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Vibration of Roadway Luminaires

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Abstract

This study intends to set up computational fluid dynamic simulations along with static and dynamic stress simulations to determine maximum possible accelerations and stress levels that may occur for poles having a single luminaire under certain typical and extreme environmental conditions.

1. Introduction

Vibrations of roadway lighting installation is not a new topic. There has been an extensive amount of research performed during a 20-year period from the mid-1960s to the mid-1980s. During that period manufacturers and departments of transportation initiated various studies to set standards for hardware and to solve field problems. The work of Van Dusen et al. [1, 2] is most referenced in this area. They tested aluminium and steel poles with a variety of luminaires with wind- and mechanically induced vibrations. Within relatively steady state winds of 5 to 35 mph the authors measured peak luminaire accelerations of 1 g or less over a vibration frequency range of approximately 0.6 to 25 Hz. Within the envelope of vibrations, Van Dusen et al. suggested that a major source of excitation for first mode and higher was vortex shedding. Another source for first mode vibration was wind gusts but unlike vortex shedding the pole vibration is not sustained over time and quickly decays avoiding major fatigue. It was suggested that designing luminaires for more than 1 g may be warranted for severe conditions and they recommended an infinite number of cycles for fatigue design. Later [3], Van Dusen gave four criteria for a comprehensive luminaire vibration test: (i) an accelerated fatigue test to simulate an infinite number of cycles at 1 g, (ii) a high intensity test of 1000 cycles at 4 g, (iii) testing in each of the luminaire's principal axes, and (iv) testing at frequencies slightly less than the fundamental frequency of the luminaire. It was noted that testing is complex and must be conducted under carefully controlled conditions.

The application conditions determine the load subjected to the luminaire, an obvious remark. The question comes down to 'what is the magnitude of this load?' and 'how is it transferred to the luminaire?'. These questions are not easily answered. Since the mid-1980s it is recognized that both wind and traffic can cause vibration problems in roadway lighting and that the more severe problems usually are on bridges where both wind and traffic provide exciting forces. Lighting manufacturers are primarily concerned with damaging fatigue that can cause structural failure of luminaires typically at their respective supports, but departments of transportation also are interested in excessive luminaire lamp and pole base failures. Usually, excessive lamp failures are found in bridge lighting installations for poles located away from bridge supports. Several studies are reported in the literature measuring the accelerations and displacements subjected to the luminaire [5, 6, 7]. Primary vibrations of luminaire-pole structures are considered low frequency and generally have been measured in the 0.6 to 25 Hz range. Peak accelerations of luminaires and lamps usually are less than 1 g. Van Dusen (1968) stated that wind generally excites a pole at various resonant frequencies, but that traffic excites poles at non-resonant frequencies.

An example eigenfrequency-acceleration plot for a luminaire standing on a bridge is depicted in Figure 1. Typical eigenfrequencies to occur are depicted in Figure 2. Main modes of concern are mode 1 and mode 2 due to the excessive displacements that occur at the lower frequencies which induce greater risk for fatigue., .

- **FIRST MODE VIBRATION** is characterized by a side-to-side movement that has a maximum displacement at the top of the pole. This behavior may be referred to as "sway". The frequency of movement is about 5 cycle per second or less and is a function of pole height, material and shape. Because the vibration frequency is comparatively small, the onset of material fatigue will take longer than poles exhibiting higher modes of vibration.

- **SECOND MODE VIBRATION** is characterized by a symmetric oscillation at or near the midpoint of the pole shaft. The oscillation frequency typically ranges from 6-40 cycles per second and is a function of pole height, material and shape.

Pole vibrations occur when air moving across a pole reaches "lock-in" velocity. At "lock-in" velocity, Vortex Shedding produces alternating transverse forces that oscillate the pole at one of its natural frequencies. The onset of fatigue cracking or structural failure may occur quickly under such conditions.

These two figures identify the complexity of the problem: pole, base and luminaire interact with each other and create a dynamical system that is a-priori not straight forward in its movements. Per today, it is generally expected that wind-induced excitation, unlike traffic-induced vibration, have a significant impact on the light system dynamic failure. Thus, it is important to

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understand the behaviour of the light pole under wind loadings.

