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Full-scale experiments of cantilever traffic signal structures

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Abstract. Wind-induced vibrations of mast arms of cantilever traffic signal structures can lead to fatigue failure. Two such structures were instrumented each with a sonic anemometer and a camera that records the motions of the tip of the arm. It was observed throughout this experiment that large amplitude vertical vibrations of mast arms with signals with backplates occur for the most part at low wind speed ranges, between 2 to 7 m/s, and as the wind speed increases the amplitude of the vertical vibrations decreases. The results of these experiments contradict the generally accepted belief that vortex shedding does not cause significant vibrations of mast arms that could lead to fatigue failure, which have been attributed to galloping in the past . Two damping devices were tested with mixed results.

Keywords: cantilevered traffic signal structures; fatigue; wind-induced vibrations; galloping; vortex shedding; vented backplates; damping plate

1. Introduction

Traffic signals (or traffic lights) are used extensively around the world. The signals, as well as their supporting structures, are manufactured in many different sizes and shapes. A commonly used support for traffic signals is the cantilever traffic signal structure. Fig. 1 shows an example of this type of structure in which the vertical component is usually referred to as the post or the pole and the horizontal element is usually referred to as the mast arm. Both the pole and the mast arm are usually made of hollow galvanized steel with circular or octagonal cross-section and tapered diameters. In Texas, poles typically are 5 to 6 m high and arms have lengths in the range of 5 to 15 m (Pulipaka 1995), although the Texas Department of Transportation (1995) uses designs for arms that go up to 20 m in length. Often the arms are manufactured in different shapes. The signal light heads supported by the mast arm are usually either 3-light heads or 5-light heads. For example, in Figure 1 the arm supports one 5-light head and two 3-light heads. Signal light heads can have backplates, which are flat plates that surround the signals extending half a light width. Backplates are usually solid and black and have the purpose of offering drivers better visibility of the signal lights against the sun. The mast arms usually have a low resonant frequency of about 1 Hz and a damping of less than 1% of critical damping (Dexter and Ricker 2002). Therefore, they have the propensity to vibrate under wind loading. Vibrations of mast arms can occur at wind speeds as low

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as 4.5 m/s (Pulipaka *et al*. 1998) or they may also be provoked by truck-induced gusts (Kaczinski *et al*. 1998).

Fig. 1 Cantilever traffic signal structure with straight mast arm

According to Dexter and Ricker (2002), the span of mast arms of cantilever traffic signal structures and other similar sign and light support structures has increased because “the setback distance of the upright from the roadway has increased for safety reasons and these structures are increasingly being used on roads with more lanes.” Typically, the longer the mast arm, the more flexible the structure is, and larger vibration amplitudes can be expected. If the vibrations of the mast are too large, they could make it difficult for drivers to see the signals or drivers could feel uncomfortable while driving under the vibrating structure (Kaczinski *et al*. 1998). Also, vibrating mast arms could create a distraction to passing motorists (Pulipaka 1995). Many drivers complain when the vibrations exceed 200 mm (Kaczinski *et al*. 1998).

Fig. 2 Fatigue failure of mast arm in Lubbock, Texas

More importantly, vibrations of the mast can be a bigger problem because they could lead to fatigue failure. Fig. 2 shows one example of the many failures reported by state departments of transportation. The state of Missouri had over 12 traffic signal mast arms fail in a period of six years (Hartnagel and Barker 1999). Similar failures have been reported in Wyoming, California, and Texas (Chen *et al*. 2001).

Vortex shedding, galloping, natural wind gusts, and truck-induced gusts have been identified as potential wind loading phenomena that could lead to excessive vibrations and fatigue of signal, sign, and light cantilever support structures (Kaczinski *et al*. 1998). In their latest edition, the AASHTO Specifications (2001) take into consideration these phenomena in the section dedicated to fatigue design. For the specific case of cantilever traffic signal structures, experimental results (Pulipaka 1995) have led researchers to believe that; galloping is the main cause of large-amplitude vibrations that cause the fatigue failure of mast; that natural wind gusts are a contributor to fatigue failure, but that vortex shedding does not cause significant vibrations and the effects of truck-induced gusts appear to be negligible, as suggested by recent research (Hartnagel and Barker 1999, Chen *et al*. 2001, Albert 2006). This is reflected in the AASHTO Specifications (2001) which do not consider vortex shedding in the fatigue design of cantilever traffic signal structures.

The objectives of this research were to determine the mechanisms that lead to mast arm vibrations and their significance in contributing to the fatigue failure of these structures. In addition, the effectiveness of various damping devices, vented backplates and damping plates in reducing wind-induced vibrations were to be evaluated. Full-scale experiments and wind tunnel tests were conducted in order to achieve this objective. Only the full-scale experiments are discussed in this paper with more comprehensive wind tunnel tests reported in a parallel paper.

Fig. 3 The two cantilever traffic signal structures tested at Reese Technology Center

2. Experimental set-up

Full-scale field experiments were conducted with two out-of-service cantilever traffic signal structures installed at the Reese Technology Center facilities of the Wind Science and Engineering Research Center of Texas Tech University (see Fig. 3). Each structure is instrumented with a sonic anemometer mounted on the pole above the mast together with a collocated video camera monitoring the motion of the tip of the cantilever mast arm.

The two structures tested are known as Traffic Signal 1 (TS1) and Traffic Signal 2 (TS2). Both TS1 and TS2 are fabricated from steel and have straight arms, 18.3 m in length for TS1 and 13.4 m for TS2. TS1 has one 5-light signal head and three 3-light signal heads; while TS2 has one 5-light signal head and two 3-light signal heads. All signals have removable backplates. The light heads are mounted horizontally at the same height of the mast arm. A street sign is also attached on the arm near the mast. More details of the geometry and light configuration of the structures for the case when the signals have backplates are shown in Figs. 4 and 5. Details of the dimensions of the signal light heads are shown in Fig. 6.

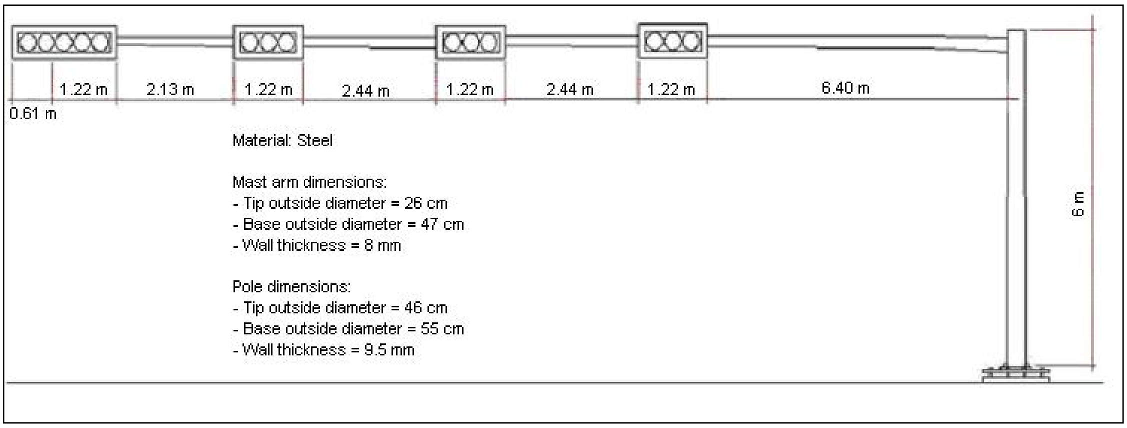

Fig. 4 Geometry and light configuration of TS1 (18.3-m mast arm)

