VALMONT MITIGATOR™ TR1

RESEARCH VERIFICATION OF THE VALMONT TR1 DAMPER PERFORMANCE

MITIGATOR TR1 VIBRATION DAMPER

The Valmont TR1 damper has been specifically designed using vibration theory and innovative patented and patented damping technologies to effectively reduce the daily vibration stress range from wind excitation thus increasing the fatigue life of the structure. The TR1 damper reduces vertical arm displacement normally above 90% caused by wind, wind induced vibration (galloping and vortex shedding), and truck gusts, as designed per AASHTO "Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals" Section 11 Fatigue Design. Use of this device will result in a more economical design, improve safety to the traveling public, extend the life of new and existing structures, and lower maintenance, inspection and repair cost resulting in more efficient cantilevered and non-cantilevered overhead traffic signal and sign support structures. ***Figure 1*** shows the Mitigator TR1 Damper attached to the end of the mast arm of a traffic signal pole structure.

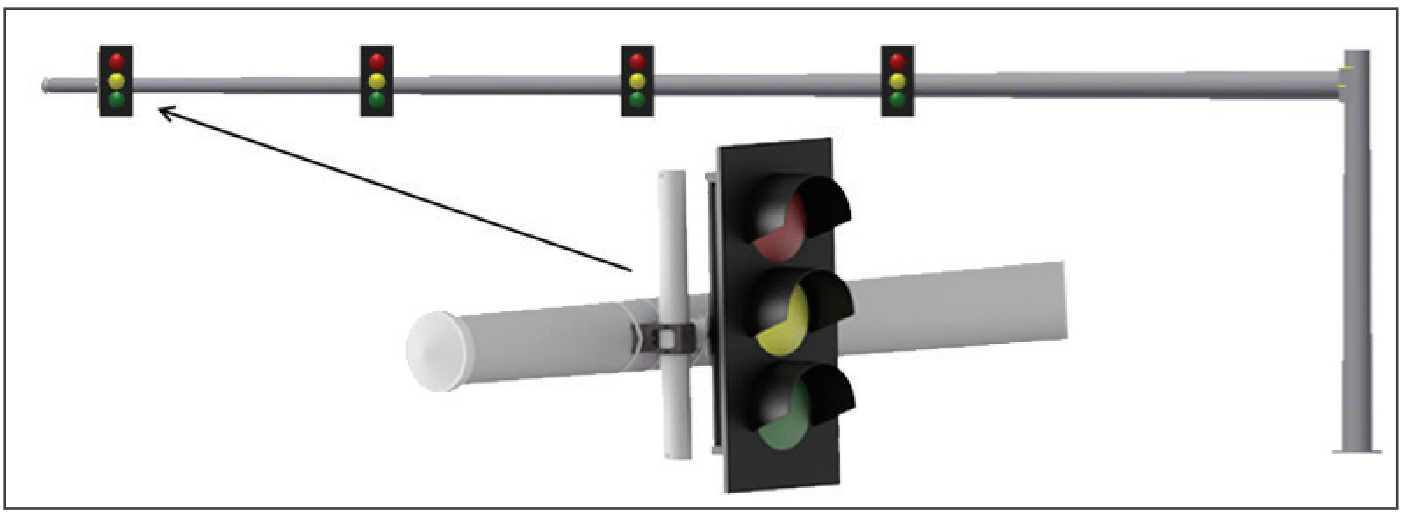


Figure 1. The Valmont Mitigator TR1 Vibration Damper is a proven, effective vibration mitigation device that is compact, self-contained and easy to install on new or existing mast arms, sign structures, or other pole structures.

TRAFFIC VIBRATION ISSUES

Traffic, sign, and lighting structures are typically characterized by their high flexibility and extremely low damping which make them particularly susceptible to wind-induced vibration. Various types of wind loading, including galloping, vortex shedding, natural wind gusts, and truck-induced gusts, can result in vibration of these structures. Low natural frequencies of these structures, typically ranging from 0.6 – 2.0 Hz, overlap with the excitation frequency of winds, as primary wind gusts range from 0.6 to 1.6 Hz, which can result in the vibration phenomenon called resonance. The large amplitude and cyclical response from the various wind-induced vibration results in repeated live load stress variations which can significantly reduce the fatigue life of these structures. Reducing the effective stress range (the difference between the maximum and minimum stress in a cycle) by minimizing the amplitude of the vibration, can significantly increase the fatigue life of that structure.

