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REDUCTION OF STACK VORTEX INDUCED VIBRATIONS

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ABSTRACT

A stack installation experienced vortex-induced vibrations (VIV) while in-service. The magnitude of the vibrations was severe enough that cracking in the welds at the base of the stacks was experienced shortly after their installation. Initially, straight strakes were placed on the stacks, per API 560, based on field serviceability. The strakes proved ineffective and it was determined that the stacks would be uninstalled for repair. During the repair process, design steps were required to reduce or eliminate the VIV experienced in-service. Due to a flaw in the initial design and the ineffectiveness of the straight strake solution, the end client required verification of any proposed design changes before their implementation. Additionally, there was a very short time frame for the investigation of solutions.

Initially, tuned mass dampers were explored for the design modification. It was determined that they could not be constructed of suitable materials for the environmental operational characteristics of the stacks. It was then agreed that aerodynamic modifications of the stacks should be explored to reduce VIV. ASME STS I specifies the design and installation of helical strakes on stacks, but does not indicate the magnitude of vibration reduction that can be expected [3]. Therefore, numerical models were used to determine if the strakes would reduce or eliminate the service vibration.

A baseline analysis was first conducted to validate that the tools - a combination of computational fluid dynamics (CFD) and finite element (FE) methods - could capture the in-service behavior. To perform this analysis a baseline CFD model was constructed of the as-built stack. Using DES methods, this model was analyzed at several wind speeds to determine the magnitude and frequency content of the VIV-forcing functions. This information was then used to perform a dynamic analysis using an FE model of the stack. This model accurately predicted the correct wind speed corresponding to VIV and the amplitude of the stack's vibration. A second model was then constructed of a stack with helical strakes, using a novel modeling methodology, and this model was analyzed over a variety of wind speeds using DES methodologies. The forcing functions predicted with the helical strake model were then used to determine the stack's in-service response. This paper contains the complete methodologies and results associated with these analyses.

NOMENCLATURE

DES	Discrete Eddy Simulation
LES	Large Eddy Simulation
k	Turbulent Kinetic Energy
ω	Turbulent Dissipation

y+	Wall y+ value, CFD specific value; u*y/ν
u*	Friction velocity
y	Distance to the nearest wall
ν	Local kinematic viscosity
f_s	Frequency of excitation
S	Strouhal number
U	Bulk fluid velocity (wind speed)
D	Diameter of cylinder
OD	OD of cylinder
C_d	Coefficient of drag

DEFINITIONS

von Karman Vortex Shedding – "A term defining the periodic detachment of pairs of alternate vortices from a bluff body immersed in a fluid flow, generating an oscillating wake (or vortex street) behind it, and causing fluctuating forces to be experienced by the object. The phenomenon was first observed and analyzed on two-dimensional cylinders in a perpendicular uniform flow, but it is now widely documented for three-dimensional bodies and non-uniform flow fields. This is a situation where the energy subtracted from the flow field by the body drag is not dissipated directly into an irregular motion in the wake, but it is first transferred to a very regular vortex motion." [1]

Detached Eddy Simulation – "Detached eddy simulation (DES) is a hybrid modeling approach that combines features of Reynolds-Averaged (RANS) simulation in some parts of the flow and large eddy simulation (LES) in others. DES turbulence models are set up so that shear layers are solved using a base RANS closure model. However, the turbulence model is intrinsically modified so that, if the grid is fine enough, it will emulate a basic subgrid scale model. In this way, one gets the best of both worlds: a RANS simulation in the shear layers and an LES simulation in the unsteady separated regions." [4]

Large Eddy Simulation – "Large eddy simulation (LES) is an inherently transient technique in which the large scales of the turbulence are solved for, and the small-scale motions are modeled. One justification is that by modeling "less" of the turbulence and explicitly solving for more of it, the error in the turbulence modeling assumptions will not be as consequential. Furthermore, it is hypothesized that the smaller eddies are self-similar and will thus lend themselves to simpler and more universal models. The downside of the approach is the computational expense, which although less than direct numerical simulation, is still excessive." [4]

INTRODUCTION

A series of five (5) stacks was installed in close proximity to a structure. During certain wind conditions, the stacks vibrated longitudinally, with a displacement amplitude of approximately 1". On-site inspection indicated that the stacks were excited at both their first and second natural frequencies. Based on past experience it was hypothesized that the stack excitation was caused by von Karman vortex shedding [1].