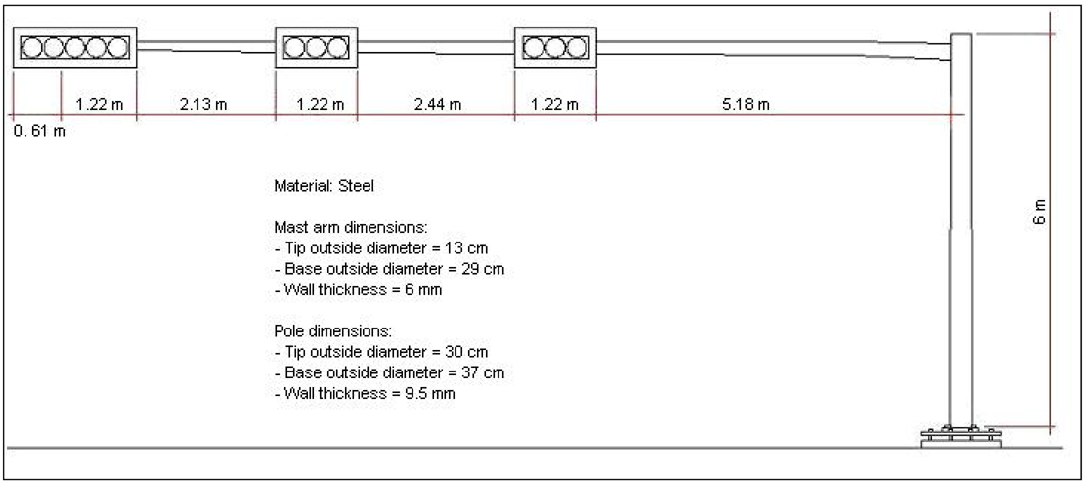

Fig. 5 Geometry and light configuration of TS2 (13.4-m mast arm)

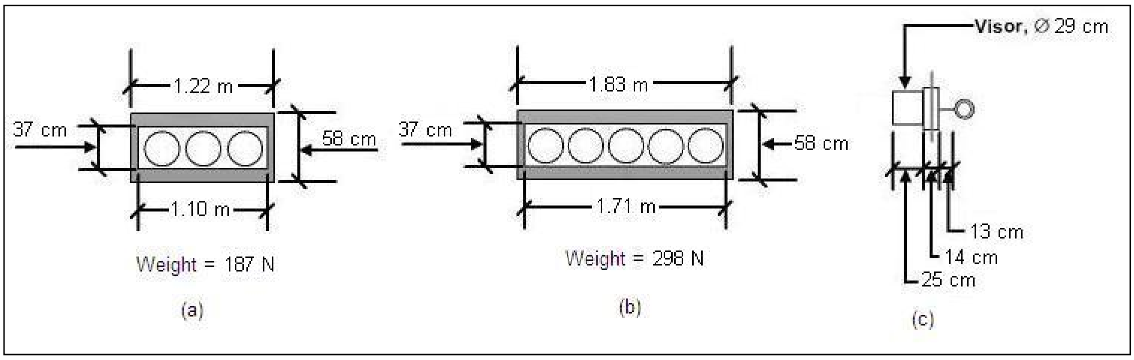

Fig. 6 Dimensions of signal light heads (shown with backplates): (a) 3-lights head, (b) 5-light head and (c) side view of 3- and 5-light heads

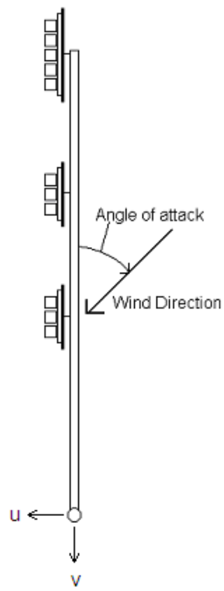

Fig. 7 Anemometer orientation and angle of attack sign convention

Each structure rests on a foundation that allows the whole pole/mast arm assembly to be rotated in 15^{o} increments of direction. Each foundation consists of a circular steel plate on top of a reinforced concrete pile.

The instrumentation consists of the following:

- Infrared target made of two Nerlite S-40 infrared lights. The target is rigidly attached near the tip of the arm.
- Basler A601 video camera with National Instrument Compact Vision System (CVS) 1454 to collect displacement data. The camera and the CVS are placed inside a camera enclosure which is mounted on top of the mast, pointing towards the tip of the arm. The camera has a filter to capture only the two lights of the infrared target and has a resolution of 3 mm at a distance of

18.3 m from the target and is set for a sampling rate of 30 Hz. The position of each infrared light is collected and used to calculate the X and Y coordinate in pixels of the midpoint between the two lights. These instruments are calibrated by using the physical separation of the centers of the infrared lights (G Systems 2005).

- R. M. Young Model 81000 ultrasonic anemometer mounted about 1.2 m above the top of the pole. The anemometer measures three-dimensional wind velocity and is also sampled at 30 Hz. It collects u, v, and w wind components as voltages. The anemometer is oriented so that positive u and v are measured as shown on Fig. 7, with w being the vertical component which is positive going upwards. Also shown on Fig. 7 is the angle of attack sign convention. The anemometers were calibrated by the manufacturer in a wind tunnel before data collection began.
- National Instruments FP-2000 Intelligent Ethernet Controller Interface for FieldPoint which gathers the data from the anemometer and the camera and sends it to a computer at the field site.

This instrumentation only measured the relative displacement of the tip of the arm with respect to the mast/pole top. It did not account for any displacement of the pole itself. This research concentrated on this relative displacement because most fatigue failures occur in the arm, close to where it connects to the pole (Pulipaka 1995, Gray *et al*. 1999, Hartnagel and Barker 1999, Hamilton *et al*. 2000, Chen *et al*. 2001, Cook *et al*. 2001).

The field site computer has software developed by G Systems (2005) and designed to save the data collected by four instruments:

1. Anemometer of TS1,
2. Camera of TS1,
3. Anemometer of TS2, and
4. Camera of TS2.

The software starts recording data from all four instruments at the same time. Fifty nine minutes later, the software stops recording, saves a time history file for each of the four instruments, and one minute later starts data collection again.

Approximately once a week, the recorded data was taken from the field computer and saved on a server at the Wind Science and Engineering Research Center. There the data was processed with software developed at Texas Tech. This software combines the four hour-long files and converts voltages to engineering units (m/s and mm, respectively).

Wind data from the West Texas Mesonet station located at Reese Technology Center was sporadically used for comparison to assure that the data collected by the anemometers on the traffic signals was of good quality. This station is located less than 460 m away from the signals.

To monitor the quality of the data collected by the camera, the time history of the X and Y coordinates of the two infrared lights was used to calculate a time history of the distance between the two infrared lights of each hour-long file. This calculated distance should remain close to constant, since the actual distance of the lights never varies. If a run had an average value with an error of more than 1.5%, then the run was not considered of good quality and it was not used for analysis of results.