VIBRATION SOLUTIONS

There are two approaches to reduce vibrations: reduce the exciting load on the structure or modify the dynamic properties of the structure. Reducing the excitation on the structure has primarily focused on modifying the aerodynamic properties of attachments to the structure (i.e., the mast arm). This approach, while effective, may limit performance to one type of wind excitation. For example, airfoil approach, whereby a sign blank is mounted horizontally near the tip of the mast arm to serve as an aerodynamic damper, can potentially provide an effective energy dissipating mechanism for galloping but may not provide any vibration-mitigation benefit for truck-induced gusts. To complicate the airfoil solution further, ongoing research is not consistent on the actual cause of excessive vibration and may actually be some combination of wind loading. Also, there is no known way to quantify the reduction of stresses using the airfoil design. There have been observed cases of galloping traffic signal mast arms with an installed sign blank airfoil in which the airfoil was deemed to be non-effective.

A second approach, changing the mass, stiffness or damping of the structure may be considered. At the design stage, signal-support vibration is commonly addressed by increasing the stiffness and strength of the structure. This results in larger poles and mast arms as well as heavy duty connection details. An alternative is the application of dampers to effectively modify the dynamic characteristics of the structure without increasing the structure's size.

AASHTO

The 2013 and 2015 AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals requires that cantilevered and non-cantilevered support structures shall be designed for infinite fatigue life to resist wind-load-induced stresses.

Fatigue Categories:
In general, fatigue categories are chosen based on the associated risk factors related to public safety as it applies to the location of the structure. Risk factors include:

- The volume of traffic on the roadway
- The posted speed limits
- Mast arm length or structure height
- Know problematic wind areas

AASHTO defines 3 Fatigue Categories; Fatigue Category I, Category II and Category III, where Category I is the most stringent and Category III the least stringent. To point out the contrast between the 3 different Fatigue Categories; Category II would be 65% of Category I and Category III would be 30% of Category I, for the fatigue galloping loads of a cantilevered traffic signal mast arm structure.

To choose the appropriate Fatigue Category, AASHTO recommends the following guidelines:

- **Fatigue Category I: Most Stringent**
    - AASHTO **Recommends** that all Structures without effective mitigation devices on roadways with a speed limit in excess of 35 mph and ADT exceeding 10,000, or ADTT exceeding 1,000 be designed to Fatigue Category I.
    - Cantilevered sign structures without mitigation devices with a span in excess of 50 feet be designed to Fatigue Category I.
    - Large sign structures, both cantilevered and non-cantilevered, including variable message signs, without mitigation devices be designed to Fatigue Category I.
    - Structures without mitigation devices located in an area that is known to have wind conditions that are conducive to vibrations be designed to Fatigue Category I.
    - Structures classified as Category I should be designed to resist rarely occurring wind loading and vibration phenomena.

AASHTO - CONTINUED

- **Fatigue Category III: Least Stringent**
  - Structures located on roads with speed limits of 35 mph or less.
  - Structures that are located such that a failure will not affect traffic.
- **Fatigue Category II:**
  - All structures not explicitly meeting the Category I or Category III criteria.

Fatigue Design Loads:
Cantilevered and non-cantilevered traffic and sign structures are exposed to several wind phenomena that can produce large cyclic loads. AASHTO identifies galloping, natural wind gusts, and truck-induced gusts as the three main wind conditions that can generate large-amplitude vibration which can cause fatigue failures.