As an initial solution straight strakes, as specified in API 560 Paragraph 13.5.6 (described below) were placed on the stacks in the field.

"Staggered vertical plates shall be not less than 6mm (1/4 in) thick and not more than 1.5m (5 ft) long. Three strakes shall be placed at 120° around the stack and shall project 0.1 diameters from the outside of the stack. Adjacent levels of strakes shall be staggered 30 ° from each other" [2]

This solution method was chosen based on fabrication considerations. The stacks' service characteristics after the implementation of straight strakes indicated that the strakes were ineffective. Subsequent inspection showed the initiation of cracks in welds at the stack base. At this point the stacks were removed from service for repair and additional solutions were sought to improve the stacks' service characteristics.

ASME STS-1-2006 Paragraph 5.3, Prevention of Excessive Vibrations, indicates three (3) acceptable methods for reducing the impact of aerodynamically induced loads [3].

- Aerodynamic methods
- Damping methods, and
- Stiffness methods

The stacks' service environment exposed them to minimum temperatures of -40 °F. This made tuned mass dampers an unsuitable solution due to their materials of construction. The stacks could be stiffened through the use of heavier gauge materials of construction, but their location in close proximity to an existing structure did not allow for the use of lateral supports or guy wires as specified in Paragraph 5.3.3. In this case the use of aerodynamic methods – specifically, helical strakes as specified in Paragraph 5.3.1 seemed to be the best method to improve the stacks' performance in the field.

Due to the poor performance of the straight strakes the client desired to validate that the helical strakes would provide an acceptable solution prior to their installation. The following tasks were required to perform this validation:

- Determine if von Karman vortex shedding could cause the response seen on-site
- Determine the aerodynamically induced loads with helical strakes, and
- Predict if the aerodynamically induced loads would lead to large stack displacements and stresses

SOLUTION METHODOLOGY

Validation of the on-site excitement mode and the expected stack response with the addition of helical strakes required a coupled fluid-structural solution methodology. Two (2) CFD models were developed to determine the expected forcing functions for the current stack configuration and for the stacks with helical strakes. Based on geometry, the current stack configuration could be modeled with a 2-dimensional model. Due to the geometry with the helical strakes, a 3-dimensional model was required. In this case a novel solution methodology using periodic boundary conditions was used to minimize the model's size. In both cases the models were developed to fully resolve the boundary layer. Transient analyses were used to determine both the amplitude of any aerodynamically induced stack forces and their frequency content.

A finite element (FE) model of a single stack was developed. A modal analysis was used to predict the first six (6) fundamental stack frequencies. Using procedures shown in this paper, the frequency information was used to determine the required grid density in the CFD models at the wind speeds where stack excitation was expected. To predict the stacks' dynamic response in their current configuration for validation of the strake solution, the results from the CFD models were used to develop forcing functions for the stack. These forcing functions were input to a frequency response model to predict the stacks' dynamic response. The results of this model were compared to field-measured displacements to validate the analysis methodology.

CFD MODELING METHODOLOGY

As previously described, the goal of the CFD models was to predict the forces, including both amplitude and frequency that could be expected on the stacks due to von Karman vortex shedding. It is known that vortex shedding is related to separation of the boundary layer from the bluff body [1]; therefore, proper CFD modeling requires that boundary layer must be fully resolved and transient analysis techniques must be used to capture the time variant component of the flow. In industry, the preferred methods of achieving these analysis goals are either DES or LES analysis techniques [5]. In this case, there was only a three (3) week window to perform the analyses and implement any recommended corrections to the stacks' design to improve service characteristics. Amongst CFD analysts, it is accepted that:

"Resolving the viscous sublayer with LES is potentially expensive, since unlike RANS simulations, it is not sufficient to stretch the mesh only normal to the wall. The streaky structures that develop in the near-zero wall region also require adequate mesh definition in the spanwise and streamwise directions. Therefore, it might be desirable to avoid having to resolve the viscous sublayer."