2.1 Pluck test

A pluck test was conducted to determine the fundamental (first mode) frequency of vibration in the horizontal and vertical directions and the associated damping ratios of the arms of the two traffic signal structures. The tests were conducted by pulling and pushing the tip of the arm in either the horizontal or the vertical direction and then letting the arm vibrate freely in the first mode until it stopped. Fundamental frequency was determined from cycle counting, while log decrement was used to estimate damping. The results obtained for three runs were used to calculate average values of fundamental frequency and damping ratio. These values are presented in Table 1. From a Finite Element Analysis, the in-plane (vertical) fundamental frequency of TS1 and TS2 were determined to be 1.089 Hz and 1.181 Hz, respectively. These yield a percentage difference of 10.5% and 18.6% for TS1 and TS2, respectively.

Table 1 Fundamental frequency (f_o) and damping ratio (ζ) of mast arms

Mast Arm Length		18.3 m	13.4 m
f_o	Horizontal	0.92 Hz	0.89 Hz
	Vertical	0.98 Hz	0.98 Hz
ζ	Horizontal	0.25%	0.55%
	Vertical	0.23 %	0.28 %

Table 2 Experimental program

Data Mode	Experiment description	Direction to which mast arm points	Dates
Test	Signals with backplates	East	March 2005
1100	Signals with backplates	North	Apr. 2005 – Mar. 2006
1101	Signals without backplates	North	Mar. 2006 – Feb. 2007
1102	Used for equipment adjustment	North	March 2007
1103	Signals with vented backplates	Southeast	March – June 2007
1104	Used for equipment adjustment	southeast	June 2007
1105	Signals with backplates and mast arm with damping device	southeast	July – Sept. 2007

2.2 Experimental Program

The experimental program is summarized in Table 2 with each experiment given a mode number, with each Mode defining a different structure orientation or signal modification. The ability to rotate the arms on the specially designed foundations allowed for a greater range of wind directions to be studied.

3. Analysis of results

3.1 Analysis of March 29, 2005 data

On March 29, 2005, data was recorded only for TS2 (13.4 m arm) when it was recently operational and had its arm pointing east and signals with backplates. The instrumentation recorded vertical vibrations of the arm tip with peak-to-peak oscillations as large as 28 cm. Figure 8 presents the structure's response over a 10 hour period. The u-, v-, and w-components were vectorially added to obtain a time history of the total wind speed and the u- and v-components were used to calculate the angle of attack (with sign convention shown in Fig. 7).

The following observations are made:

- Horizontal vibrations had larger amplitudes when the wind was more turbulent.
- Vertical vibrations had larger amplitudes when the total wind speed averaged between 4.5 and 5.5 m/s and when the wind direction was between 90 and120 degrees.
- Vertical vibrations reached much higher amplitudes than horizontal vibrations.
- There was no correlation between the two vibration modes.

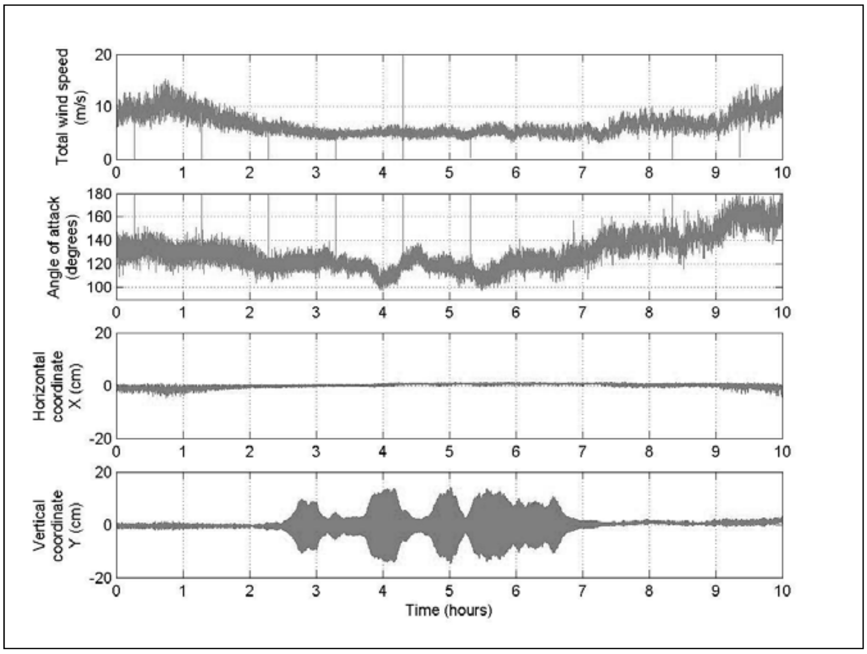

Fig. 8 Time histories of total wind speed, angle of attack, and tip displacement

After evaluating sample lengths of between 30 and 300 seconds, 100 cycles of vibrations was selected for subsequent analyses. Knowing that the fundamental frequency of the structure is close to 1 Hz, the data presented in Fig. 8 was divided into smaller segments of 100 seconds. For each segment the mean and the standard deviation of the total wind speed and the angle of attack were calculated, along with the standard deviation of the horizontal and the vertical displacements. These values were used to produce the plots presented in Figs. 9 to 11.

The results indicate that there was a slight increase in horizontal vibration amplitudes over the wind speeds measured (4-12 m/s) but more significantly high-amplitude vertical vibrations were observed when the total wind speed was between 4.5 and 5.5 m/s as shown in Fig. 9. No clear relationship was observed between the horizontal and the vertical vibrations with the turbulence intensity.

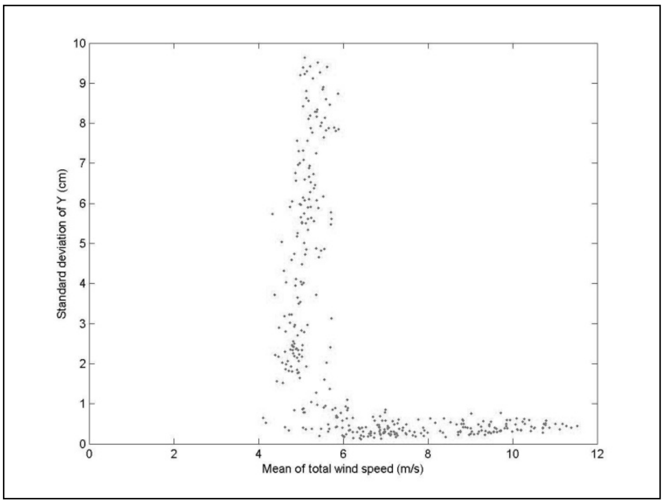

Fig. 9 Effect of total wind speed on vertical vibrations of the arm

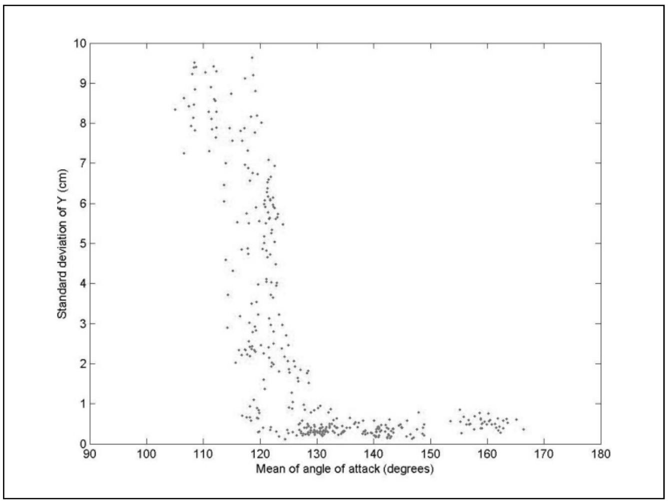

Fig. 10 Effect of wind angle of attack on vertical vibrations

Fig. 10 shows that larger vertical vibrations occurred when the angle of attack was below 130°.