- Galloping – In-plane vibration normal to the direction of wind flow caused by wind striking the attachments such as signs and traffic signals. Galloping usually generates the highest cyclic loads and thus controls the fatigue design. AASHTO recommends that structures classified as Fatigue Category I should be designed to resist galloping fatigue loads. Galloping loads do not need to be included in the fatigue design when an owner approved effective mitigation device is installed at the time of installation. As an option for traffic signal structures, the Owner may choose to install an effective mitigation device as quickly as possible after the galloping problem appears.
- Natural Wind Gust – Out-of-plan vibration in the direction of wind flow caused by the inherent variability in velocity and direction. AASHTO requires that all traffic and sign structures be design to resist the prescribed Natural Wind Gust criteria.
- Truck Induced Gust – In-plane vibration caused by wind gusts from the passage of trucks beneath the support structures. AASHTO requires that all sign structures be designed to include Truck Induced Gust Fatigue loading. AASHTO states that for all traffic signal structures, truck-induced gust loading shall be excluded unless required by the Owner. Since the vibration of both Truck Induced Gust and Galloping are in the same in-plane direction, an effective mitigation device that dampens Galloping will also dampen Truck Induced Gusts.

Applying the AASHTO fatigue loading criteria to traffic signal and sign support structures in conjunction with an effective mitigation device, will result in a more efficient design that reduces the cost of new structures, improve safety to the traveling public, extend the life of new and existing structures, and lower maintenance, inspection and repair cost.

WHAT IS THE TR1?

The Valmont Mitigator TR1 Vibration Damper, shown in ***Figure 2***, is a self-contained vertical damper unit weighing 35 lbs., which is housed within a 4.5" diameter aluminum tube 43" in length. A steel mass is suspended in the tube with a stainless-steel extension spring. Magnets located on the moving mass create a magnetic field passing through the aluminum tube that creates eddy-current damping in the unit especially effective at low-amplitude motion. Specifically designed bearings on the mass provide proper pneumatic damping more effective at larger amplitudes. The patented design ensures effective mitigation for a broad range of poles and amplitudes of vibration, quiet operation, and a compact and fully sealed housing.

WHAT IS THE TR1? - CONTINUED

The TR1 damper has been tested to over seventeen million cycles with no observable degradation in the unit or the performance of the damper. The Valmont Mitigator TR1 Vibration Damper is attached to the mast arm using specially designed mounting hardware near the tip of the mast arm. Because of the patented design, the unit is more robust and less likely to being mistuned. Therefore, the unit will work properly even if installed with some misalignment.

