Wind-Induced Vibration Monitoring Program For Alpine Pipelines

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Abstract

As part of the Alpine development project, Phillips Alaska, Inc. has installed a 305 mm (12-inch) diameter utility line and a 356 mm (14-inch) diameter produced oil line between the Alpine and Kuparuk oil fields on the Alaskan North Slope. In sections of the pipeline alignment that are oriented nominally perpendicular to the prevailing wind directions, a system of pipeline vibration dampers (PVDs) has been installed to mitigate potential fatigue damage due to wind-induced vibration (WIV). As part of the right-of-way agreement for the pipelines, Phillips has implemented a pipeline WIV monitoring program with the objectives of insuring that the PVD systems are performing as designed and to confirm that the spans without PVDs are not experiencing frequent and significant WIV. The Alpine WIV monitoring systems represent the most extensive, long-term WIV monitoring program ever undertaken on the North Slope. This paper provides an overview of the Alpine pipelines WIV monitoring program including; a description of the layout of the instrumentation, the data acquisition and the power supply systems, and a description of commissioning these systems. A summary of the WIV monitoring approach and the pertinent wind observation and vibration data gathered is also provided. The paper concludes with a summary of the overall findings and conclusions from this program.

Introduction

The Alpine pipelines run approximately 48 km (30 miles) between Alpine and Kuparuk. The Alpine pipelines were designed by Michael Baker Jr., Inc. As part of the overall design, wind-induced vibration (WIV) evaluation and pipeline vibration damper (PVD) tuning studies were performed by SSD, Inc. as a sub-contractor to Baker. The utility line has a wall thickness of 8.4 mm (0.330 inches) and the produced oil line has a wall thickness of 7.9 mm (0.312 inches). Both lines are fabricated from API 5LX-65 grade pipe material. The lines are constructed in a typical arctic cross-country configuration which consists of long straight run sections between thermal anchors and expansion loops.

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Within the long straight pipe runs, the pipes span 19.8 m (65 feet) between vertical support members (VSMs). With this span length, these pipelines are the longest spanning 305 mm (12-inch) and 356 mm (14-inch) diameter lines on the North Slope. These lines have primary vertical mode vibration frequencies in the range from about 1.5 to 5 Hz. Based on WIV analyses of the pipelines, it was concluded that they could be susceptible to significant WIV in pipeline sections oriented nominally perpendicular to the prevailing wind directions. Based on this assessment, a system of PVDs was installed on both pipelines in segments with orientations between N45^{o}W and N30^{o}E. Phillips Alaska, Inc. implemented a pipeline WIV monitoring program to insure that the PVD systems are performing as designed and to confirm that the spans without PVDs are not experiencing frequent or significant WIV.

Description of Test Stations

The Alpine pipelines are being monitored at three stations along the alignment. The stations are monitoring the wind speed, wind direction, air temperature and the mid-span vertical acceleration of pipelines using digital data logger systems. Within each test station, the motion of each pipeline is monitored within three different spans (referred to as the "U" or "upstream" span, the "K" or "key" span, and the "D" or "downstream" span). Each test station is also being monitored with a "scratch gage" (as shown in Figure 1) which measures the maximum displacement of the pipe in the "U" span.

Test Station 1 is a 17 span section located to the south-southwest of Alpine. It has an azimuth of 170.7^{o} and hence is approximately perpendicular to the prevailing wind directions. Test Station 2 is a 19 span section located West of the Kuparuk Drill Site 2H road crossing. The azimuth of this section is 82.5^{o} which is nearly parallel to the prevailing wind directions and outside of the design wind fan. Test Station 3 is a 14 span section located near Kuparuk CPF2. As shown in Figure 2, Stations 1 and 3 are located within the design wind fan and hence have PVDs installed, while Station 2 is outside the design wind fan and hence no PVDs are installed.

Data Acquisition System

The data acquisition system selected for the field monitoring program is the Campbell CR5000 system by Campbell Scientific, Inc. (Campbell, 2000). This system is capable of measuring input channels at measurement rates of up to 5000 samples/sec. The logger is programmed to collect data in tables which are written to a data card. This logger unit was selected to provide a balance between processor speed and relatively low power demands.

