^{-e^{-\left(\frac{V-\mu}{\sigma}\right)}} \quad \mu = 8.913 \frac{\text{m}}{\text{sec}} \quad \sigma = 2.96 \frac{\text{m}}{\text{sec}} \quad (1)$$

where P is the probability of not exceeding the 3-second gust wind speed, V , with an annual return period, T , on any given day. The Gumbel distribution parameters, μ and σ , are selected to achieve the best agreement with the wind speed correlation curve generated by CPP for the specific site in question.

A Monte Carlo analysis is performed to determine the average number of impacts expected during a “typical” year. A set of 365 uniformly-distributed random numbers are selected between 0 and 1 and used to obtain the 3-second gust wind speed for each of those 365 days. The dynamics model indicates that the TMDs do not contact the shock absorbers for wind speeds lower than about 24 m/sec, so any day for which the selected wind speed is less than 24 m/sec can be ignored. For the remaining days when impacts are expected, the impact velocity histogram is obtained from interpolation within a “library” of histograms developed from impact simulations

performed with different 3-second gust wind speeds. This single-year simulation is repeated tens of thousands of times to obtain the impact velocity histogram shown in Figure 5 for an “average” year assuming that the wind condition persists for 3 hours during that day. The assumption of a 3-hour high wind period is purely arbitrary and the results shown in Figure 5 may be scaled accordingly for a different assumed duration. Under this assumption, one can expect that each shock absorber will see about 96 impact events per year with an average impact velocity of 200 mm/sec.

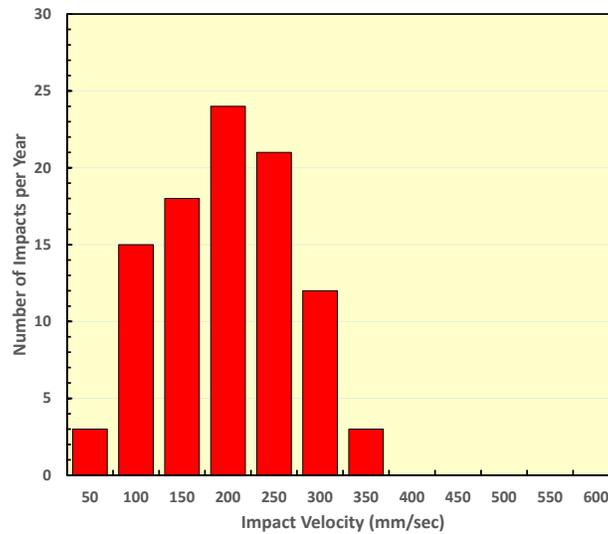


Figure 5 Expected Average Annual Shock Absorber Impact History

The computed average annual impact history is much less severe than the worst-case impact velocity histogram shown in Figure 4. There will be years when the number of impacts will be higher, but there will also be years when fewer impacts occur. Maintenance and serviceability of the shock absorbers may be assessed based on the impact history shown in Figure 5. Special inspections of the hardware may be required on a case-by-case basis following particularly severe storms.

The reduced sway space and introduction of the shock absorbers will adversely affect the structural load mitigation provided by the TMDs because the TMDs will not be able to freely sway as the motion of the host structure dictates. The base shear for three configurations: (a) the structure with no TMDs, (b) the structure with TMDs and the shock absorbers, and (c) the structure with the TMDs and full sway space capability are summarized in Table 1. If the TMDs were allowed to move freely within the full sway space, they would reduce the base shear by about 38%. The limited sway space and the action of the shock absorbers effectively cuts the mitigation in half to 19%.

Table 1 Summary of Base Shear Force for Different Configurations

Configuration	Base Shear	Mitigation
No TMDs	6474 kN	—
TMDs with Shock Absorber	5269 kN	19%
TMDs with Full Sway	4030 kN	38%