Therefore, a DES solution methodology was chosen. Based on research [6, 7], the DES SST k-ω turbulence model was chosen. Successful implementation of this model requires that the grid be constructed to provide a wall y+ value less than unity [4]. To determine the level of grid refinement required to meet this value, the expected excitation velocities were predicted using empirical techniques. The frequency of excitation can be estimated using the Strouhal number, as shown in Equation 1.

$$f_s = \frac{SU}{D} \quad (1)$$

For initial calculations the Strouhal number for a cylinder in perpendicular flow can be taken as 0.4 [8]. Combining this information with the expected stack modes of vibration (determined from the modal analysis) indicated that the stacks' second mode of vibration should be excited at a wind speed of 28 mph. In this case, a grid density that should provide a nominal y+ value of 0.75 at this bulk velocity was selected. To achieve the required grid density, a linear grid bias was used in the near wall vicinity with a switch to exponential grid biasing within y+ distances below thirty (30). Figures 1 and 2 show the near-wall grids developed for both the 2D cylinder model and 3D model with strakes.

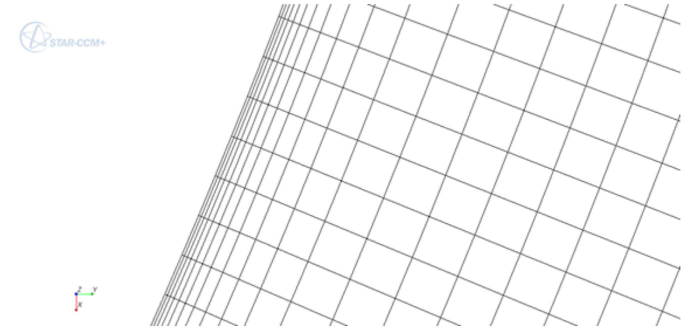

FIGURE 1 – NEAR-WALL COMPUTATIONAL GRID USED FOR 2D ANALYSIS

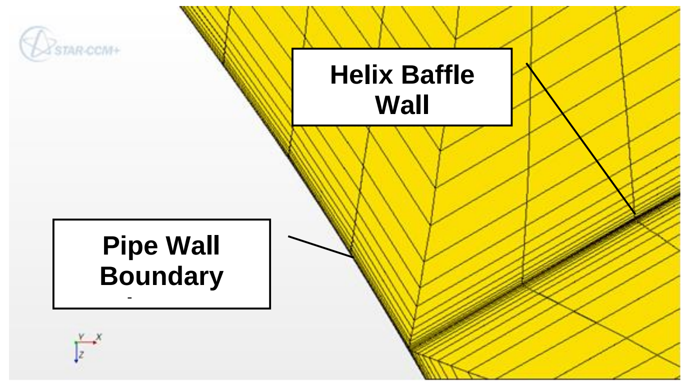

FIGURE 2 – NEAR-WALL COMPUTATIONAL GRID USED FOR PERIODIC STRAKE ANALYSIS

The model that included helical strakes used the design guidance provided in STS-1: pitch = 5 OD, extension = 10% OD [3].

Franke, et.al. provide guidance on the selection of domain size for atmospheric modeling [9]. The domain selected for analysis should extend at least 5 diameters upstream and to the side of features under consideration, and 15 diameters downstream from the features. For this modeling effort, these minimums were assigned to the domains under consideration. For both models, the inlet was treated as a velocity inlet at the bulk wind velocity under consideration. The outlet was defined as a pressure outlet and the model sides were defined as symmetry boundary conditions. For the 3D strake model one strake revolution was modeled using a zero thickness surface for the strake (i.e., the strake thickness was not considered). Periodic boundary conditions were included on the top and bottom model surfaces, approximating an infinite strake length. This technique does not capture flow effects at the end of the strake. Due to the compressed project schedule, it was determined that these effects could be considered secondary. Figure 3 shows the periodic boundaries defined for the 3D model.