Data Logger Power Supply and Housing

The test stations are located at least 1 km from the nearest existing power source. A local power source for each test station was determined to be the most appropriate power design solution. This power source consists of a Teledyne Energy Systems

Model 2T thermo-electric generator or “TEG” (Telen, 2000), battery storage system, associated fuel system, and an overall housing. The TEG unit uses propane as the source fuel. Both 12 volts of DC electrical current and heated air are generated as outputs. The fuel system for each TEG consists of three 18 kg (40 lbs) propane tanks, a common manifold, and pressure hose. The automobile sized 100 amp-hour sealed gel cell storage battery supplies TEG ignition power and short-term system voltage. The enclosure housing, heated by the rejected hot air provides a suitable environment for these systems and the Campbell CR5000 unit.

The enclosure is composed of a foam filled plywood panel with a full sized hinged lid, hinged end panel access door, and removable side ports. Small thermostatically controlled ventilation fans were incorporated for the maintenance of a nominal temperature range between -12.2^{o}C and 26.7^{o}C (10^{o}F and 80^{o}F). A fuel system solenoid valve is included to shut the TEG down if the enclosure temperature gets too warm (43^{o}C or 110°F). The TEG exhaust is routed from the dual exhaust stacks to a common header and then out the side of the enclosure. For reliability, the control system is completely independent of the logger control system.

Accelerometers

The primary measurements of interest are the pipe mid-span accelerations. The accelerometers selected for this project are Crossbow single-axis units (Crossbow, 2000) with an onboard voltage regulator. These devices are high stability, capacitive beam type accelerometers with a band width from DC to 125 Hz and a span of ±2g. These accelerometers are attached at the mid-spans of the U, K and D spans of the pipes oriented to measure the vertical acceleration of the pipe.

Weather Stations

The additional measurements of interest are the wind speed, wind direction and the air temperature. The wind speed and direction are measured using a R. M. Young Wind Monitor (Campbell, 1996). The anemometers are located a minimum of 9 meters (30 feet) away from the pipelines with the elevation of the propellers nominally equal to the elevation of the pipelines. The anemometers are oriented to be aligned with the Alaska State Plane coordinate grid. The air temperature is measured using a R. M. Young RTD Temperature Probe (Campbell, 1997).

Data Logger Program

A site specific data logger program was developed to control the operation of the CR5000 systems at each of the three WIV monitoring stations. The pipe motion trigger condition is that either the standard deviation of the pipe acceleration or the standard deviation of the corresponding integrated pipe velocity is above a triggering threshold value. The largest motions from the monitored mid-spans of the utility line and the monitored mid-spans of the produced oil line are compared to the acceleration and velocity trigger threshold values. If a motion trigger occurs, the logger is programmed to record the data to a 60 second "motion event" file on a data card. For wind, the trigger condition is that the mean value of the perpendicular component of the wind speed is within a certain range and that the corresponding turbulence intensity (defined as the ratio of the standard deviation of the wind speed to the mean wind speed) is below a certain threshold. If a wind trigger occurs, the logger is programmed to record a "wind event" file which contains a synopsis of the data conditions over the duration of the wind event.

Once a pipe motion or wind triggered event is complete, the data logger will return to monitoring mode and will trigger again as soon as another trigger condition is met or until the data card is full. The number and type of the triggers is computed and stored every 15 minutes along with the other pertinent logger status information.

Monitoring Procedure

Once the WIV monitoring stations were installed and commissioned, the monitoring plan was to let the systems gather data for a time period of approximately 3 weeks. At the end of each monitoring period, weather permitting, a data retrieval team was sent to the field to collect the data cards containing the data, replace them with new cards, re-supply the TEGs with propane, and to document the scratch post information and reset the scratch posts. In addition, the overall system was checked out and any observed problems were addressed and/or repaired.