There was no significant relationship between horizontal vibration and wind direction. While lateral turbulence (variation in wind direction) did not have a great influence on horizontal vibrations, lower values of lateral turbulence were associated with higher vertical vibrations.

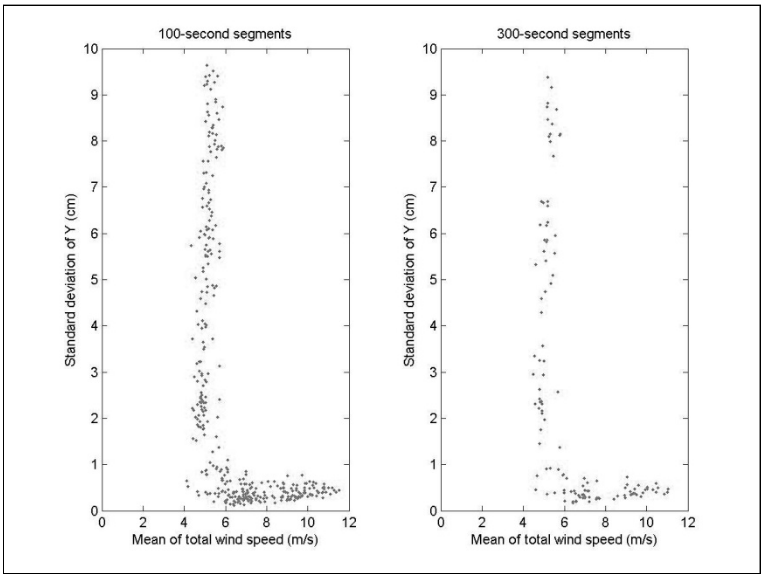

Fig. 11 Comparison of data analysis using segments of 100 and 300 seconds

This initial analysis was undertaken using data segments of 100 seconds. Data was also analyzed using longer and shorter segments and the same trends were observed as evidenced in Fig. 11 where data for 100- and 300-second segments are presented. In both cases it can be seen that high-amplitude vertical vibrations are observed when the total wind speed is between 4.5 to 5.5 m/s. This is not unexpected since with a natural frequency of ~1 Hz, 100 seconds is capturing a significant number of oscillations, and yet is small enough to not be influenced by wind speed and direction changes.

The Strouhal number (*St*) when the wind was approximately perpendicular to the arm vibrating at 0.98 Hz and using a wind speed (*U*) of 5 m/s and a cross-wind body width (*B*) of a traffic signal head with backplate is

$$St = f\,B\,/\,U = (0.98\text{ Hz})\,(0.58\text{ m})\,/\,(5\text{ m/s}) = 0.114$$

The Strouhal number for a flat plate perpendicular to the flow is ~0.15 (Blevins 1977, Hirsch and Bachmann 1995) and for flat plates with trailing features or T-shaped *St* ranges from 0.11 to 0.14 (ASCE 1961). The value obtained here lies within this range. In addition the response shown in Figs. 8 and 9 demonstrates the classic ‘lock-in’ phenomena of vortex shedding.

3.2 Data mode 1100 analysis

From April 2005 to March 2006, data was collected under Mode 1100 with the arm pointing north and the signals having backplates. During this period, 4858 hours of data were collected for each TS1 and TS2. All the data was analyzed by dividing the long time histories into 2-minute segments, calculating summary statistics for the different measured parameters. Some of the results are presented and discussed here. Outlying data points have been retained for completeness and have not been individually validated.

Figs. 12 and 13 show the effect of the mean wind speed (the vector sum of u, v, and w) on the vertical vibrations of the mast arm of TS1 and TS2, respectively. In both cases, the standard deviation of vertical displacement (Y) never exceeds 5 cm when the mean wind speed is over 10 m/s.

Figs. 14 and 15 show the effect of wind direction on the vertical vibrations of the arms of TS1 and TS2, respectively. (The sign convention of the angle of attack was given in Fig. 7.) For the case of TS1, there is a concentration of cases at around 60 and 300 degrees, but again very few cases exceeded a standard deviation of Y of 5 cm. For both TS1 and TS2, most of the higher vibrations (standard deviation of Y over 5 cm) occur between 0 and 180 degrees, which corresponds to when there is a wind component blowing from the back of the signals. The exceptions are one and three data points for TS1 and TS2, respectively.