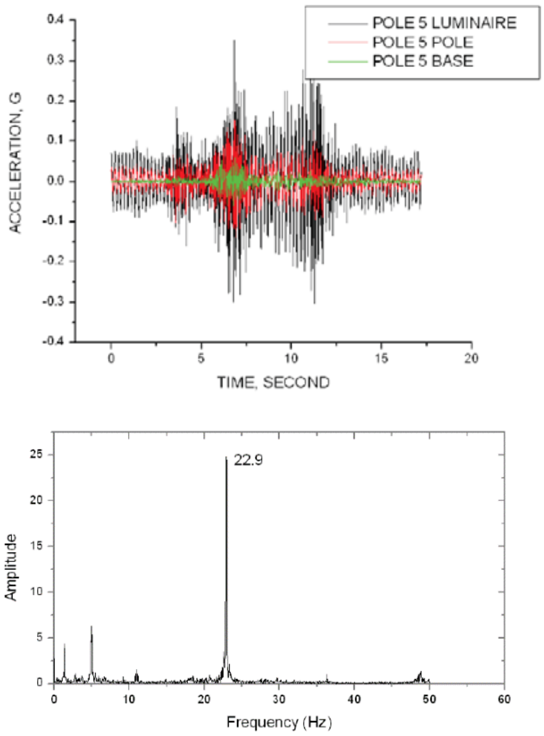


Figure 1: Example pole on a bridge. Left side: accelerations are transferred from the base to the pole to the luminaire. Right side: frequency plot on luminaire level.

Figure 2: First and Second Mode Pole Vibration

Mechanisms for wind to cause pole and luminaire system acceleration are, see also Figure 3:

- Turbulence (or buffeting)

Turbulence or buffeting is a high frequency forced vibration that is caused by airflow separation from one object striking another because of an impulse of increased load.

- Vortex shedding

Vortex shedding is the phenomenon caused by a steady, constant velocity wind moving across a slender object like a pole. Vortices forming on the sides of the pole create localized pockets of low pressure. These pockets alternate, creating alternating forces that act on the pole perpendicular to the wind direction.

- Galloping

Galloping is the self-induced crosswind oscillations of flexible structures due to aerodynamic forces that are in-phase with the motion of the structure. It is characterized by the progressively increasing amplitude of transverse vibrations with increased wind speed.

In terms of sustained vibrations, vortex shedding is the worst mechanism that must be designed for and the wind speeds associated with this phenomenon must be understood and analyzed.
AASHTO sign support specifications [8], ANSI [9] and EN40 [10] indicate that wind effects due to vortex shedding could be expected strongest for wind velocities in the range 15-55km/h [10-35 mph].

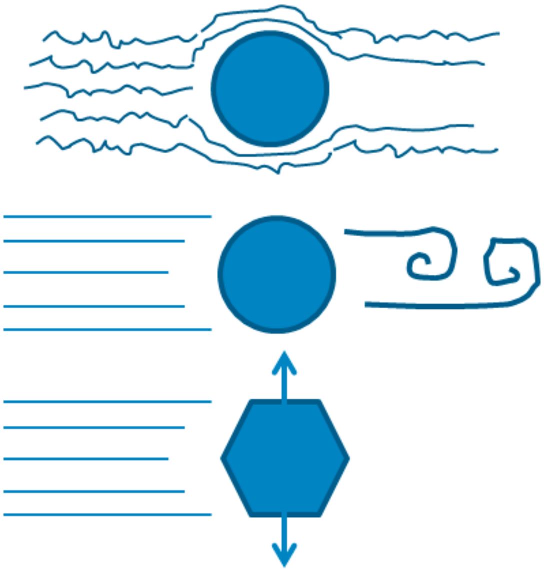


Figure 3: Top: turbulence; middle: vortex shedding; bottom: galloping.