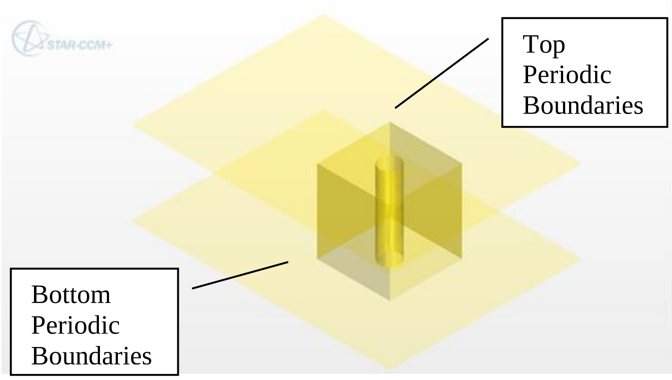

FIGURE 3 – PERIODIC BOUNDARIES DEFINED FOR 3D STRAKE MODEL

The 2D model consisted of 436,000 cells; the 3D model with strakes consisted of approximately 21.6 million computational cells.

The time-step for the analysis was based on techniques developed in previous, similar analyses performed by GE Hydro [10]. Based on the reference, acceptable results can be achieved using a time step that is 1/100th of the period under consideration. As determined from the modal analysis, the second mode of vibration for the stacks was approximately 10 Hz. For this reason, a default time-step of 0.001 seconds was used for all analyses. The analyses were allowed to proceed for a long enough period of time that the predicted forces on the stack became periodic.

The 2D model was originally analyzed at velocities of 7 (expected to excite the first stack mode) and 28 mph. Analyses at these velocities indicated a CFD-predicted Strouhal number of 0.32. In this case, the expected bulk velocity to excite the second stack mode should occur at 34 mph. For this reason, a second analysis was performed at this velocity to provide force data for the 2D model. The 3D model with strakes was analyzed at 7 and 34 mph.

CFD RESULTS

Figure 4 shows typical line velocity contours from the 34 mph analysis of the 2D cylinder. As can be seen from the figure, eddy velocities which are indicative of von Karman vortex shedding occurred downstream from the cylinder.

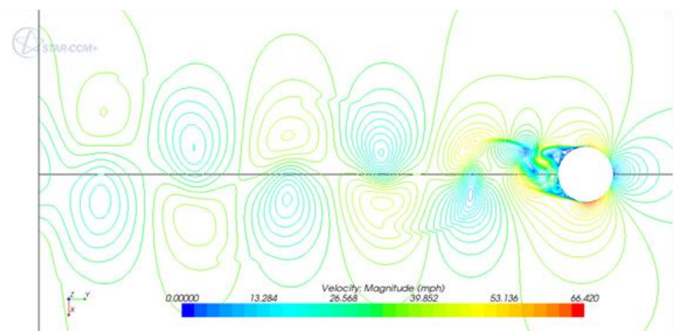

FIGURE 4 – VELOCITY CONTOURS FROM 34 MPH ANALYSIS OF 2D CYLINDER MODEL

Figure 5 shows a trace of the longitudinal force versus time extracted from the same CFD model. As can be seen in the force plot, the forcing function can be characterized as periodic, with a peak-to-peak forcing amplitude of approximately 240 lbs at a frequency of approximately 9.4 Hz.