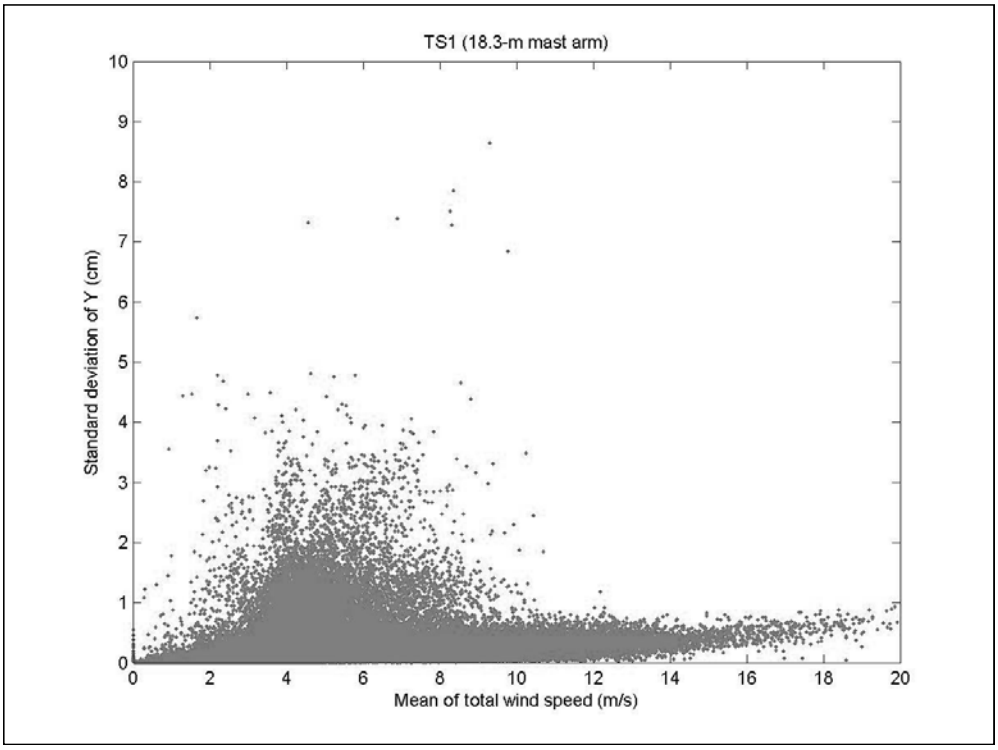

Fig. 12 Effect of mean wind speed on vertical vibrations of TS1 with backplates

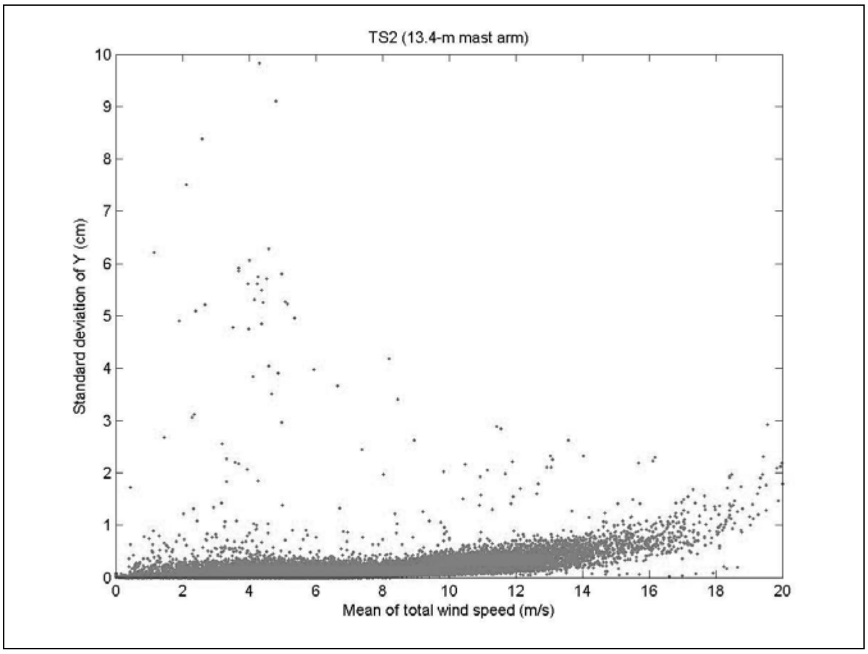

Fig. 13 Effect of mean wind speed on vertical vibrations of TS2 with backplates

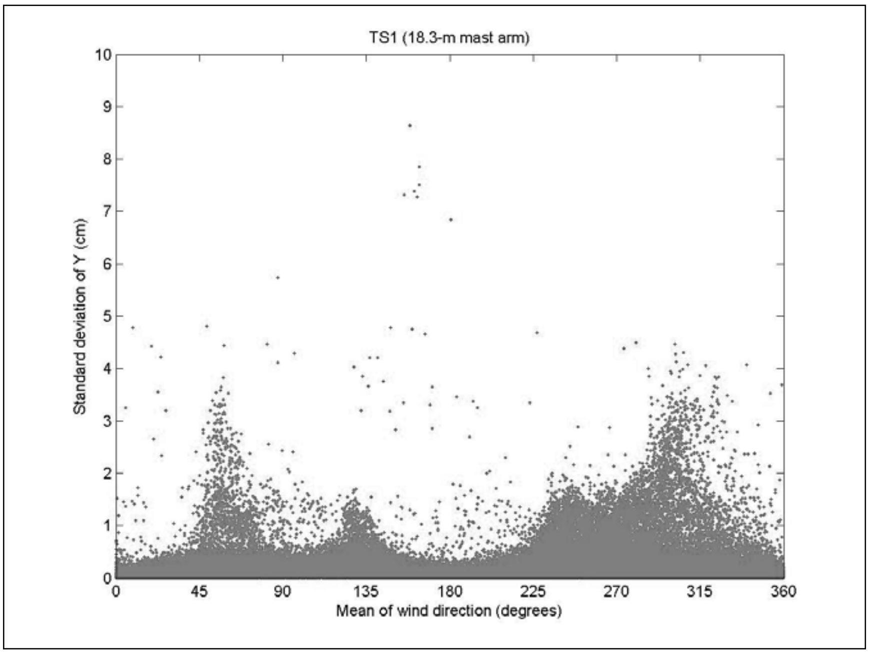

Fig. 14 Effect of angle of attack on vertical vibrations of TS1 with backplates

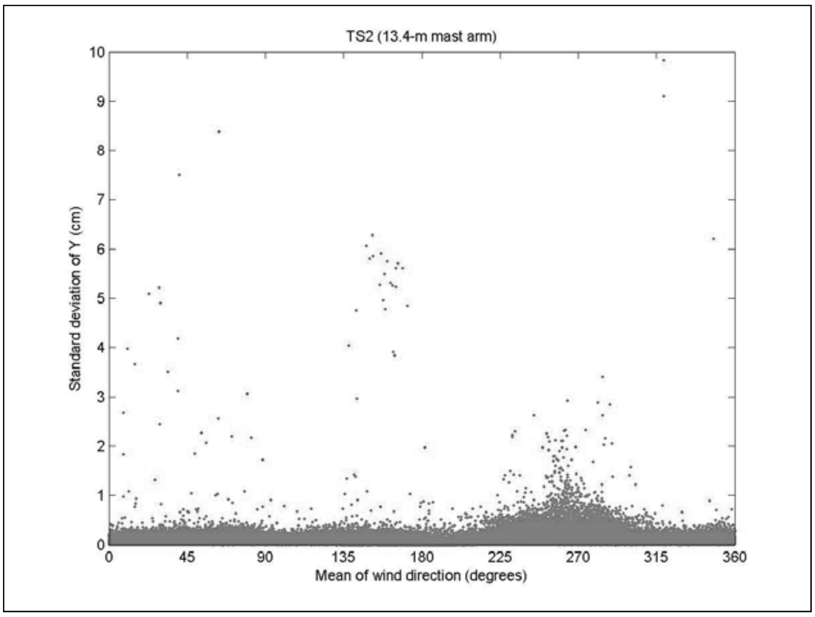

Fig. 15 Effect of angle of attack on vibrations of TS2 with backplates

Very few cases of large vibrations were observed under Data Mode 1100, possibly because wind conditions were less than ideal given that most of the time the angle of attack was between 180 and 360 degrees.

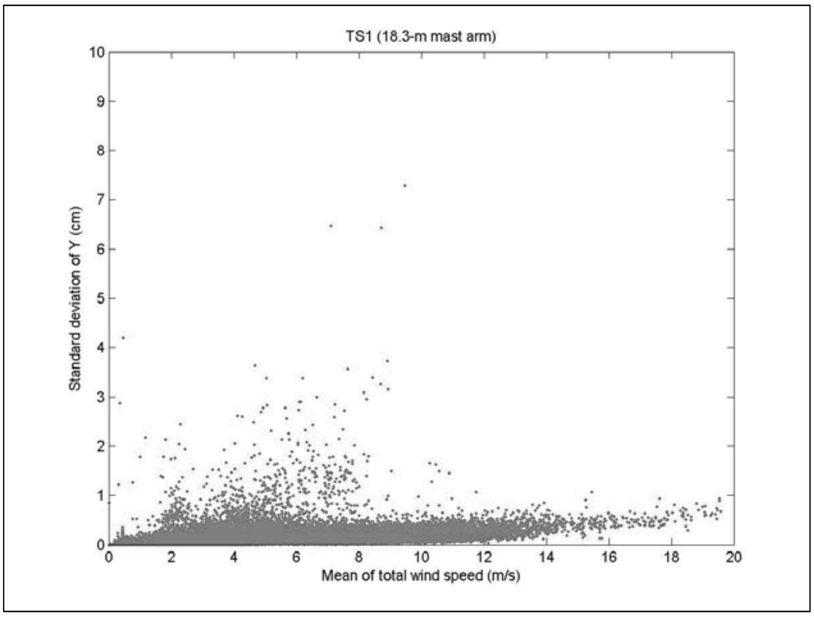

Fig. 16 Effect of mean wind speed on vertical vibrations of TS1 without backplates

3.3 Data mode 1101 analysis

From March 2006 to February 2007, data was collected under Mode 1101 with the arm pointing north and backplates removed. During this period, 2862 hours of data were collected for TS1 and 2037 hours of data were collected for TS2. Again all data was analyzed by dividing the long time histories into 2-minute segments and calculating summary statistics for the different measured parameters.