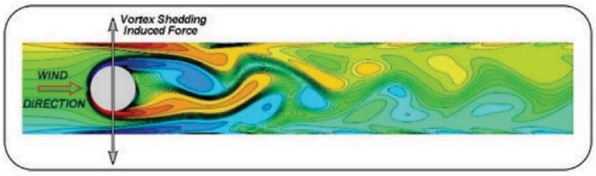
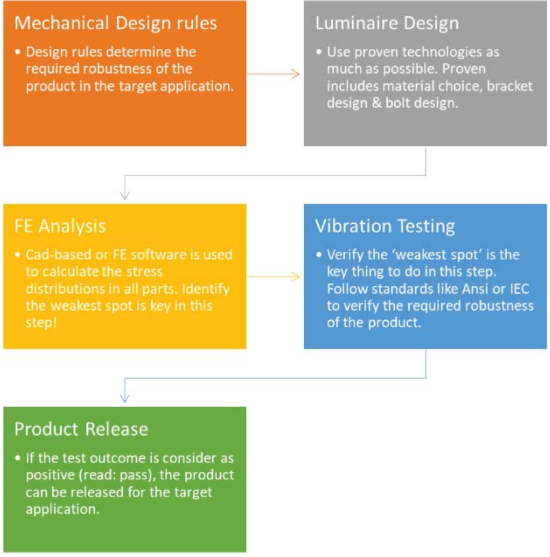


Figure 4: Vortex Shedding simulation about a cylinder demonstrating alternating low-pressure zones in wake.

Given all the above, the dynamic behavior of a luminaire is quite complex. It depends on the design, loading, pole height, materials, mass distribution, and many more. So, it is key to follow pre-defined steps to prevent luminaire failures due to wind loading conditions. These steps are highlight in Figure 5. In short:

- Each design starts with obeying the design rules. Design rules may come from engineering experience, from field response and/or from numerical or analytical analysis.
- Following the product requirements, the luminaire is designed. Here it is vital to use as much as possible proven concepts.
- Perform a structural Finite Element analysis. In such an analysis the weak spots, that are areas with highest stress or strain levels need to be identified.
- Verification by testing. Verification of the structural analysis is needed as to safeguard the

design. Typical tests are frequency sweep sinusoidal vibration and/or shock testing.
- Product release. With positive outcome of the above tests, the product can be released for the intended function and application.



Mechanical Design rules
- Design rules determine the required robustness of the product in the target application.

Luminaire Design
- Use proven technologies as much as possible. Proven includes material choice, bracket design & bolt design.

FE Analysis
- Cad-based or FE software is used to calculate the stress distributions in all parts. Identify the weakest spot is key in this step!

Vibration Testing
- Verify the 'weakest spot' is the key thing to do in this step. Follow standards like Ansi or IEC to verify the required robustness of the product.

Product Release
- If the test outcome is consider as positive (read: pass), the product can be released for the target application.

Figure 5: Flow chart for the design verification approach.

2. Pole and Luminaire Lock in phenomenon

A phenomenon known as "Pole Lock In" occurs when the vortex shedding frequency of the pole approaches the natural frequency of the pole-luminaire system. As the system resonant frequency is approached, a range of velocities exist that begin to cause pole sway in a perpendicular direction to the airflow as previously shown in Figure 8, while at the same time receiving buffeting forces and minor oscillations in the same direction as the wind.

It should be noted that for round and square poles, although average buffeting forces may be high compared to vortex shedding forces especially at higher wind speeds, the oscillating force creating possible dynamic vibrations is quite low when compared to the oscillating forces occurring due to vortex shedding about its average. Also, buffeting frequency of oscillation is typically much higher (factor of 2X) than the vortex shedding frequency for any given wind speed.

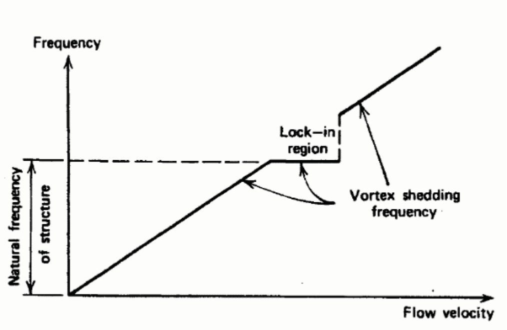


Figure 6: Illustration of "Pole Lock In" as flow velocity is increased.

If the natural frequencies of the pole and luminaire system are known, then wind velocities may be determined that will cause the pole and luminaire system to resonate either due to vortex shedding, buffeting, or both. Using Computational Dynamics Software (CFD), one may then estimate the forces in G's due to vortex shedding and buffeting at the determined wind velocities that may cause system resonance. It is these forces that will act at the support structure and will either act uniformly across the structure if not at resonance or will be amplified at other parts of the structure away from the supports depending on the structures damping characteristics, as well as its transmissibility during resonance conditions.

