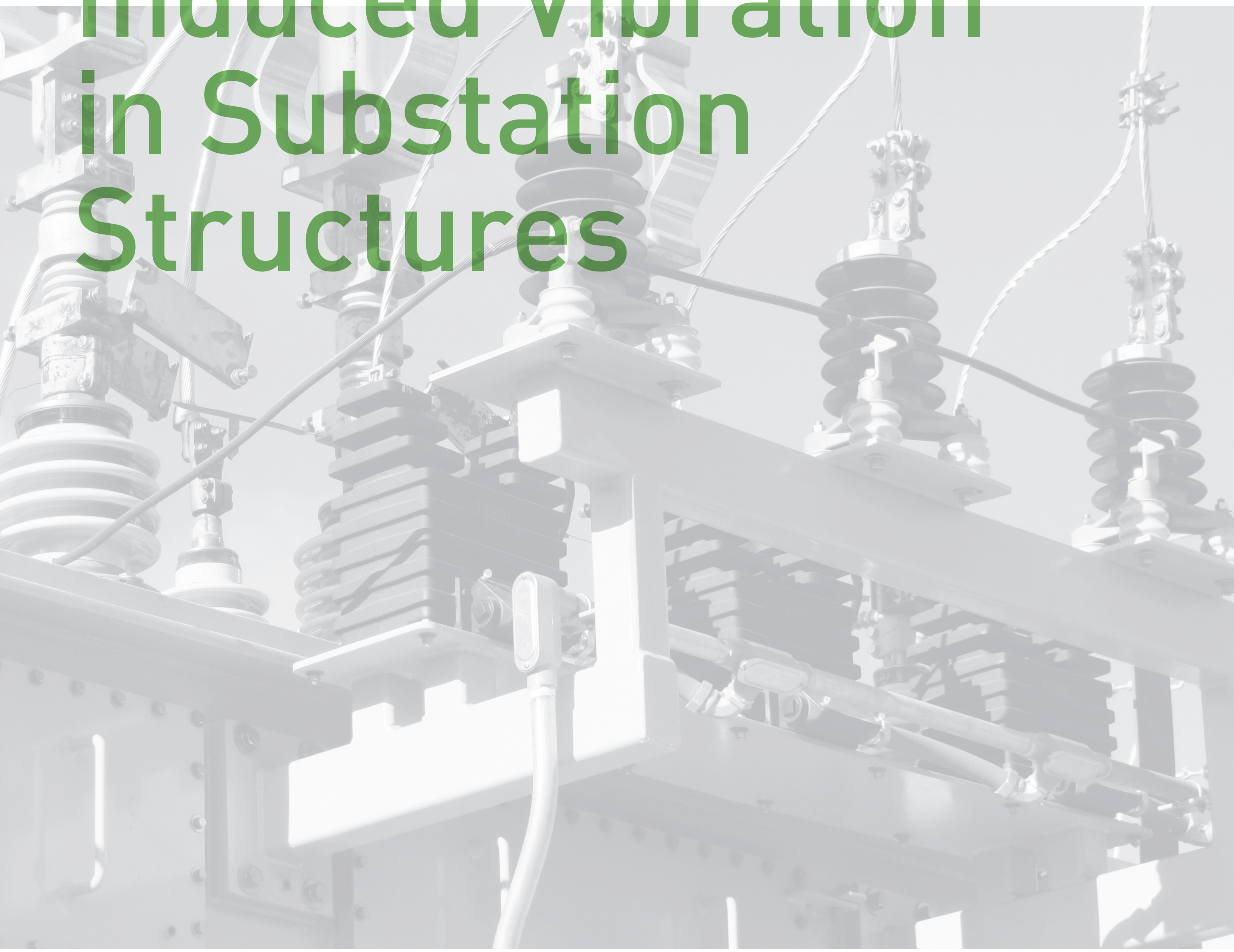
Mitigating Wind-Induced Vibration in Substation Structures



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When designing exceptionally slender structures, it's important to keep wind-induced vibration in mind. It may be an issue despite the structure passing all demand checks during the design phase. This article will cover why it's important for engineers to consider vibration when designing and detailing a slender structure. Common examples of vibration-susceptible structures are static masts, light poles, overhead line termination structures (dead-ends), and rigid bus.

Even a simple structure such as a light pole can undergo multiple modes of vibration depending on its natural period of vibration. First and second modes are the two most common modes of vibration experienced by substation structures. First mode of vibration, also referred to as 'sway' is commonly experienced by static masts, light poles, and similar structures. This mode has the lowest frequency, longest natural period of vibration, and maximum deflection occurs at the top of the pole. Under high wind conditions, sway is typically not a cause for concern. For example, we have all at one point seen a traffic light swaying on a windy day. These tall and slender structures are designed with a code-prescribed deflection limit and can accommodate the low frequency of sway with little impact on their lifespan.