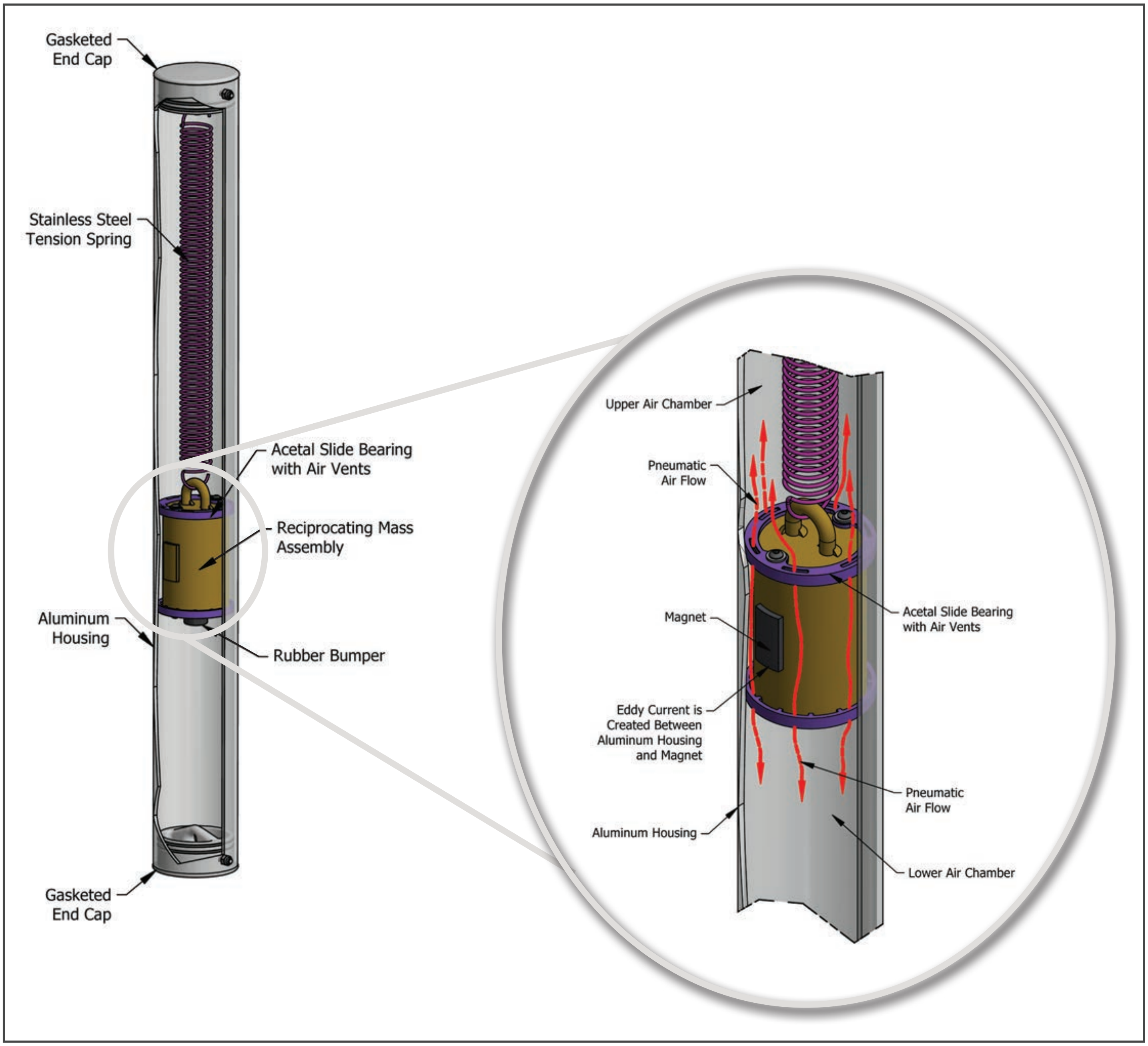


Figure 2. The Mitigator TR1 Vibration Damper has both eddy-current damping and pneumatic damping resulting in a 90% reduction of mast arm movement in most situations.

GETTING TECHNICAL

The Valmont Mitigator line of dampers has been specifically designed using the theory of structural dynamics. The fundamental natural frequency in Hertz (cycles per second), given as f_n, can be estimated for a pole structure by determining the mass and stiffness of the traffic-signal support structure. The mass can be determined as:

$$m = \int_0^L \bar{m}(x)\phi(x)\phi(x)dx + \sum_{i=1}^{n} M_i\phi(L_i)$$

Where the mass per unit length is given as: $\bar{m}(x) = \rho A(x)$, where ρ is the mass density (mass per unit volume) and A is the cross-sectional area which is given as: $A(x) = \pi/4\ (D_o^2(x) - D_i^2(x))$, where D_o and D_i are the outer and inner diameters of the pole and mast arm, as functions of length, and where M_i is the mass of the nth discrete signal or sign location at length L_i from the base, and where $\phi(L_i)$ is a shape function of the assumed deflected shape, where an effective shape has been proven here to be:

$$\phi(x) = [\sin\beta L - \sinh\beta L]\left[\sin\frac{\beta L}{L}x - \sinh\frac{\beta L}{L}x\right] - [\cos\beta L - \cosh\beta L]\left[\cos\frac{\beta L}{L}x - \cosh\frac{\beta L}{L}x\right]$$

Where $\beta L = 1.8751$, for the first mode behavior. The stiffness can be determined as:

$$k = \int_0^L EI(x)\phi''(\mathrm{x})\phi''(x)dx$$

Where the E is the modulus of elasticity, I is the moment of inertia calculated as:

$$I(x) = \frac{\pi}{4}\left[\left(\frac{D_O(x)}{2}\right)^4 - \left(\frac{D_i(x)}{2}\right)^4\right]$$

and ϕ is the second derivative of the shape function, $\phi(L_i)$, with respect to length x. The natural frequency is then determined as:

$$\omega_n = \sqrt{k/m}$$

$$f_n = \omega_n/2\pi$$

Frequency and mass are now used to uniquely characterize each pole structure. As mass can be an awkward term, the more familiar term weight was chosen for use in this process. The dynamic weight W_d is defined as $W_d = mg$ where g is gravity, 32.2 ft/sec^2 or 386.4 in/sec^2.

