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Experience With Wind-induced Vibration of Power Transmission Substation Structures

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SUMMARY

Based on structural vibrations observed at one of American Electric Power's substations, a study has been performed to evaluate current structural design methodology for preventing wind-induced vibrations. The reported case was used as the case study to establish a vortex-induced vibration (VIV) prediction method for steel structures. The related governing equations are defined and used to describe the methodology. The results show that the presented method assists in identifying when VIV may occur which can significantly improve future designs. In addition, the applied VIV mitigation method using strakes is presented in the case study. The method includes the installation of vertical strakes on the surface of the steel structure, which according to the performed vibration monitoring, has been successful to prevent VIV.

KEYWORDS

Wind induced structural vibrations, Vortex Shedding, Reynold number, Strouhal number, Transmission substation structures, Fatigue damage, Strakes

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INTRODUCTION

In the past 15 to 20 years, there has been a gradual transition in the types of structures used in the utility industry – from lattice poles and towers to tapered tubular steel. This change is the result of lower construction and maintenance cost of tubular steel structures. These structures include fewer numbers of parts, which will reduce the construction cost significantly. This change is also facilitated by better steel fabrication and transportation technologies that make production of such structures comparatively feasible. In general, the tapered tubular structures have smaller surface against the wind and drag force compared with equivalent lattice designs. This makes them more efficient in terms of aeolian design. However, these structures may face other challenges such as wind-induced vibration. One of the main causes of the structural wind induced vibration is vortex shedding, also known as vortex induced vibration (VIV). VIV is a major cause of fatigue damage on exposed and slender tubular structures. This study investigates a reported case of tubular structure vibration, determines the cause of the vibration, and establishes a simplified method to predict the possibility of these structural vibrations occurring on current and future designs. It must be mentioned that the proposed methodology is preferred to use common engineering design tools such as any finite element (FE) software. In this work we review the theory behind this phenomenon, develop a method to predict structural susceptibility to wind, and apply the prediction method to different types of steel structures that are used at substations.

BACKGROUND

Vortex shedding occurs when fluid flows past a blunt object and creates alternating low-pressure vortices on the downwind side of the object that are released (shed) alternatively. The object will tend to move toward the low-pressure zones (vortices) as they are formed and shed on both sides of the object alternatively, thus causing a side to side vibration. Fig. 1 shows the formation of vortices around a circular object.

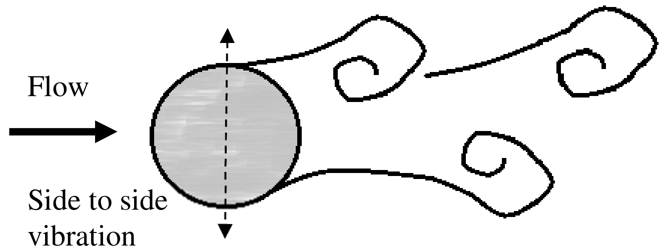

Fig. 1 Vortex shedding on a bluff body forming the vortex street

The formation of the vortices is dependent on the Reynolds (*Re*) number such that for very low *Re*, there will be no vortices formed around the object. Table 1 presents the variation of flow regime with regards to Reynolds number for a circular object in air flow. The *Re* is defined as

$$\mathrm{Re} = \frac{U \times D}{\nu} \tag{1}$$

where U is the fluid velocity, D is the diameter, and ν is the fluid kinematic viscosity. In this study $\nu = 1.6\times10^{-4} \frac{ft^2}{s}$.

Table 1. Flow Regimes vs. Reynolds Number [1]

***Re* Range**	**Regime of the Flow**
$Re < 5$	Unseparated flow
$5 \text{ to } 15 \le Re < 40$	A fixed pair of vortices in wake
$40 \le \mathrm{Re} < 150$	Laminar vortex street
$150 \le Re < 3\times10^5$	Vortex street begins to transition and becomes fully turbulent
$3\times10^5 \le Re < 3.5\times10^6$	Turbulent transition is complete and wake is narrower and disorganized
$3.5\times10^6 \le Re$	Re-establishment of turbulent vortex street

As is presented in Table 1, for *Re* values less than five, there will be no vortices formed and there is an unseparated flow around the object. As the *Re* increases there will be vortices formed in the wake. *Re* between 40 to 150 is the range that the laminar vortex street occurs and is the most studied range for vortex shedding phenomenon. As the *Re* increases, the vortex street becomes turbulent and for values above 3×10^5 there are no vortices formed.