Free Vibration Tests

SSD has a significant amount of experience in performing free-vibration ("pluck") tests on operating pipelines to investigate the dynamic characteristics. A pluck test involves statically loading a span into a deflected shape then quickly releasing the load to initiate free-vibration. The pipe was jacked into a deflected configuration in the K span using the loading set ups shown in Figure 3. A wooden pallet loaded with approximately 20 sand bags provided a reaction weight of over 454 kg (1000 lbs). The top and bottom rigging straps were jacked towards each other using a come-along until the pallet began to lift off of the ground. With the pipe in the deflected configuration, the data logger was manually triggered on and then after a delay of about 5 seconds, piece of all thread holding the load was cut using bolt cutters initiating free-vibration.

An example of the acceleration Fourier Amplitude Spectrum obtained from a typical pluck test is shown in Figure 4 with a comparison of the experimental and analytical vibration frequencies (obtained using AutoPIPE (Rebis, 2001) modal analysis). The pipe frequencies and the frequency range of the vertical primary modes (as well as the secondary modes) were identified in the instrumented spans and confirmed to provide a close match with the corresponding analytical values. The damping ratios in the pipes with PVDs (1.7% to 2.2% of critical) and without PVDs (0.4% to 0.8% of critical) were also estimated. Additional pluck tests on the installed PVDs confirmed that the damper frequencies correspond very well to the "target" pipeline frequencies. More details on PVD design can be found in Reference (Norris, 2000).

Summary of Wind Direction Measurements

Figure 5 presents a comparison of the histograms of raw wind direction (degrees, clockwise from North) at Station 3 over monitoring periods between November 2000 and August 2001. The dashed vertical lines shown on this figure correspond to wind directions that are perpendicular to pipeline orientations within the design wind fan (N45^{o}W and N30^{o}E). It is observed that the wind histograms for all sites have similar distributions (e.g., prevailing wind directions from essentially East-North-East with significant occurrences of winds from West-South-West). The solid lines oriented perpendicular to the boundaries of the Kuparuk design fan shown quite reasonably encompass or span the prevailing wind direction bins.

Summary of Event Counters

Figure 6 presents a comparison of the number of wind and motion triggered events recorded at Stations 1, 2 and 3 over the course of the monitoring to date. It is observed that the number of wind triggered events is nominally proportional to how perpendicular the test station is to the prevailing wind directions. The number of motion triggered events shown in this figure is composed mainly of transient pipe response events or spurious triggers caused by accelerometer drift which have nothing to do with pipeline WIV. Only a handful of these motion triggers actually correspond to WIV. The absence of any significant WIV events in the presence of wind conditions favorable to WIV represents a very significant finding for the WIV monitoring program.

Description of Pipe Motion Events

Once a pipe motion event is stored, the data over the entire event duration is post-processed to provide various measures of the pipeline response and the wind conditions. Some events were subject to a more refined level of screening including processing of the acceleration signals using a Fast Fourier Transform to establish the frequency content of the motion.

Once "transient" and "spurious velocity" triggers are excluded from the motion event counts, a handful of "real" motion events remained which are associated with low level WIV. An examination of the frequency content of the pipe vibration indicates that the 305 mm diameter and 356 mm diameter pipe motions were both broad-banded extending over the entire frequency range of the primary, secondary, and tertiary vibration modes of both pipes. The estimated maximum pipe stress ranges in both lines was less than 21 N/mm^2 (3 ksi), i.e., the pipe stress ranges are benign. The design of the Alpine lines assumed that the perpendicular component of wind with any crossing angle would produce WIV. The data show that the crossing angle of the wind must be within approximately 10° of being perpendicular to the pipe to induce WIV, confirming that the design assumption was conservative.

Summary of Wind Triggered Events

As shown in Figure 6, a total of nearly 145,000 wind triggered events have been recorded by the loggers at Stations 1, 2 and 3 to date. This means that the perpendicular component of the wind speed was within the 12.9 km/hr to 25.8 km/hr (8 mph to 16 mph) range where there is the potential for vortex shedding at and near the primary mode frequencies of the two pipelines. The number of events is also consistent with the azimuth of the test stations in relation to the Kuparuk wind fan as shown in Figure 2.