3. Failure modes due to vibration

In principle, each component in the luminaire, be it a bolt, a casing, or a light source, could fail when subjected to dynamic loads. The two main failure modes that can occur under wind loadings are:

- Overstress
- Fatigue

When stress is placed on a device or component to a higher level than the material (e.g. metal) in the component can resist, then failure of the metal component or device occurs by overstress. Turbulence is the main source for the overstress and occurs at high or extreme wind load levels. Under such loading, the spigot can break, the luminaire can open or even part of it can fall, see also Figure 7.

Figure 7: Overstress failure modes with spigot failure (left) and internal housing failure (right).

Metal fatigue is a weakening of metal due to cyclic sustained stress, resulting in an accumulation of small cracks. It occurs at forces that are repeated over time. In case of pole and luminaire systems subjected to wind loadings, the earlier mentioned galloping, vortex shedding, and pole/luminaire lock in can be the cause of that. Vortex shedding is a function of the Reynolds numbers which is defined as the ratio of the inertial force and the viscous force as a fluid passes by a body of a certain shape. For round and square pole shapes, vortex shedding is strongest between Reynolds numbers 300 and 3x10^5. The frequency at which the vortex shedding is occurring is defined by the Strouhal number and imparts oscillating loads upon the pole at this frequency. When these oscillating loads happen to match the pole and luminaire system eigenmode frequencies then high cycle fatigue will occur due to resonance.

The fatigue occurs in distinct steps, see Figure 8, being:

- Crack initiation, in most case this is due to stress concentrations at corners or at imperfections
- Crack propagation, due to the continuous load cycling
- Full fracture, the last part can't carry the load anymore and crack instantaneously

The first one to develop a luminaire test procedure based on fatigue was Van Dusen [1-3], see also the introduction. He did not suggest loading levels or how to determine them but instead suggested, depending on the material type, to

- perform an accelerated fatigue test to simulate an infinite number of cycles at 1 g,
- perform a high intensity test of 1000 cycles at 4 g,
- test in each of the luminaire's principal axes
- test at frequencies less than the fundamental frequency of the luminaire.

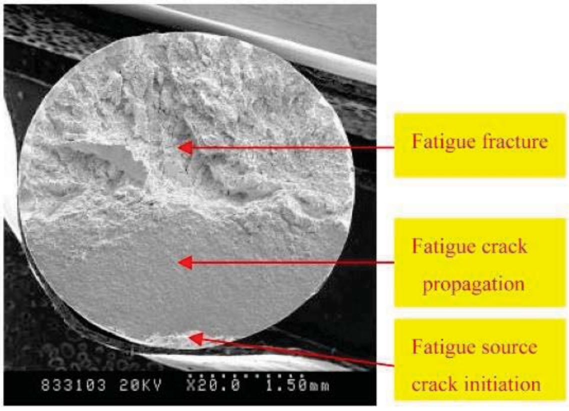


Figure 8: Stages of metal fatigue.

The method to determine the maximum level of wind in a region is to use wind maps (different for each country) and terrain categories (general). Both AASHTO and EN40 specifies that maximum wind levels should be determined such that they can be exceeded only once in 50 years. Note that EN40 does not provide any calculations for accelerations and only defines maximum displacements that poles may endure using fudge factors and, as such, is not really physics-of-failure based. Once wind velocity data is known for a particular application region, then one can determine the maximum forces imparted to the pole and luminaire system for two distinct situations, one being at maximum wind loading, the other being at wind speeds that may dynamically excite the pole and luminaire system in 1st and 2nd Eigenmode resonance.

The steps are:

1. Find historic wind maps to determine the maximum wind speed level occurrence in 50 years
2. From wind velocity, the force imparted to the pole and luminaire system is computed based on factors for:
   a. Altitude, column size, dynamic behavior, topography, exposure (terrain, height), and shape.
   b. Reynolds Number for the pole shape to determine velocity range when vortex shedding may occur causing additional high dynamic loading. Compare this velocity range with respect to the application area.
   c. Estimating 1st and 2nd Eigenmode frequencies for the pole plus luminaire system that could cause high dynamic loading and lock in phenomenon.
   d. Via Strouhal number, estimate the wind speeds that would excite the system at Eigenmode frequencies found from step c. Compare this velocity range with respect to the application area.