VIV occurs when the frequency of the formation of the vortices and their shedding is close to the natural frequency of the object in the flow. This will cause a resonance called lock-in of the structural oscillation that will amplify the motion and can cause significant damage on the structure especially on the joints. That is why it is very important to predict and prevent VIV at or near one of the structure's natural frequencies in structural design process. VIV has been observed in many applications. In general, slender structures or parts with low damping ratios which are exposed to fluid flows are the main victims of this phenomenon. Some examples include cable stayed or suspension bridges, offshore oil exploration structures and under water production risers, roadside lighting, and traffic sign poles and arms. In the utility industry, this problem has been observed on cables and rigid buses more often with the use of circular or multisided tubular or tapered tubular poles, arms, and structures.

The frequency of the vortex shedding is related to the Strouhal number and is defined by

$$St = \frac{f \times D}{V} \tag{2}$$

where St is the dimensionless Strouhal number, f is the vortex shedding frequency, and V is the flow velocity. The value of the Strouhal number is related to the *Re* as shown in Fig.3 for a circular cylinder or tube.

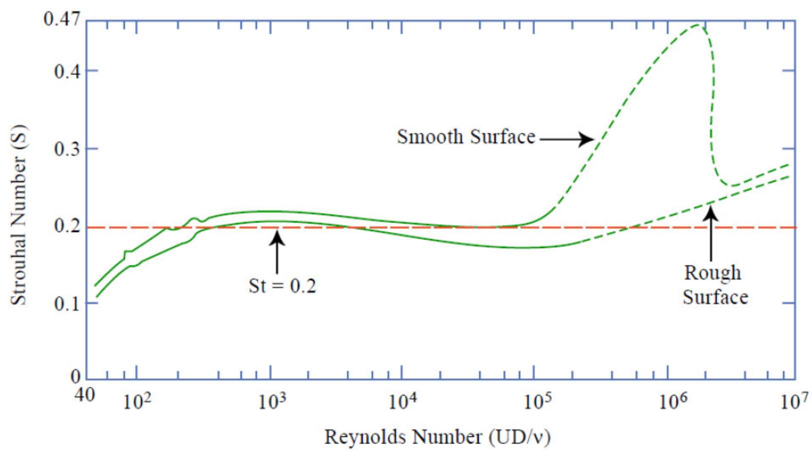

Fig. 2 Strouhal Number vs. Reynolds Number [2]

According to Fig. 2, St is almost constant (≈ 0.2) for $Re \leq 2\times10^5$. The two equations defined above were next used to predict the possibility of VIV in a structure.

REPORTED VIBRATION AND CASE STUDY

The structure with reported wind induced vibration is a substation dead-end structure. This is a 4-legged structure that is intended to withstand the tension of the conductors. Fig. 3 shows the shape and dimensions of the structure.