Data from the wind triggered events was processed to provide various measures of the pipeline response and the wind conditions. Figure 7 provides an example of the key wind and motion parameters during each of the events recorded at one monitoring period. During many of these events, low level "background" pipe wind-induced vibrations were occurring. However, even during the strongest of these events, the pipe motions were on the order of 10% of the level required to cause a motion trigger. There were no narrow-banded, resonant WIV events recorded during the data collection period at any test station. The estimated maximum stress range during these conditions was in the range from 7 to 21 N/mm^2 (1 to 3 ksi). With respect to the potential for causing fatigue damage at pipeline girth welds, we consider stress ranges below 40 N/mm^2 (5.8 ksi) to be entirely benign based on project specific fatigue criteria. This supports that the PVDs (where required) are performing as designed and that PVDs are not required in locations where they are not installed. Spans without PVDs (e.g., in Station 2) have not experienced WIV significant enough or with enough frequency to cause weld fatigue damage or failure.

Summary of Scratch Gage Data

When the data retrieval team visited the test stations, the scratch gage plates were either photographed and the pointers reset or the plates were retrieved and replaced with new plates. For many of the periods, the plates exhibited the presence of longitudinal scratches which are associated with longitudinal movement of the pipes. Close examination of the plates indicates a distributed sequence of numerous "dwell spots" along many of the longitudinal scratches where the scratch gage pointer has worn into the scratch plate. These spots appear to be associated with the time periods between incremental longitudinal shifts of the pipes. The vertical dimension of these dwell spots provides an indication of the level of vertical pipe vibration that occurred since the gages were set. In general, the vertical dimension of the dwell spots was approximately 3 mm (1/8-inch), peak-to-peak, which correspond to "Level Green" screening conditions (i.e., benign WIV stress ranges). We believe that the vertical pipe motions that caused the dwell spots are associated with essentially ambient "background" level WIV response of the pipelines similar to what was observed in the digital data.

Conclusion

As part of the right-of-way agreement for the Alpine pipelines, Phillips Alaska, Inc. implemented a pipeline WIV monitoring program with the objectives of ensuring that the PVD systems are performing as designed and to determine if the segments within the design wind fan are the only locations that require PVDs. In addition, the program was intended to confirm that the spans without PVDs are not experiencing frequent and significant WIV. These objectives have been accomplished. In terms of the number of instruments deployed and the number of monitored days, the Alpine WIV monitoring systems represent the most extensive, long-term WIV monitoring program ever undertaken on the North Slope. At Stations 1, 2 and 3, both the digital data and the scratch gage observations consistently indicate that the WIV response of both pipes has been benign for the entire monitoring period to date. Only broad-banded, background level WIV has been observed. This provides an excellent indication that the PVDs are performing as expected and that spans without PVDs are not experiencing frequent or significant WIV. Perhaps the most useful finding to date is the absence of any significant WIV in the presence of wind conditions that could lead to WIV. The locally measured wind direction histograms are consistent with the expected ENE and WSW wind directions and the data indicates that the Kuparuk design wind fan sufficiently encompasses or spans the prevailing wind direction bins. The design wind fan is adequate to identify the sections requiring WIV mitigation and does not need to be broadened for the Alpine pipeline system. The maximum estimated WIV stress ranges are less than 21 N/mm^2 (3 ksi) compared to a project specific 40 N/mm^2 (5.8 ksi) endurance limit for pipeline girth welds. This indicates that zero fatigue damage has been accumulated due to WIV stress ranges.

Acknowledgments

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Figure 1 Typical Installation of Scratch Gages for Alpine Pipelines