4. Finite Element modelling

It needs to be understood that both AASHTO and EN40 standards take conservative approaches to the dynamic behaviours of poles and state that the phenomenon is still not well understood. Due to the advance in FEA simulation technology, this phenomenon can be studied in more detail than possible before.

Performing Finite Element analysis for covering high-vibration and/or dynamic responses of luminaires is vital, we cannot do without it. Although FE modelling is a well-established technique for predicting thermomechanical behaviour of product and processes in many industries, they are not frequently used in the lighting industry. So, it means we need to define that properly, i.e., the way to use it for calculating the dynamic response of luminaires. Given the CAD design of a luminaire, the FE flow is like this:

1. Eigenfrequency analysis (modal analysis)

Eigenfrequencies or natural frequencies are certain discrete frequencies at which a system is prone to vibrate. Natural frequencies appear in many types of systems, for example, as standing waves in a musical instrument or in an electrical RLC circuit. When vibrating at a certain eigenfrequency, a structure deforms into a corresponding shape, the eigenmode. Eigenfrequency analysis will display the modes the luminaire is most likely to be deformed. Typically, this will be in the range 1-90Hz, the higher the better. Knowing the frequency of the first mode and second modes, one can take certain measures to increase or decrease it.

2. Time domain analysis

An eigenfrequency analysis can only provide the shape of the mode, not the amplitude of any physical vibration. The true size of the deformation can only be determined if an actual excitation is known together with damping properties. This is done in a time domain analysis.

There are two approaches to perform and evaluate simulation: design for the field or design for a test. The former is meant to make sure that all parts in the product sustain stresses under endurance strengths and can last forever in the field. As mentioned in chapter one, luminaires typically experience less than 1G for normal applications and less than 2G for overpass or bridge applications. The other approach is meant to examine the maximum stress amplitude of all parts being under fatigue limit under certain number of vibration testing cycles (usually 5x10^8 cycles). The top priority for an engineer is to ensure the safety of the product. Therefore, the bottom line is to confirm the first approach that the product will be safe in the field, especially while being aware that the standards are with flaws which can potentially have products pass tests but still may cause safety issues later in the applications. On the other hand, some products may need overdesign to pass certain tests, especially for customer-required testing procedures. In this case, further simulation or evaluation is needed, especially for predicting the dynamic behaviour of the product in the test.

Examples of stress results resulting from static and dynamic simulations are depicted in Figure 9 and Figure 10, respectively.

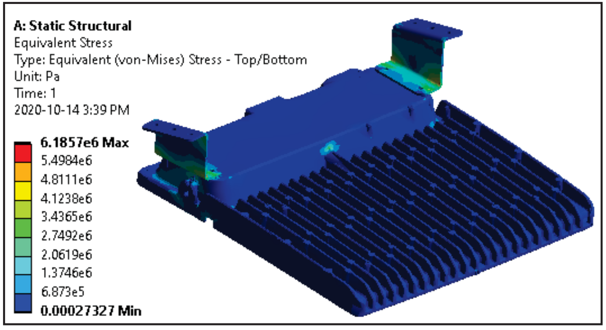


Figure 9: Von-Mises stress in static analysis.

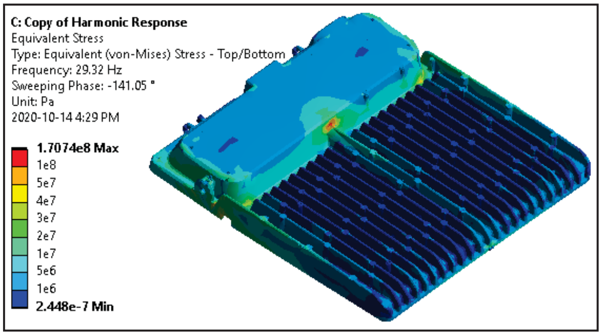


Figure 10: Von-Mises stress in harmonic analysis.

5. Discussion & Conclusions

Vibration analysis of the system pole - luminaire is a complex subject. CFD and FEM solutions are being performed in order to understand the dynamic behaviour of this combination. In this paper, we present a generic framework for performing stress analysis on this combination. During the presentation, we will present examples of the modelling approach.

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