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In addition to high winds, sway may also occur under sustained, low speed winds--generally less than 30 mph. Sway under these conditions poses a greater risk to the structure; the pole

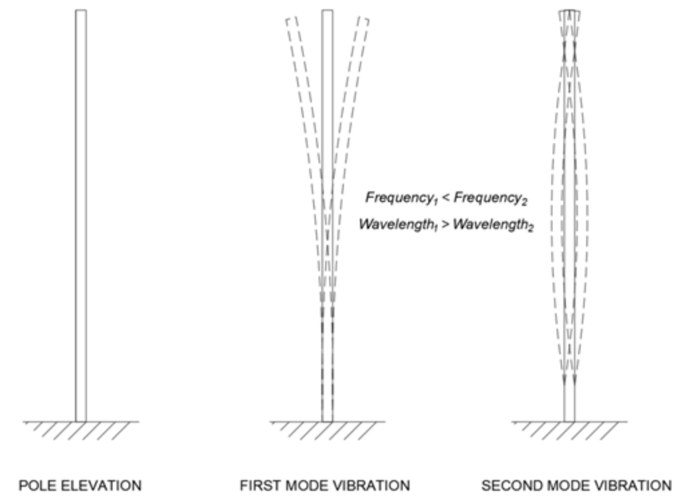

Figure 1. First and second modes of vibration for a pole-type structure.

may be susceptible to second mode vibration as wind speed increases. The key factor in these sustained wind situations is vortex shedding. In fluid dynamics, vortex shedding is the phenomenon of alternating low-pressure zones (vortices) forming on the leeward side of a body under a steady stream fluid flow. In response, the body will begin to oscillate in the direction perpendicular to the wind flow as these vortices alternate. Issues arise when the exciting force frequency starts to match a natural frequency for the system. You then start to excite a particular mode of vibration and the magnitude of the vibration is amplified. Swing analogy comes to mind. If you push or extend your legs at the right time, swinging increases. Push or extend your legs at the wrong time, swinging decreases. As the frequency of the oscillation increases with wind speed, it can approach the structure's natural frequency for second mode vibration and lead to harmonic resonance. Frequency of vortex shedding is closer to second mode of vibration which is why this mode gets excited.

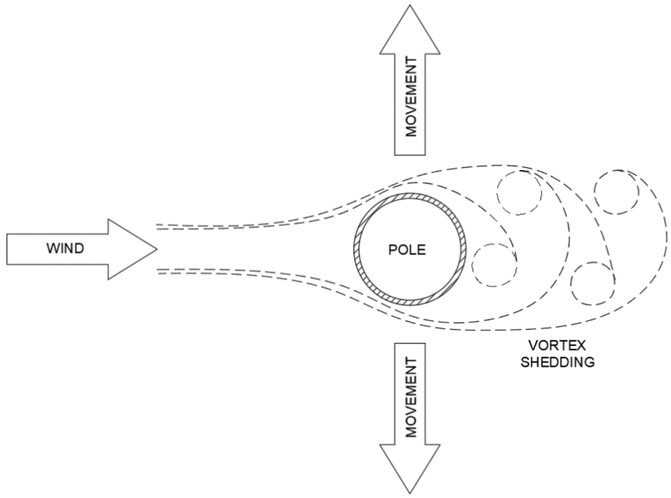

Figure 2. Pole vibration induced by vortex shedding.

Second mode vibration, also known as 'aeolian vibration,' is a much more serious condition. It may lead to early fatigue failure of the structure. Under first mode vibration, the top of the pole undergoes horizontal translations as the dominant mode shape of deformation. Under aeolian vibration, an inflection point is formed near the top of the pole, leading to a mode of vibration as shown on Figure 1. This causes the middle of the pole to vibrate at a lower wavelength but much higher frequency than the first mode. Therefore, it may be easier to hear the fluttering of aeolian vibration than it is to see it. The cyclical loading induced by the higher frequency aeolian vibration can cause early fatigue failure of welds and corners of the pole. This vibration is difficult to predict. The wind criteria that cause second mode vibration are specific to the terrain conditions for the project site. The historical performance of a structure at previous locations cannot be relied on for predicting performance at future locations. As expected, aeolian vibration is more common in flat, rural terrain with few ground-level obstructions.

Aeolian vibration is not limited to light poles or static masts. It may also occur in rigid bus and dead-end structures as well. Rigid bus is a common component of substation design projects, and of the two, is more readily identifiable as a vibration risk. As the bus span increases, so does its susceptibility to aeolian vibration. This is partly why many utility companies impose a limiting bus span in their design criteria, typically 15 feet or less. On the other hand, the susceptibility to vibration of dead-end structures may not be as obvious as rigid bus but could pose a greater danger during construction. Dead-end structures typically consist of two tapered steel columns with a tubular steel beam connecting the two. The beam supports insulators that are designed to withstand thousands of pounds of tension forces from incoming overhead transmission lines. Depending on the phase spacing of the incoming lines and existing conditions on-site, these beams can often have spans in excess of 30 feet. For long span beams, it's crucial to minimize the time between installing the dead-end structure and installing the conductors. The reason for this will become apparent after we discuss damping.

"In theory, an undamped system can have infinite vibration amplitude at resonance."