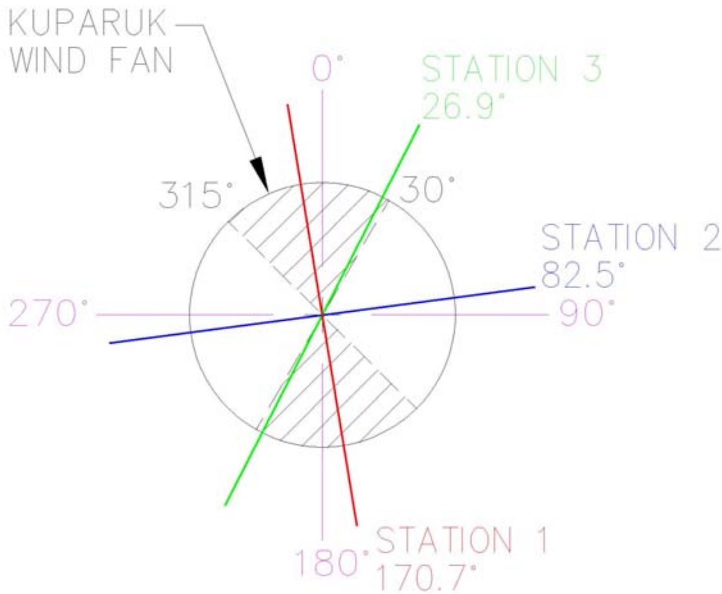
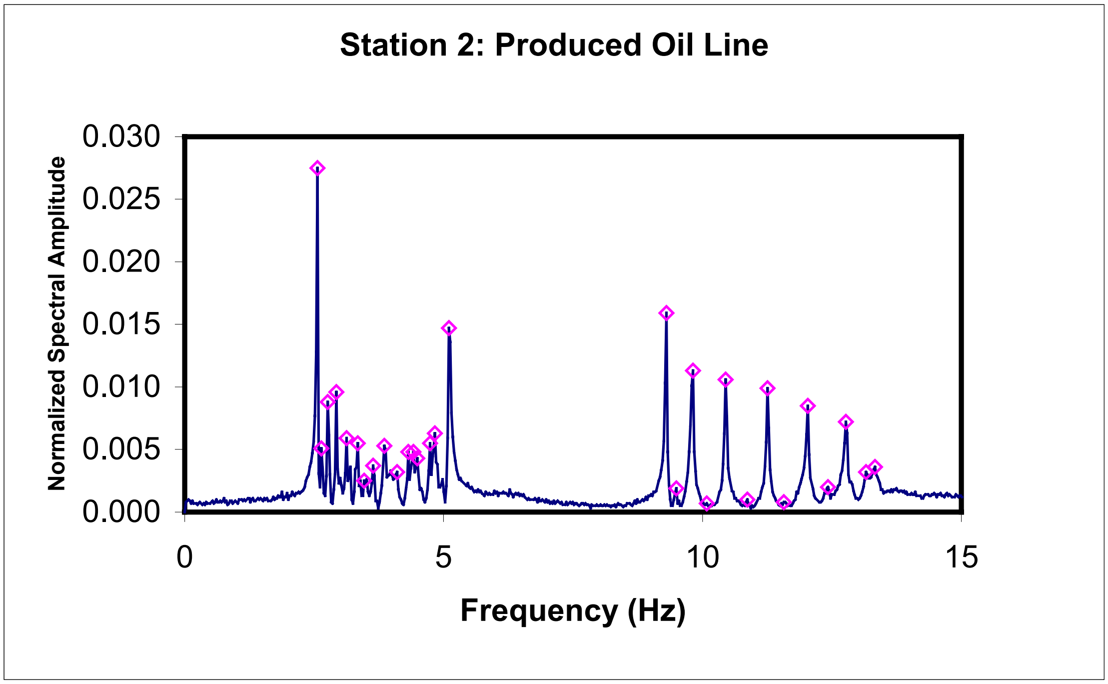