The analytical calculation of the dynamic properties of traffic mast arms has been shown to be quite accurate, less than 5% error for the mast arms examined. For example, a 50' slender mast arm tested in the laboratory was experimentally determined to have a frequency of 0.70 0.69 Hz and dynamic weight is 198 265 lbs. The calculated frequency is 0.73 Hz and dynamic weight is 189 250 lbs. A larger sized 50' mast arm experimentally determined to have a frequency of 0.90 0.99 Hz and dynamic weight is 318 396 lbs has a calculated frequency of 0.921.04 Hz and dynamic weight of 320 334 lbs.

The performance of the Valmont Mitigator TR1 Damper is then determined using a validated analytical model of the TR1 Damper obtained from dynamic System Identification and over one thousand nonlinear dynamic time series simulations. The accuracy of the simulations have been validated with full-scale laboratory tests. The calculated performance is provided in tables used by Valmont engineers to insure effective vibration mitigation devices are being installed onto your pole structures.

LABORATORY TESTING

The Mitigator TR-1 damper is subjected to over 17 million cycles at large amplitude. The damper was inspected and no damage to the damper was identified.

Laboratory tests were conducted on two different 50' mast arms, one slender and one large, each with two different dynamic masses to validate performance and predictions. The results, shown in ***Figure 3***, illustrate the ability to accurately predict the performance of the Valmont Mitigator TR1 Damper for the four conditions tested. The results for the 50' large mast arm are presented in ***Figure 4***.

CALCULATED DAMPING RESPONSE REDUCTION – ONE DAMPER

50’ slender mast arm
Calculated 0.99 Hz, Tested 0.95 Hz Frequency
Calculated 136 lbs, Tested 144 lbs Dynamic Mass
Calculated 7.2%, Tested 9.5% damping
99% Calculated vs. 99% tested reductio

50’ large mast arm
Calculated 1.28 Hz, Tested 1.20 Hz Frequency
Calculated 219 lbs, Tested 271 lbs Dynamic Mass
Calculated 2.3%, Tested 2.7% damping
97% Calculated vs. 97% tested reduction

One Damper - Damping Response Reduction from + - 12" (%)
(0.08% Assumed Inherent Damping)