Though steps can be taken during the design stage to reduce the likelihood of aeolian vibration--such as adding weight or increasing the stiffness of the structure to alter the natural frequency of the system--the possibility for the system to undergo vibration at resonance

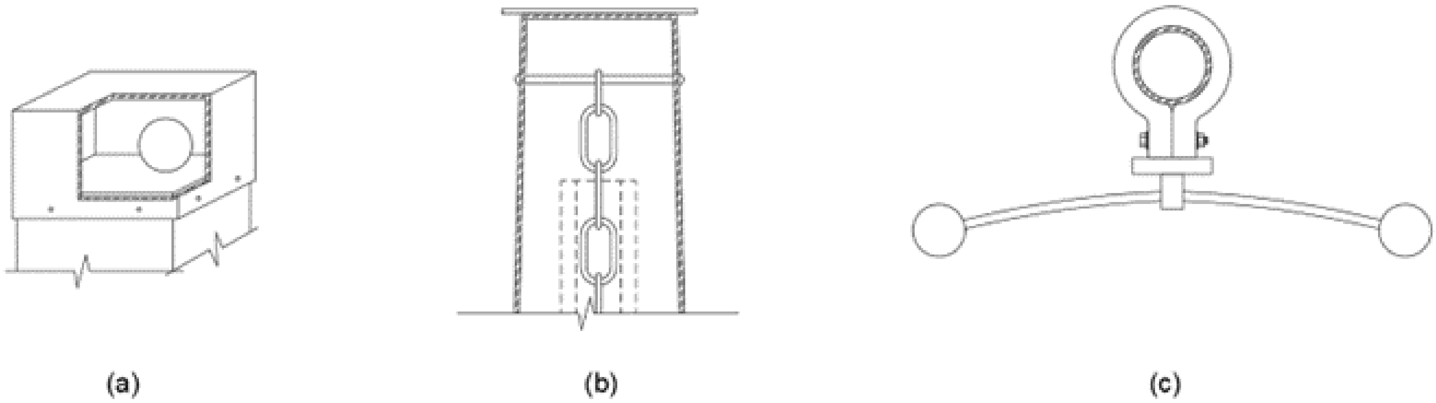

Figure 3. Examples of vibration dampers, (a) weighted ball for first mode in poles, (b) chain with optional noise-reducing wrap for first and second mode in poles, (c) externally mounted weight for second mode in rigid bus.

still exists. In theory, an undamped system can have infinite vibration amplitude at resonance. To mitigate this, dampers can be installed on the structure. They come in a variety of forms, but essentially serve the same function--to interrupt the harmonic resonance and reduce the amplitude of vibration during a critical wind event.

In light pole type structures, there are different dampers for different modes of vibration. Although first mode vibration is of low concern structurally, it may be beneficial to reduce sway in poles with a brittle finish or simply for aesthetics. A common first mode damping solution is to install an enclosed weighted ball at the top of the pole. As the pole begins to sway, the ball will move to counteract and dampen the sway. This effect can also be accomplished by hanging a short length of chain from the top interior of the pole.

To combat second mode vibration in poles, weights can be fastened to the inner wall of the pole during fabrication to alter the pole's fundamental frequencies. Another option is to extend the first mode chain down through the middle half of the pole; its motion will interrupt the harmonic frequency of aeolian vibration. For tubular rigid bus, a simple yet effective method of vibration damping is to thread the bus with conductor cable. There are instances, however, when bus damping with conductor cable is not a cost-effective solution. This can be due to availability of the required conductor size, or the total length of bus required to be damped. A solution to this problem is to install commercially available damping weights around the exterior of the bus at prescribed intervals. Adding weight to the structure is the most effective method for mitigating damaging aeolian vibration.

Circling back to the case of the dead-end cross beam, it's now clear why conductors and other equipment should be installed shortly after the dead-end structure has been constructed; the weight of the equipment also serves as an efficient damper. An unloaded cross beam left undamped for a prolonged amount of time may risk failing due to aeolian vibration. An engineer that is cognizant of the construction

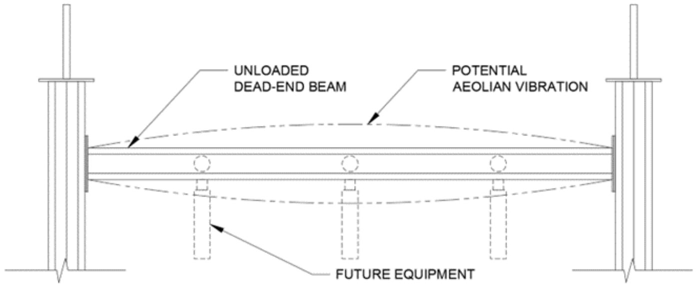

Figure 4. Potential aeolian vibration in an unloaded h-frame beam.

timeline can mitigate this risk. If the timeline calls for the dead-end structure and remaining equipment to be installed later, the structure should be damped with temporary weights such as scrap insulators or structural shapes until the specified equipment can be installed.

Even as design standards continue to develop and be refined for substation structural engineering, it's unlikely that prescriptive dampening requirements can be codified for a topic that is so heavily influenced both by project location and structure geometry. As such, it is in the engineer's best interest to be aware of potential aeolian vibration and how to best assuage possible hazards while still meeting project and client requirements.

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