Figs. 16 and 17 show the effect of the mean wind speed on the vertical vibrations of the mast arm of TS1 and TS2, respectively. Comparing Figs. 12 and 16, TS1 Response, there is clearly a much weaker vertical response without backplates. Without backplates TS2 did not exhibit any significant response (no standard deviation higher than 5 cm).

The effect of wind direction on the vertical vibrations of the arms of TS1 and TS2, respectively did not indicate anywhere near the directional dependency shown in Fig. 14 for TS1.

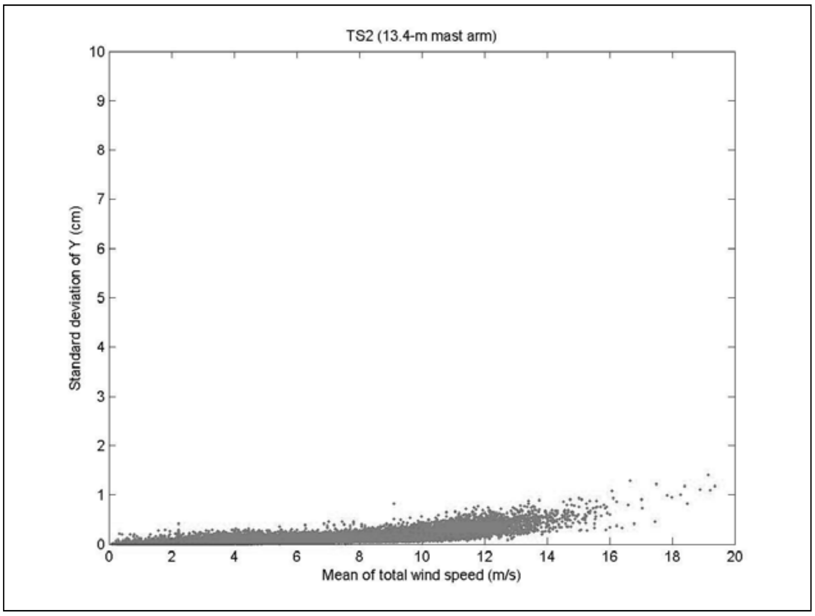

Fig. 17 Effect of mean wind speed on vertical vibrations of TS2 without backplates

3.4 Data mode 1103 analysis

From March to June 2007, data was collected under Mode 1103 with the arm pointing southeast and the signals having vented backplates. The vented backplates (manufactured by Econolite) are similar to the regular backplates used in Mode 1100, except that these backplates consist of louvers. During this period, 2613 hours of data were collected for TS1 and 2481 hours were collected for TS2. As usual, all the data was analyzed by dividing the long time histories into 2-minute segments and summary statistics for different measured parameters calculated.

Figs. 18 and 19 show the effect of the mean wind speed on the vertical vibrations of TS1 and

TS2, respectively. In the case of TS1, higher than average values of the standard deviation of Y were observed when the mean of the total wind speed was about 5.5 m/s. Again, there was no discernible pattern for TS2.

Fig. 20 shows the effect of wind direction on the vertical vibrations of TS1. Here higher than average values of the standard deviation of Y were observed when the mean wind direction was about 300 degrees. For the case of TS2, there was again no discernible relationship of response with wind direction.

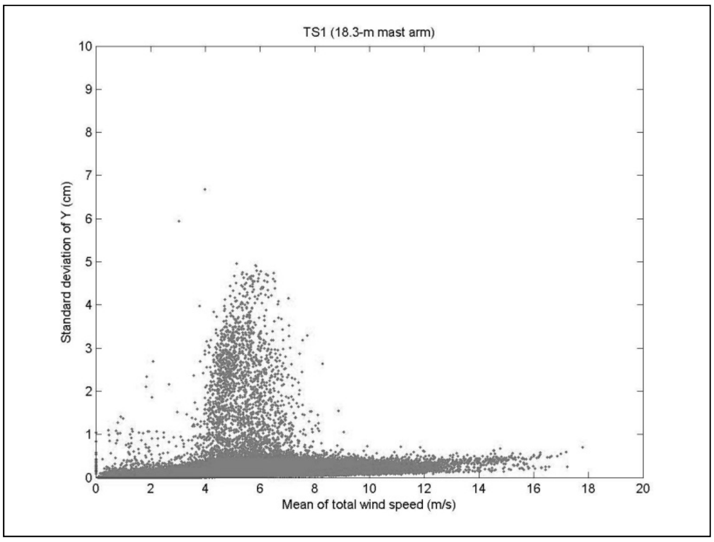

Fig. 18 Effect of mean wind speed on vertical vibrations of TS1 with vented backplates

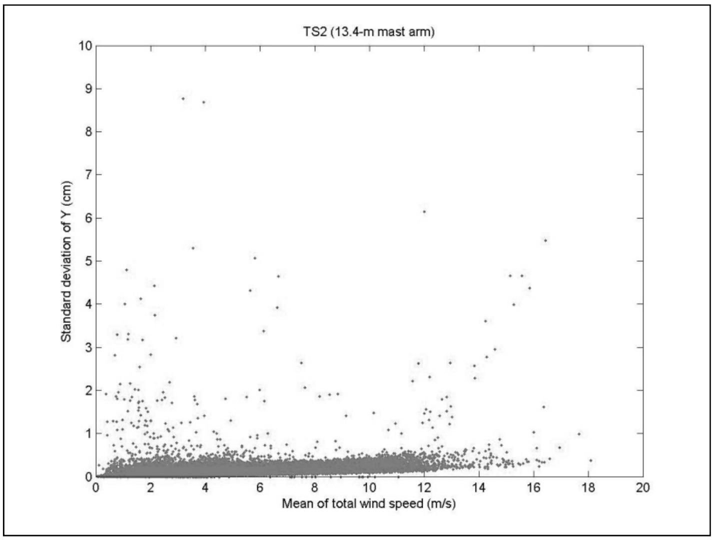

Fig. 19 Effect of mean wind speed on vertical vibrations of TS2 with vented backplates