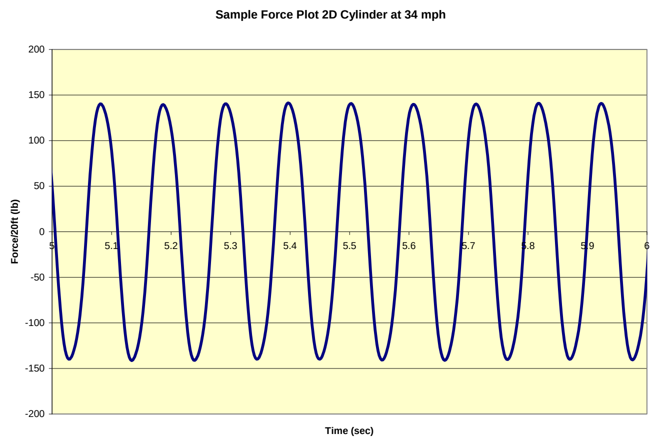

FIGURE 5 – LONGITUDINAL STACK FORCE FOR 34 MPH 2D CYLINDER MODEL

Figures 6 - 8 show typical velocity contours downstream from the stack for the 3D helical strake model with a bulk wind velocity of 34 mph. While initial review of the velocity profiles seems to indicate that coherent flow structures exist downstream from the stack, further review demonstrates that the shape and position of the flow structures downstream from the stack are not consistent.

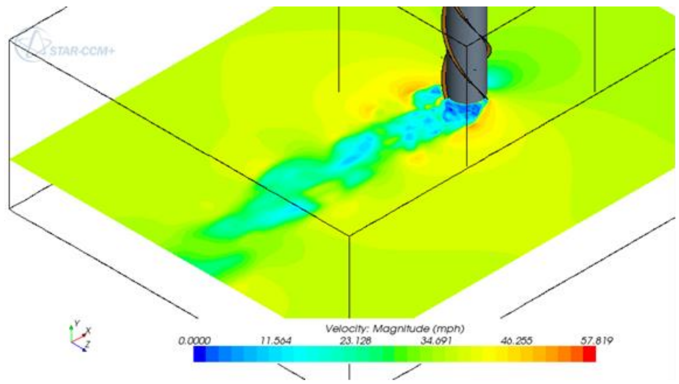

FIGURE 6 – FLOW VELOCITIES DOWNSTREAM FROM 3D STACK WITH STRAKES, 0.75 m ABOVE LOWER PLANE

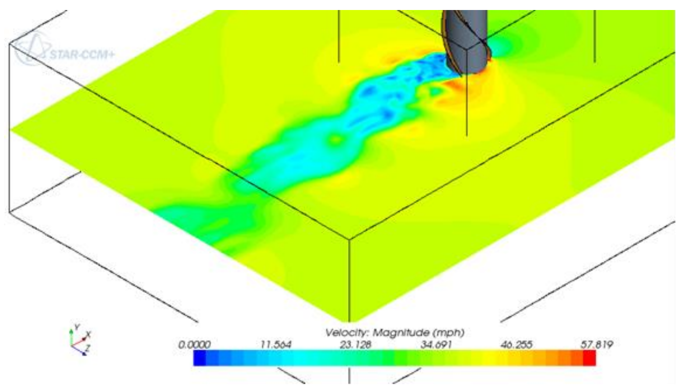

FIGURE 7 – FLOW VELOCITIES DOWNSTREAM FROM 3D STACK WITH STRAKES, 1.25 m ABOVE LOWER PLANE

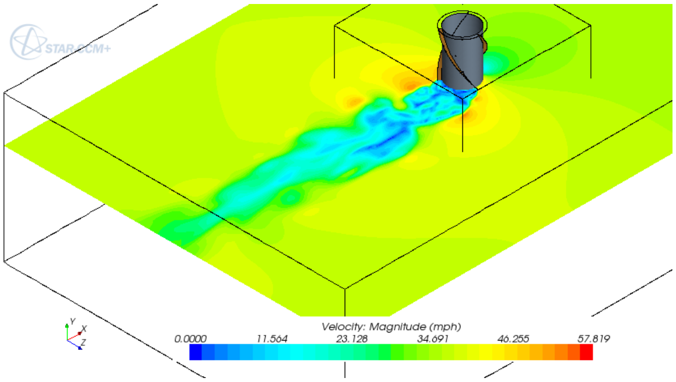

FIGURE 8 – FLOW VELOCITIES DOWNSTREAM FROM 3D STACK WITH STRAKES, 1.75 m ABOVE LOWER PLANE

Figure 9 shows the longitudinal force occurring on the stack with helical strakes. As can be seen from the figure, there is a time varying component to the stack force. However, no true coherent structures exist in the trace. Where the cylinder model exhibited a very periodic force behavior, the strake model exhibits small amplitudes for the time-varying force components with a static offset, indicating wide spectrum stack excitation. As specified in STS-1 this increased static force caused by an increased coefficient of drag should be considered in the stack's design. While the final C_d calculated for the stack is not presented with this paper the ASME-specified value of 1.4 was shown to be slightly conservative when compared to the CFD calculated values.