	Fundamental Frequency (Hz)										
Dynamic Weight (lbs.)	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60
100	96.7%	98.3%	99.0%	99.4%	99.2%	98.9%	98.6%	98.2%	97.9%	97.6%	97.3%
120	96.5%	98.2%	99.0%	99.4%	99.0%	98.7%	98.3%	97.9%	97.6%	97.2%	96.9%
140	96.3%	98.2%	99.0%	99.3%	98.9%	98.5%	98.0%	97.6%	97.2%	96.8%	96.4%
160	96.1%	98.1%	99.0%	99.2%	98.7%	98.3%	97.8%	97.3%	96.9%	96.4%	96.0%
180	95.9%	98.0%	99.0%	99.1%	98.6%	98.1%	97.6%	97.0%	96.5%	96.0%	95.6%
200	95.7%	97.9%	98.9%	99.0%	98.5%	97.9%	97.3%	96.7%	96.2%	95.7%	95.2%
220	95.5%	97.8%	98.9%	98.9%	98.3%	97.7%	97.1%	96.5%	95.9%	95.3%	94.8%
240	95.3%	97.7%	98.8%	98.8%	98.2%	97.5%	96.9%	96.2%	95.6%	95.0%	94.5%
260	95.1%	97.7%	98.8%	98.7%	98.1%	97.3%	96.6%	95.9%	95.3%	94.7%	94.1%
280	94.9%	97.6%	98.7%	98.6%	97.9%	97.2%	96.4%	95.7%	95.0%	94.3%	93.8%
300	94.7%	97.5%	98.7%	98.5%	97.8%	97.0%	96.2%	95.4%	94.7%	94.0%	93.4%
320	94.5%	97.4%	98.6%	98.4%	97.7%	96.8%	96.0%	95.2%	94.4%	93.7%	93.1%
340	94.3%	97.3%	98.6%	98.3%	97.5%	96.6%	95.8%	94.9%	94.1%	93.4%	92.8%
360	94.1%	97.2%	98.5%	98.2%	97.4%	96.5%	95.6%	94.7%	93.9%	93.1%	92.5%
380	93.9%	97.1%	98.4%	98.1%	97.3%	96.3%	95.4%	94.5%	93.6%	92.9%	92.2%
400	93.7%	97.0%	98.3%	98.0%	97.1%	96.1%	95.2%	94.2%	93.4%	92.6%	91.9%
420	93.5%	96.9%	98.2%	97.9%	97.0%	96.0%	95.0%	94.0%	93.1%	92.3%	91.6%
440	93.4%	96.8%	98.2%	97.8%	96.9%	95.8%	94.8%	93.8%	92.9%	92.1%	91.3%
460	93.2%	96.7%	98.1%	97.7%	96.8%	95.7%	94.6%	93.6%	92.6%	91.8%	91.1%
480	93.0%	96.6%	98.0%	97.6%	96.6%	95.5%	94.4%	93.4%	92.4%	91.6%	90.8%
500	92.8%	96.5%	97.9%	97.6%	96.5%	95.3%	94.2%	93.1%	92.2%	91.3%	90.5%

50’ slender mast arm with added mass
Calculated 0.73 Hz, Tested 0.69 Hz Frequency
Calculated 250 lbs, Tested 265 lbs Dynamic Mass
Calculated 3.6%, Tested 2.5% damping
98% Calculated vs. 97% tested reduction

50’ large mast arm with added mass
Calculated 1.04 Hz, Tested 0.99 Hz Frequency
Calculated 334 lbs, Tested 396 lbs Dynamic Mass
Calculated 3.2%, Tested 3.2% damping
97% Calculated vs. 97% tested reduction

Figure 3. Table of predicted damping as compared to three laboratory tests of measured damping.

TESTING AT UCONN – *TEST SETUP (50' LG ARM W/125 lbs. MASS - 0.99 Hz)*

EXPERIMENTALLY MEASURED

- Natural frequency is 0.99 Hz.
- Dynamic Mass is 396 lbs.
- This mast arm has a large dynamic mass

Measured Test Data (50' Lg Arm w/125 lbs. Mass - 0.99 Hz)
Free vibration shows increase in damping from 0.07% to 3.2% (98% theoretical response reduction)

- Forced vibration shows 97% (acceleration) and 96% (strain) measured response reduction