Figure 2 Kuparuk Wind Fan

Figure 3 Jacking Reaction Weight and Releasing to Initiate Free-Vibration



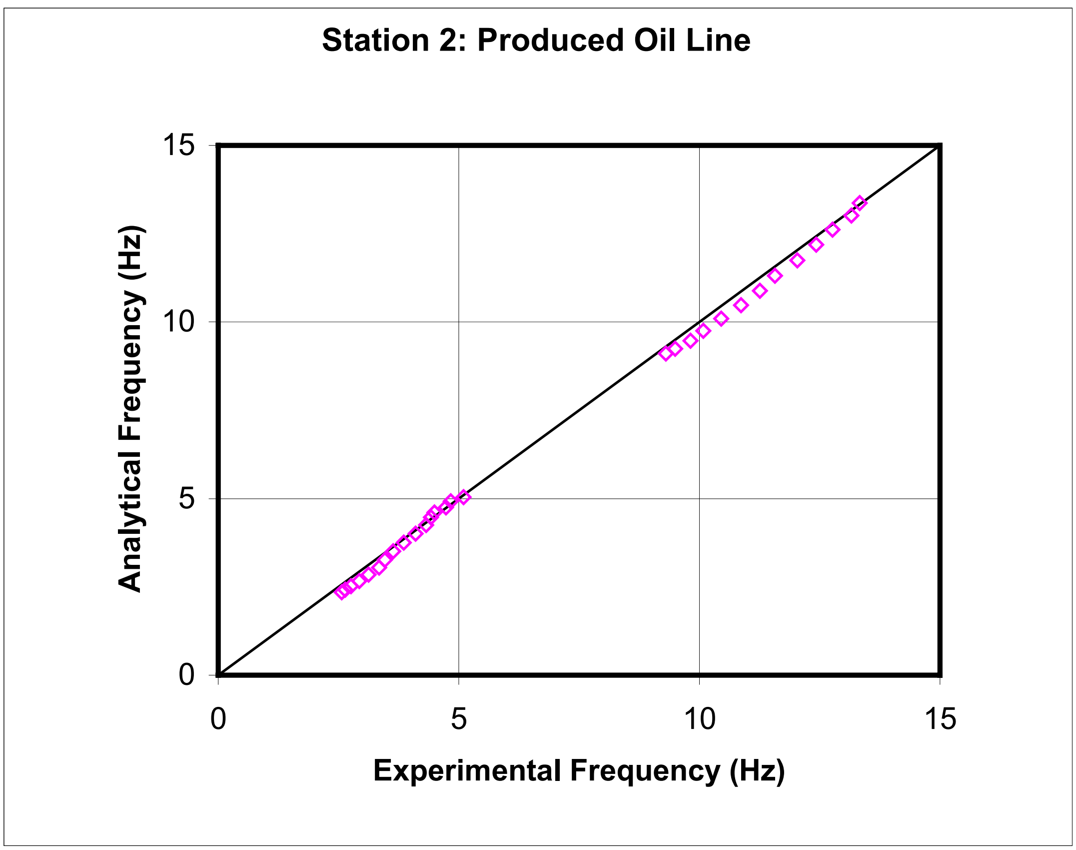


Figure 4 Example Primary and Secondary Mode Frequency Response from Free-Vibration Test and Comparison with Analytical Frequencies