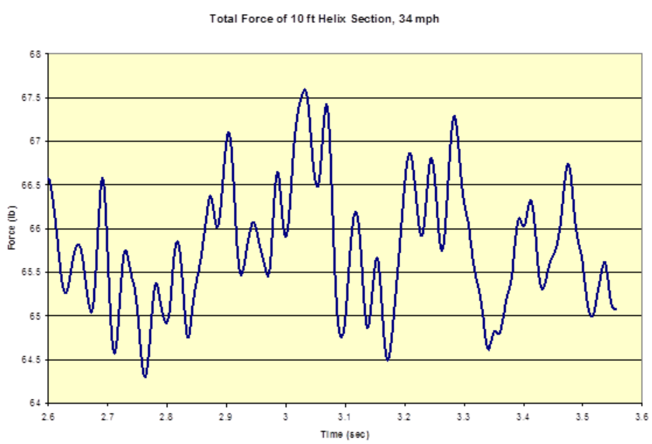

FIGURE 9 – LONGITUDINAL STACK FORCE FOR 34MPH 3D MODEL WITH HELICAL STRAKES

FE MODEL

Afinite element model was constructed of the stack, as shown in Figure 10.

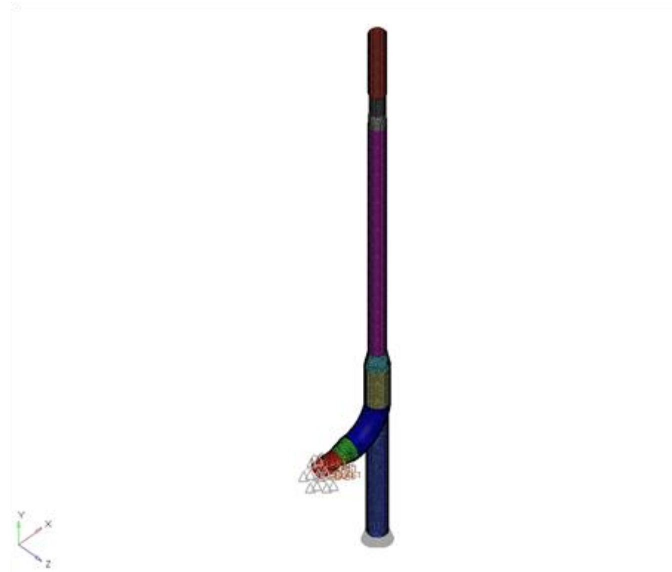

FIGURE 10 – FE MODEL OF AS-INSTALLED STACK

The model consisted of 14,272 shell elements and 12 spring elements used to represent the flexible coupling between the stacks and the adjacent building. Initially, a modal analysis was performed to determine the fundamental frequencies of excitation for the stack. As previously described, this information was required for development of the CFD models. The stack geometry was not perfectly symmetric. For this reason the modal analysis indicated that there were two modes clustered at both the first and second fundamental frequencies.

To validate the CFD model, a second analysis was performed to predict the stacks' displacement due to the CFD-predicted dynamic loads. To perform this analysis, the CFD-predicted Strouhal number (0.32) was used to estimate the exciting frequency at wind speeds from 0 to 45 mph. From first principles, it is expected that the energy in the flow is proportional to the square of the bulk wind velocity. For this reason, a second-order fit was performed using the forces predicted in the three (3) CFD analyses performed on the 2D model. This fit was then used to predict the magnitude of the forcing function over the same bulk wind speed range. Figure 11 shows the input forcing functions developed for the frequency response analysis. These functions were input to the FE model at a position 5/6th of the distance up the stack, as specified in STS-1 [3]. A frequency response analysis was performed using Algor's frequency response module [11] with an assumed damping of 2%.