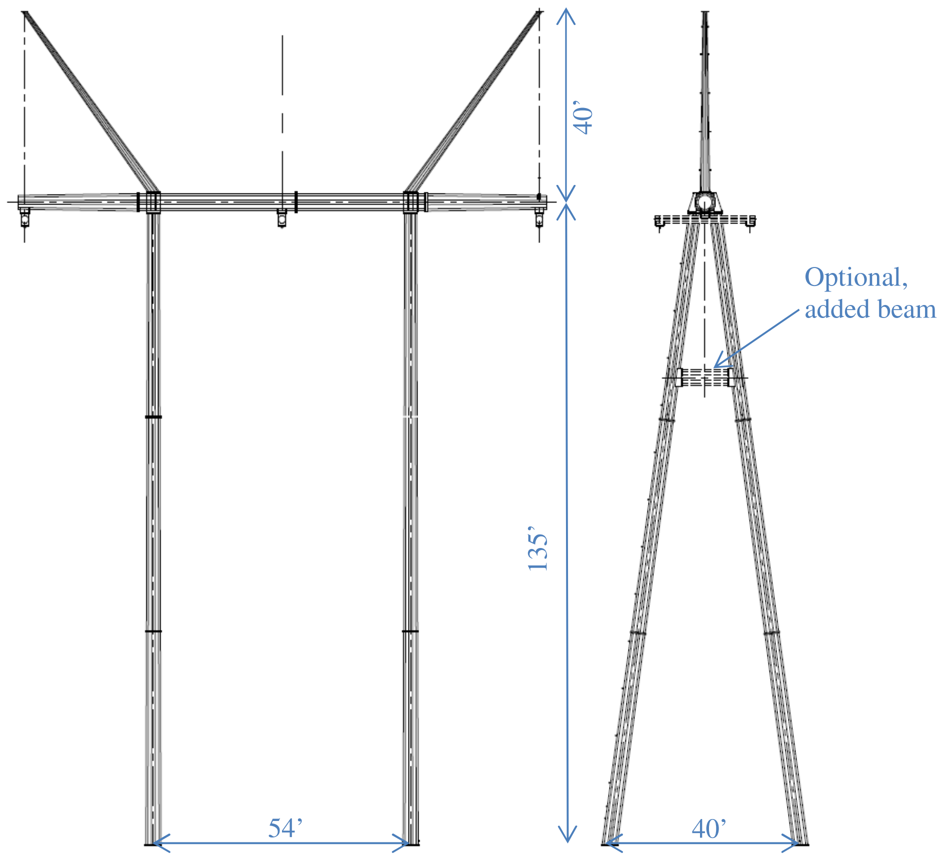

Fig. 3 Three phase dead-end structure with reported vibrations

The vibration was reported on the two legs of the structure that are connected at top. The two legs were moving towards and away from each other at the mid-height. Fig. 4 (a) shows the reported mode of vibration. Based on the reported vibration, short beams were added to connect the two legs to each other at an elevation close to the two thirds of the height to prevent the vibration by changing the geometry and thus the natural frequency of the structure. However, after installation a new mode of vibration was reported on this structure. The new oscillation was such that the two poles move in and out of the "A" plane together as shown in Fig. 4 (b).

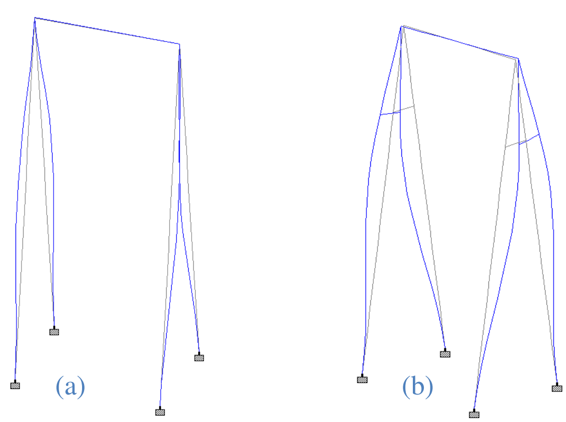

Fig. 4 (a) First observed mode of vibration, (b) second observed mode of vibration after addition of the short beams

Based on the two observations, a more in-depth study was performed to identify the reason for the vibration and to possibly predict and prevent this problem in future. A finite element model of the structure was created and analyzed for both geometries, and the natural frequencies of the structure were calculated. Table 2 presents the values of the natural frequencies for both cases. The effect of davit arms and the top static masts on these modes are negligible and therefore not included in the model to reduce the number of analytical modes.

Table 2. Natural Frequencies of the Dead-End Structure

Mode	Dead-end structure, natural frequencies (Hz)	Dead-end structure after additional beam, natural frequencies (Hz)
1	0.68	0.69
2	2.17	2.29
3	2.52	2.45
4	2.78	2.58
5	3.16	3.69
6	3.16	4.86
7	3.17	4.94

Per Table 2, the frequencies of modes that matched the observed vibrations are 3.17Hz and 2.58Hz respectively. It must be noted that the field observed frequencies may vary from the analytical model due to the differences between as built structure and FE model; however, in this study the intension is to identify the possibility of VIV using simple FE models without as built vibration monitoring information.

Based on the defined equations provided in the previous section, the critical wind velocities for these modes were calculated. Since these legs are dodecagonal (12 sided) tapered tubular members, the equations for circular sections were considered to be applicable, and calculations were performed for the top and bottom section diameters – to cover the full range of critical winds. It must be noted that the top parts of the legs are more exposed to the wind and contribute more to the vibration. However, the minimum and maximum diameters were used in the calculations to obtain the full range of critical wind speeds. Table 3 presents the calculations for the two mentioned modes of interest.