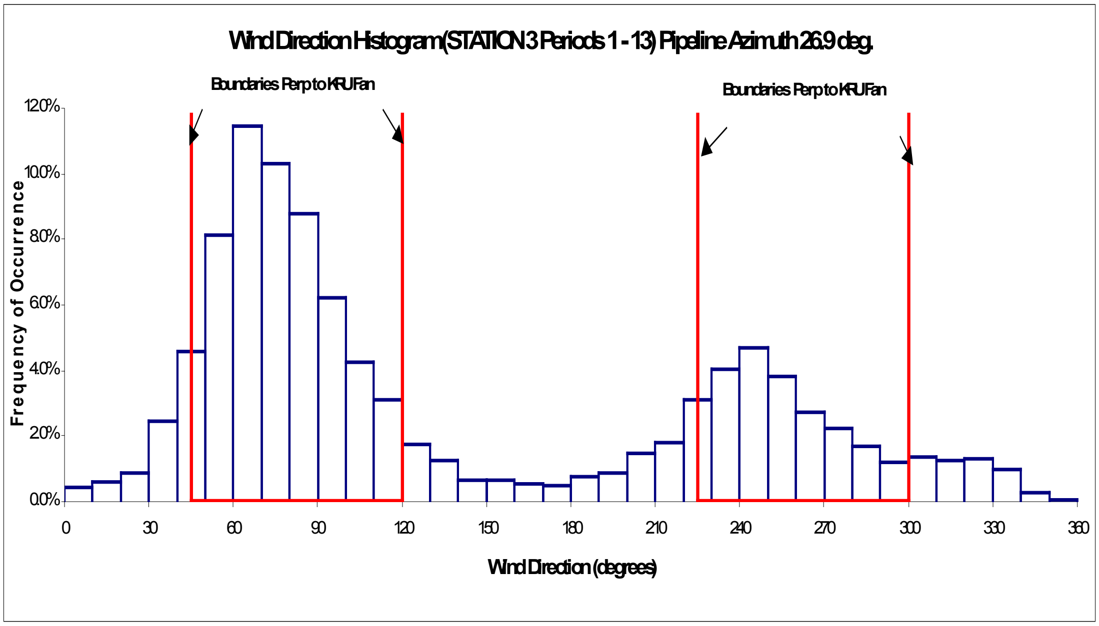


Figure 5 Typical Wind Direction Histogram

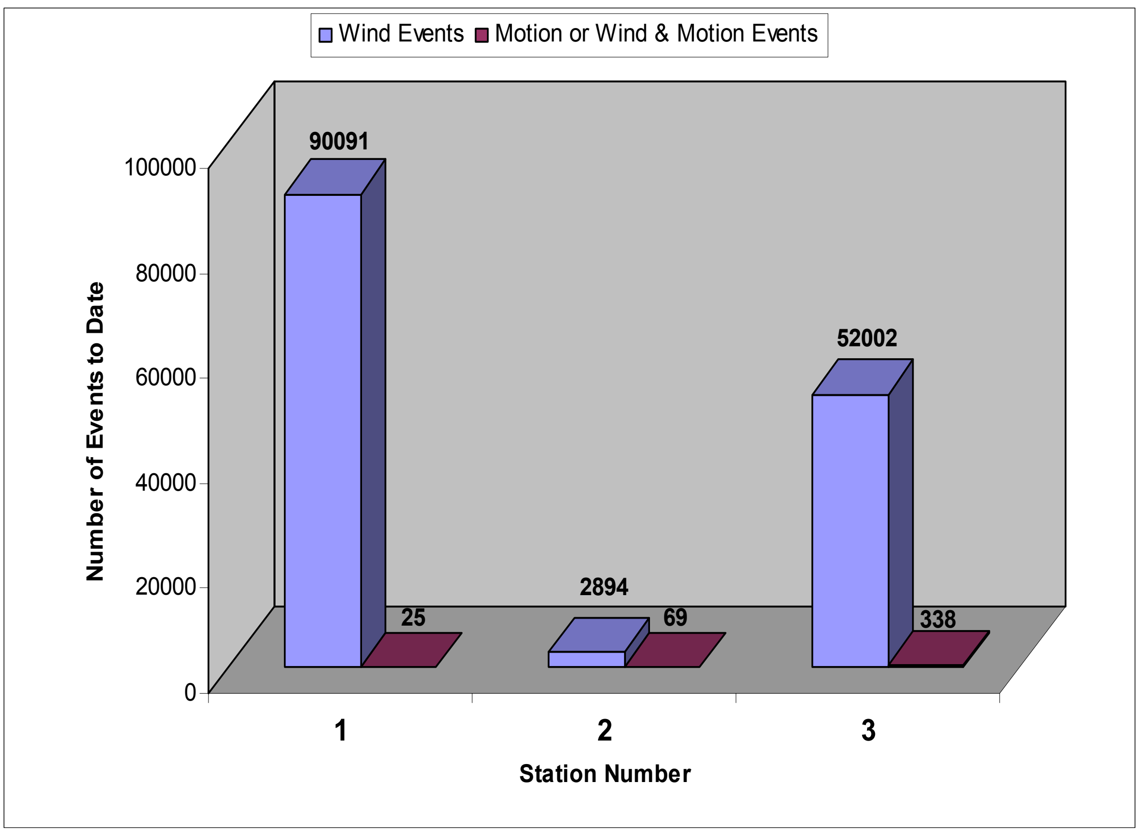