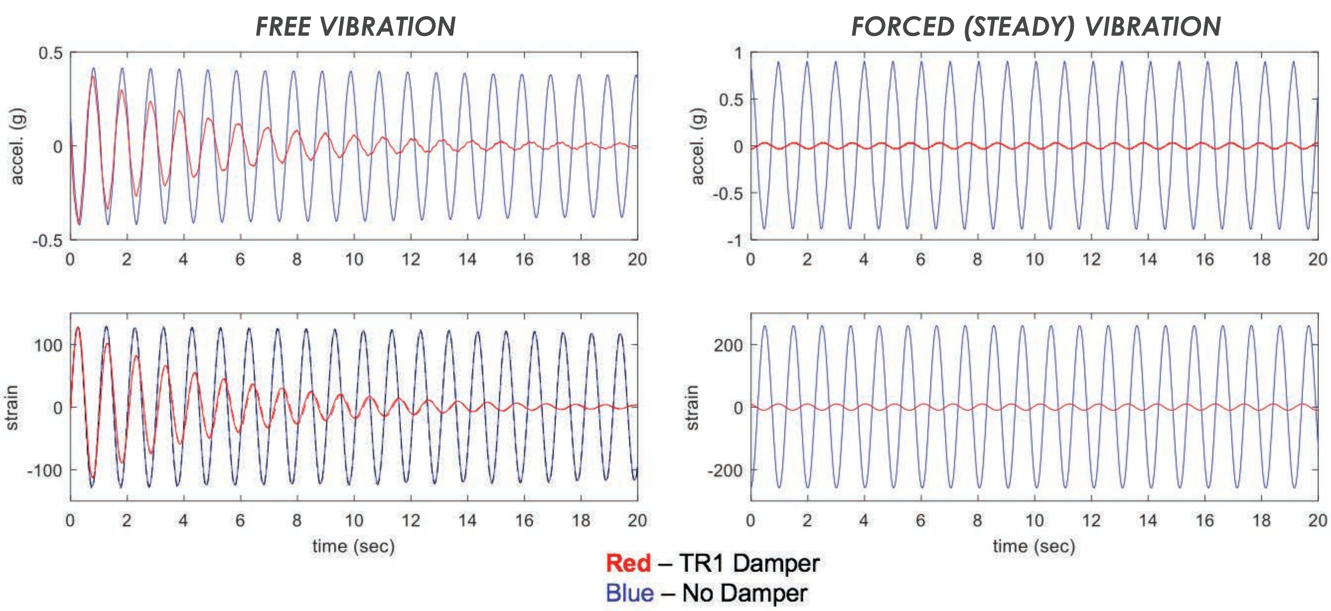


Figure 4. Free vibration (pluck) and forced (eccentric mass) tests of a 50' large mast arm showing increased damping of the system from 0.07% for the undamped mast arm to 3.2% damping for the mast arm with the Valmont Mitigator TR1 Damper, corresponding to 98% response reduction.

FIELD TESTING

Field testing of the Valmont TR1 Mitigator vibration damper has been done at various locations throughout the country in conjunction with the corresponding DOT. In ***Figure 5*** shows a picture of each location, Omaha, NE, Erda Utah, and Seattle, WA. The results from the field testing at all locations showed comparative results as the Laboratory testing, validating the theory. At the Utah location, 7 poles at 2 separate intersections were retrofitted with the TR1 Damper. Attached to each mast arm were strain gauges to measure the stress range during the test. Test results for four poles at the intersection of SR-36 and Bates Canyon Road in Erda, Utah is presented in ***Figure 6***, showing a vibration response reduction from 86% (P4 - 75' arm) to 92% (P1 – 45' arm).

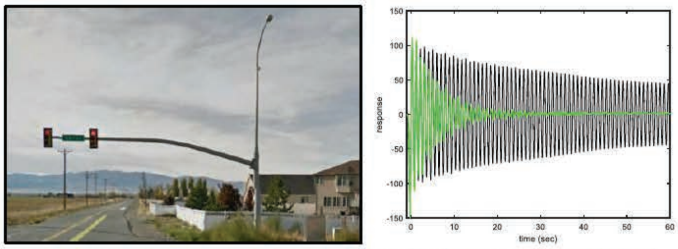
City of Omaha, NE - 06/18/2016

City of Seattle, WA - 11/09/2016

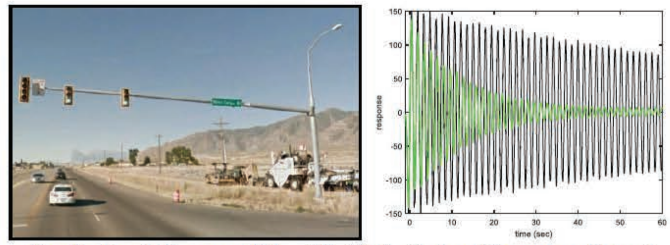
State of Utah - 08/03/2016

Figure 5. Free vibration (pluck) where preformed at three different locations including the City of Omaha, NE, State of Utah, and the City of Seattle, WA.