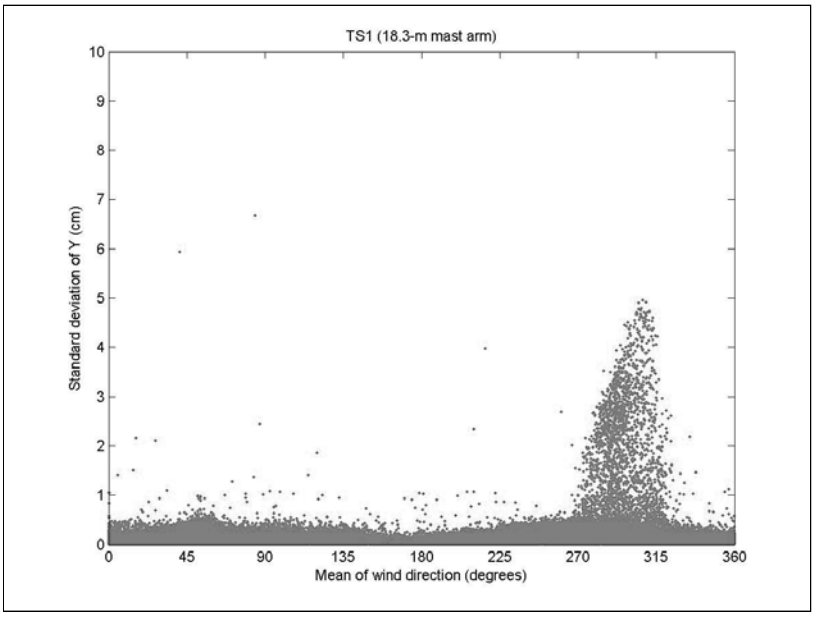

Fig. 20 Effect of wind direction on vertical vibrations of TS1 with vented backplates

3.5 Data mode 1105 analysis

From July to September 2007, data was collected under Mode 1105 with the arms pointing southeast and the signals having regular backplates. In addition, each arm had a plate installed as a damping device, as shown in Fig. 20. Each plate was 1.5 by 0.4 m and was located 140 mm above the top of the mast arm. For TS1, the center of the plate was located 2.2 m from the tip of the arm, while for TS2, the center of the plate was located 2.1 m from the tip of the arm.

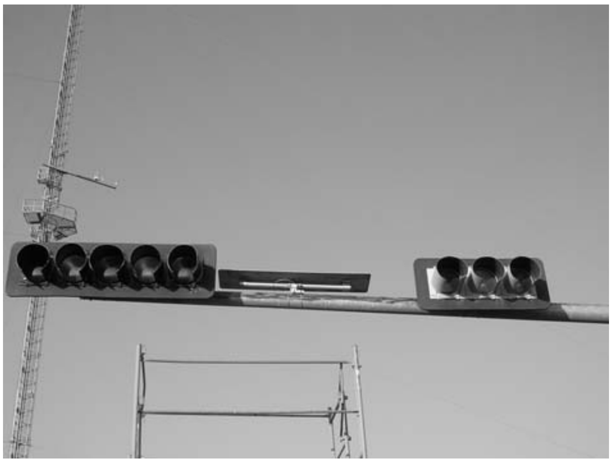

Fig. 21 Mast arm with damping plate

During this mode, 1175 hours of data were collected for both TS1 and TS2. As before, all data was analyzed by dividing the long time histories into 2-minute segments and summary statistics for different measured parameters calculated.

Figs. 22 and 23 show the effect of the mean wind speed on the vertical vibrations of TS1 and TS2, respectively. For the case of TS2, the standard deviation of Y was over 5 cm mostly when the mean of the total wind speed was about 3 m/s.

Figs. 24 and 25 show the effect of wind direction on the vertical vibrations of TS1 and TS2, respectively. In the case of TS2, the standard deviation of Y was over 5 cm mostly when the mean wind direction was about 50 degrees.

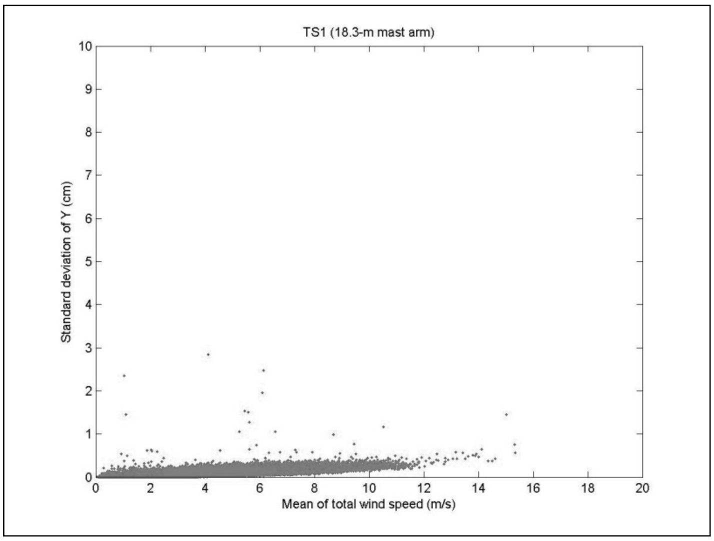

Fig. 22 Effect of mean wind speed on vertical vibrations of TS1 damping plate

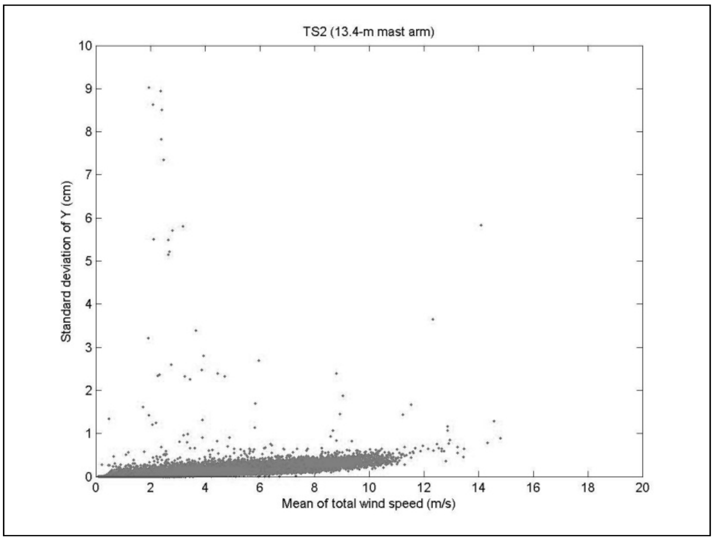

Fig. 23 Effect of mean wind speed on vertical vibrations of TS2 with damping plate

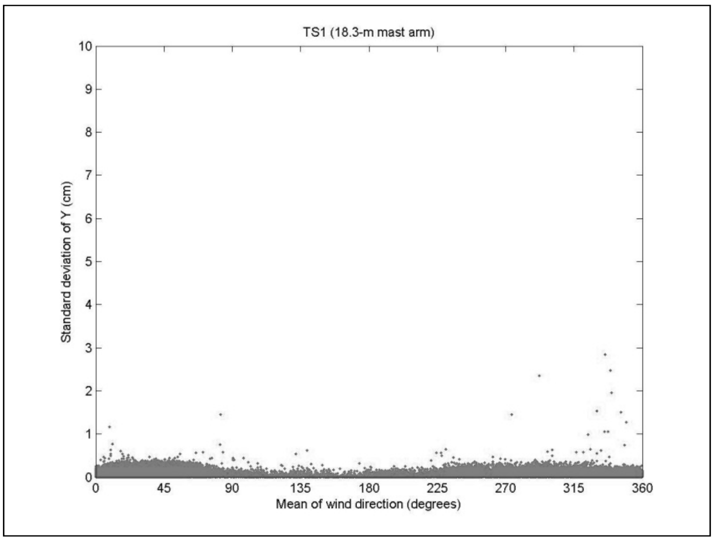

Fig. 24 Effect of wind direction on vertical vibrations of TS1 with damping plate