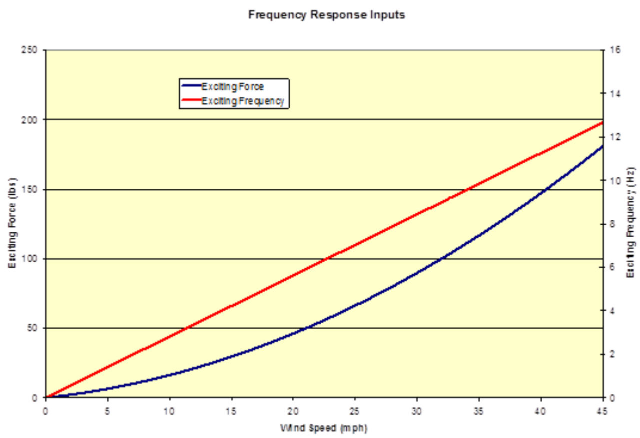

FIGURE 11 – INPUT FORCING FUNCTIONS FOR FREQUENCY RESPONSE ANALYSIS

Figure 12 shows the predicted displacements at the tip of the stack. As can be seen from the figure the stack displays two primary excitations, at wind speeds of approximately 7 and 34 mph. The tip displacements are approximately 1”, which compared favorably with the field-measured displacements. This agreement provided validation of the CFD techniques used in the 2D analysis, allowing for a degree of confidence in the forces predicted for the model incorporating helical strakes.

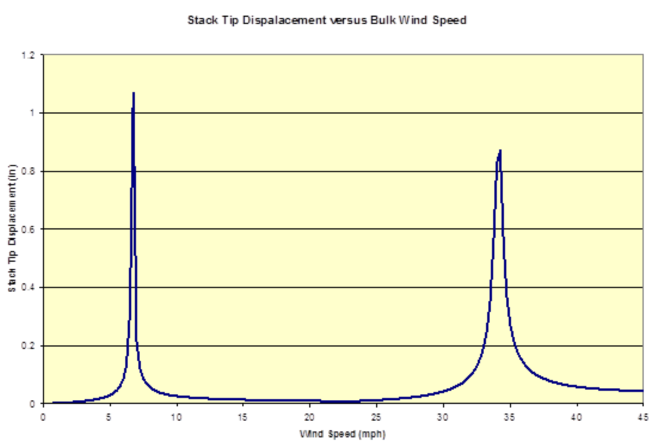

FIGURE 12 – PREDICTED STACK TIP DISPLACEMENTS VERSUS WIND SPEED

CONCLUSIONS

Unexpected in-service vibrations occurred with a set of stacks due to von Karman vortex shedding. API 560 indicates that straight strakes can be suitable for minimizing or eliminating vibrations caused by vortex shedding. In this case, this solution was adopted, allowing for field installation. It was found that the strakes provided little or no improvement in the stacks’ dynamic response. Inspection of the stacks after the installation of the strakes indicated the initiation of cracks in welds located at the stacks’ base. The decision was made to uninstall the stacks for weld repair and the incorporation of design features to minimize the stacks’ dynamic response.

Based on the performance of the straight strake solution it was decided to develop a validated numerical model to predict the effectiveness of any proposed solutions. To accomplish this task, a simplified CFD model was constructed of the baseline stack configuration. This model was then analyzed to predict the time varying forcing functions occurring on the stack. These predicted forces were then used as inputs to a frequency response model that demonstrated good agreement with site measured stack displacements. This agreement provided validation of the techniques adopted for the CFD analysis and allowed a degree of confidence in the proposed stack modifications.

The analyses presented in this paper do not match the “textbook” recommended procedures for numerical analysis, including grid and boundary condition sensitivity studies. In this case incorporating thorough literature research on best-practices and the state-of-the-art of the tools, then implementing these practices up-front in the analysis process, it was shown that complex analyses can be completed in a short time-frame.

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