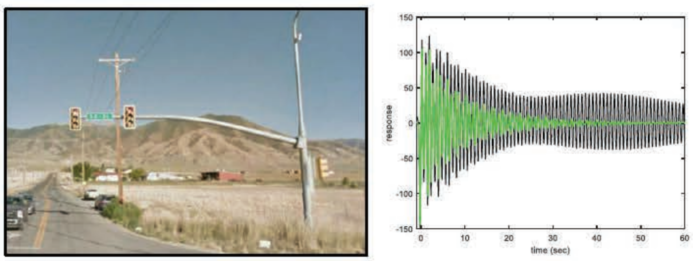
FIELD TESTING CONTINUED



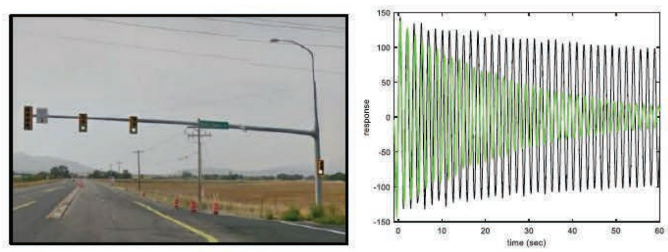
North West Corner P1 – SR-36 & Bates Canyon Road



North East Corner P2 – SR-36 & Bates Canyon Road



South East Corner P3 – SR36 & Bates Canyon Road



South West Corner P4 – SR-36 & Bates Canyon Road

Mitigator TR1 Vibration Damper State of Utah Field Testing Erda, Utah, SR-36 & Bates Canon Road, 08/03/2016 Summary of Results				
Pole Location	**P1**	**P2**	**P3**	**P4**
Mast Arm Length, (ft)	45	75	40	75
Frequency, (Hz)	1.00	0.68	1.20	0.61
Original Damping, (%)	0.20	0.19	0.20	0.14
TR1 Damping (%)	2.60	1.90	1.50	1.00
Reduced Response, (%)	92%	90%	87%	86%

Figure 6. Free vibration (pluck) tests in Erda, Utah at SR-36 & Bates Canon Road demonstrating the high damping characteristics of the Valmont Mitigator TR1 Damper mounted to a wide array of cantilever mast arm configurations.

USING THE VALMONT MITIGATOR

The Valmont Mitigator TR1 Vibration Damper can be installed onto **existing** pole structures to:

1. Increase the safety of traveling public from fatigue failures of our aging traffic/signage pole infrastructure
2. Extend the fatigue life of the structures
3. Eliminate a current vibration problem
4. In some cases, make older traffic signal pole structures (designed to the AASHTO 1994 or previous versions) compliant to the latest AASTHO Standard
5. Increase the signal and sign loading, when galloping and truck gusts control the design
6. Reduce vertical motion on cantilever arms for clearer traffic camera imagery and vehicle detection
7. Reduce vertical motion on cantilever arms for more accurate radar detection of vehicles
8. Reduces the loosening of signal and sign hardware due to vibration

The Valmont Mitigator TR1 Vibration Damper can be installed on **new** pole structures to:

1. Increase the safety of the traveling public from fatigue failures
2. Extend the fatigue life of the structures
3. Eliminate a potential vibration problem
4. Reduce the size and cost of the structure and foundation (using the TR1 Damper will typically reduce the weight of traffic mast arm structures by over 50% when designing the structure to meet galloping and truck gust fatigue loading per the AASHTO LTS Specifications)
5. Reduce vertical motion on cantilever arms for clearer traffic camera imagery and vehicle detection
6. Reduce vertical motion on cantilever arms for more accurate radar detection of vehicles
7. Reduces the loosening of signal and sign hardware due to vibration

Valmont engineers have the tools to determine what the expected damping performance will be when using the TR1 Damper. This check can be performed on new or existing structures. On new installation, the Valmont engineer can indicate the cost/benefit of using the TR1 damper showing the reduction of the overall weight of the structure.

TMP8293 11/18