Table 3. Calculated Critical Wind Speeds and *Re* Values for the Two Observed Modes of Interest

Diameter (inch)	Strouhal	Frequency (Hz)	Critical wind speed (mph)	*Re*
30	0.2	3.17	28.5	6.5×10^5
38	0.2	3.17	36.1	10.4×10^5
30	0.2	2.58	23.2	5.3×10^5
38	0.2	2.58	29.4	8.4×10^5

Using the constant Strouhal number of 0.2, the critical wind velocity ranges are 28.5-36.1 mph, and 23.2-29.2 mph respectively. These wind velocities, though not impossible, are not close to the average wind speeds observed for the region on the structure, erected in northeastern Indiana.

Also per Fig. 2, these *Re* values are out of the range of flow regimes with the possibility of formation of vortex shedding. This finding may seem to be a limitation for the simplified equations defined previously. However, considering Fig. 2, the Strouhal number is not always constant with respect to *Re*. Using the provided graph for smooth surfaces, the Strouhal number was updated through multiple iterations for convergence, and new values for critical wind speed and *Re* were calculated and are presented in Table 4.

Table 4. Updated Critical Wind Speeds and *Re* Values for the Two Modes of Interest

Diameter (inch)	Strouhal	Frequency (Hz)	Updated critical wind speed (mph)	*Re*
30	0.33	3.17	17.4	3.9×10^5
38	0.41	3.17	17.5	5×10^5
30	0.3	2.58	15.7	3.5×10^5
38	0.36	2.58	16.3	4.7×10^5

As indicated in Table 4, the updated *Re* values for the top diameters of the structure legs (30") are in the range of vortex shedding formation (per Table 1 for both vibration modes). Note that these calculations include approximations, and for safety reasons, a larger range of *Re* for vortex shedding occurrence must be considered. Therefore, a range of *Re* up to 4×10^5 was considered for VIV. This indicates that there is a possibility for occurrence of this type of modal vibration.

To further evaluate the possibility of predicting VIV using the aforementioned method, another similar structure installed at the same substation was analyzed. This dead-end structure, though geometrically similar to first dead-end structure, has had no observed vibrations, and has larger leg diameters and plate thicknesses. Table 5 presents the calculated critical wind speeds and corresponding *Re* values.

Table 5 Updated Critical Wind Speeds and Re Values for the New Dead-End's Same Modes of Interest

Diameter (inch)	Strouhal	Frequency (Hz)	Updated critical wind speed (mph)	*Re*
44	0.42	3.62	38.2	7.5×10^5
55	0.42	3.62	47.8	11.8×10^5
44	0.39	4.62	31.3	10.4×10^5
55	0.44	4.62	34.6	15.1×10^5

These values are clearly beyond the range of vortex shedding formation regimes per Table 1. These are promising results for this analysis method that will be further investigated as other cases of vibration are encountered and monitored.

MITIGATION METHOD

There are several known applicable methods to mitigate the wind-induced vibrations on structures. One is to make the design such that the possible lock-in frequencies are high enough that the corresponding *Re* values are beyond the range of formation of vortex shedding. Though this can be used for new designs, it is not suitable for installed structures. One retrofit method is the addition of dampers to the structure. This will not prevent the formation of vortices on the body of the structure, but it will reduce the amplitude of the induced vibrations, and prevent possible damage to the structure and the base joints. Another method is the installation of steel chains inside the vertical tubular poles. In the case of dead-end structures, the chain method is not possible since the legs are slanted. A third common mitigation method is the installation of strakes or other attachments to disrupt the flow around the structure preventing the formation of vortices or to move them away from the surface of the structure. Some additional common methods of VIV mitigation are presented in [3], including helical spoilers or vertical strakes.

For this project the installation of straight vertical strakes on different sides of the structure was chosen to mitigate the vibration. The vertical strakes were installed in a helical pattern on the surface of the legs of structures using rivet nuts as shown in Fig. 5.

Fig. 5 Retrofitted dead-end structure with strakes

After installation of the strakes, vibration monitoring was performed for three weeks to verify that the mitigation method was successful.

CONCLUSION

Based on the observations, assumptions, and calculations performed in this study, the theoretical and empirical equations from literature to describe the vortex shedding phenomenon seem to be able to help predict the occurrence of VIV. This is important since the current guides and manuals for power industry such as ASCE 113 Substation Structure Design Guide [4] do not provide methods to predict and prevent VIV on transmission structures. The methodology presented here will be evaluated and calibrated with the future field monitoring and data collections on these types of structures.

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