Figure 6 Event Counts Block Diagram Periods 1-13

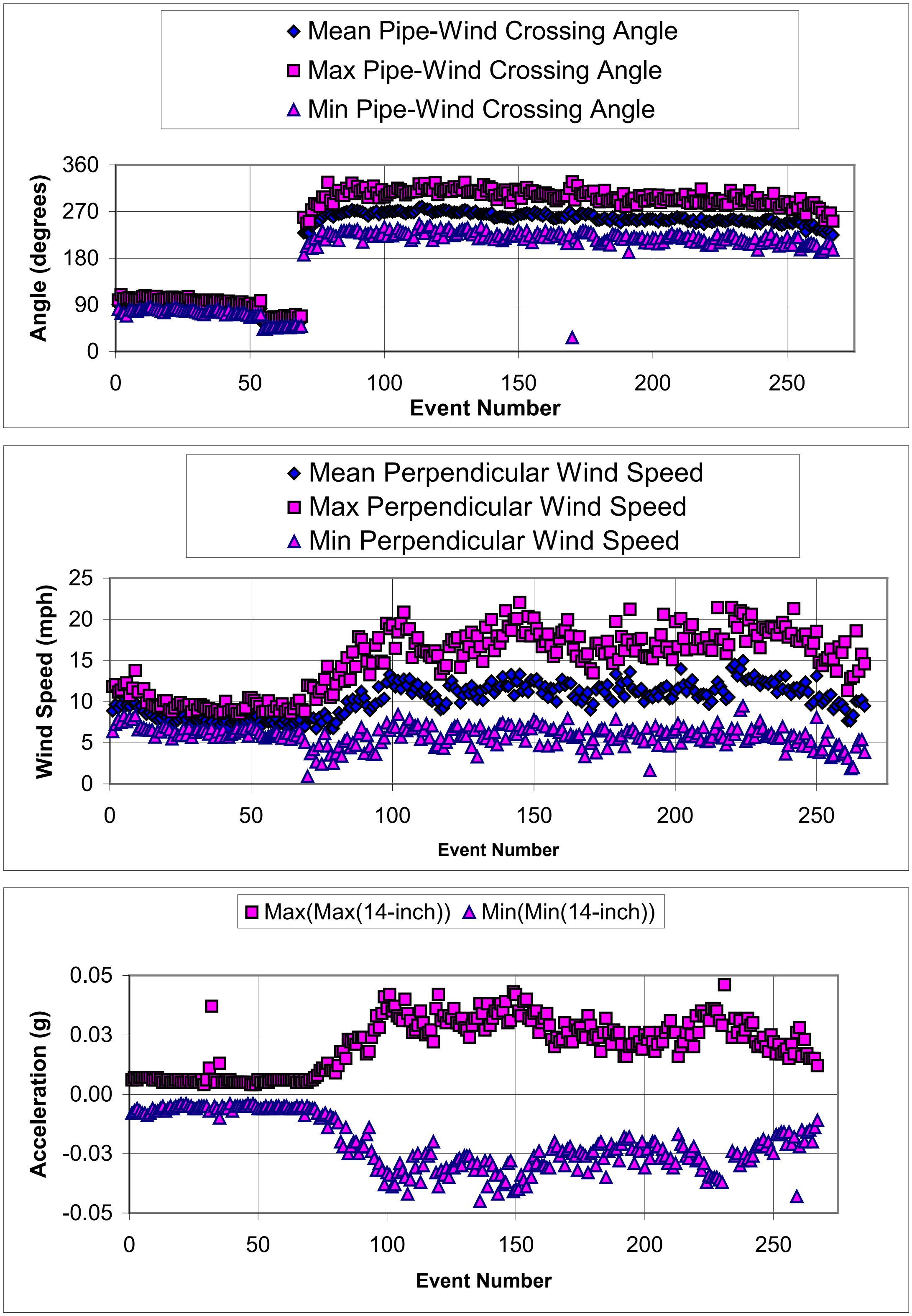


Figure 7 Example Results for a Monitoring Period