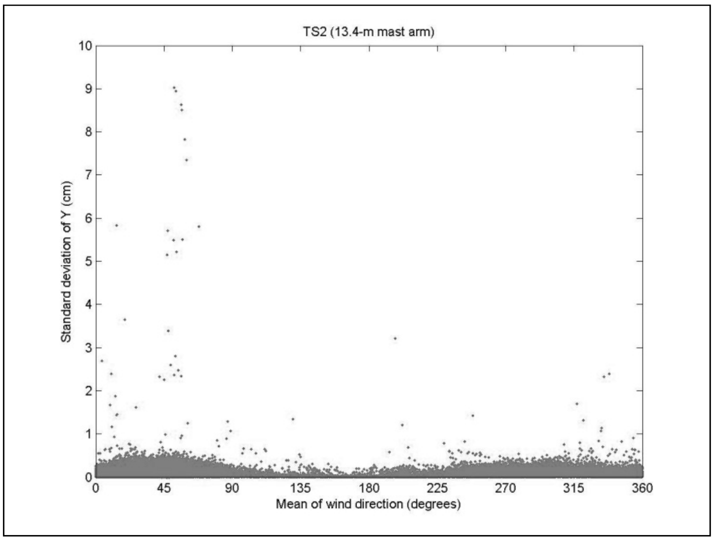

Fig. 25 Effect of wind direction on vertical vibrations of TS2 with damping plate

3.6 Discussion of results

To compare the results obtained for the different data modes, the calculated standard deviations of the vertical displacement data were segregated into angle of attacks discrete categories. The discrete categories used were 0° - 30°, 30° - 60°, 60° - 90°, … , 330 - 360°. Then for each category, the mean of the standard deviation values of Y was calculated. Thus Figure 26 shows a plot of the mean values for each angle of attack discrete category (the horizontal axis shows the midpoint of the category).

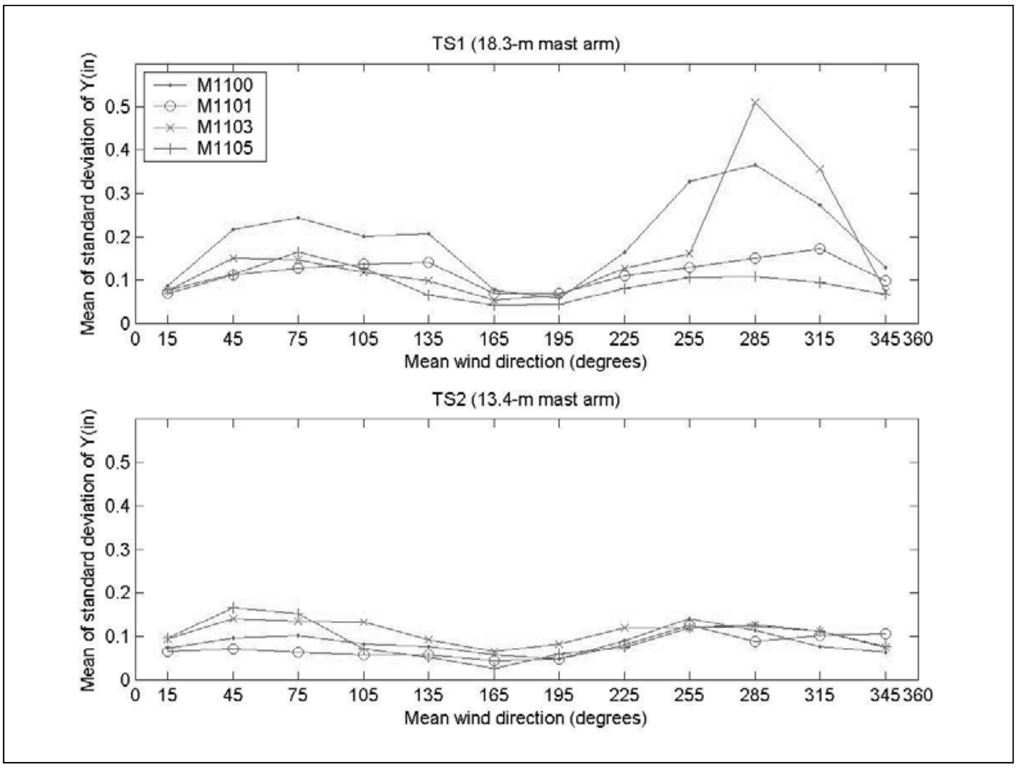

Fig. 26 Comparison of results of Data Modes 1100 (backplates), 1101 (without backplates), 1103 (vented backplates) and 1105 (damping plate)

The following observations can be made:

- The response was generally much more pronounced for the longer structure TS1 (18.3m arm) than the shorter TS2 (13.4m).
- Backplates (M1100) led to higher amplitude vibration than cases without backplates (M1101).
- The vented backplates appeared to be effective in reducing the amplitude of vibrations of TS1 (18.3-m arm), except when the angle of attack was close to 300^{o}.
- The damping plate was effective in reducing the amplitude of vibrations of the longer TS1 (18.3-m arm) but not the shorter TS2 arm.

4. Conclusions

It has been observed throughout these experiments that large amplitude vertical vibrations of mast arms with signals and backplates occur for the most part at low wind speed ranges with wind approaching from behind the signal. As the wind speed increases the amplitude of the vertical vibrations decreases. Having large vibrations at a certain wind speed and direction ranges reflect the typical behavior of vibrations induced by vortex shedding. This contradicts the generally accepted belief that vortex shedding does not cause significant vibrations of mast arms that could lead to fatigue failure. This is generally attributed to galloping (Pulipaka *et al*. 1998, Kaczinski *et al*. 1998, AASHTO 2001,Cook *et al*. 2001, Dexter and Ricker 2002), where larger vibrations occur at increasingly higher wind speeds. This phenomenon was not captured in this experiment.

It seems that the higher amplitude vertical oscillations have a higher probability of occurring when the wind speed is between 2 to 7 m/s. It also appears that they are more likely to occur when the wind approaches the mast arm from the back of the signal (i.e., an angle of attack between 0 and 180^o in this study) and when the signals have backplates.

Very few large-amplitude vibration cases were observed under Data Mode 1100 (signals with backplates), possibly because wind conditions and arm orientation were less than ideal. This is a typical difficulty of conducting full-scale experiments. Still, the large amplitude vibrations that were collected on March 29, 2005, clearly indicate that cantilever traffic signal structures are susceptible to vibrations due to vortex shedding. Full-scale experiments that followed the tests presented here confirm that large-amplitude vibrations of the cantilevered arm at low wind speeds are due to vortex shedding (Zuo and Letchford 2010).

Two methods to minimize the amplitude of the vertical vibrations were tested in the full-scale experiments: (1) vented backplates and (2) a damping plate. In the case of the 18.3-m arm, the damping plate appeared to be effective in minimizing the amplitude of vibrations, but the vented backplates appeared to make the arm susceptible to vibrate under other specific conditions, - mean wind direction is close to 300 degrees. Meanwhile, the vented backplates were observed to lower the amplitude of vibrations of the 13.4-m arm, but the damping plate was largely ineffective for this length arm.

Additional wind tunnel tests were conducted to verify the results of these full-scale experiments are presented in a companion paper.

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