The Impact of High Frequency Wind-Induced Vibration on Arctic Pipeline Systems

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ABSTRACT

Narrow-banded, well-organized vortex shedding associated with relatively low frequency vibration and relatively high amplitudes at lower wind speeds (8-18 mph) has resulted in several pipeline weld failures due to high cycle fatigue attributed to primary mode wind-induced vibration (WIV) in the Alaskan Arctic. Based on these failures, numerous studies of the phenomena have occurred with modeling techniques developed to predict the characteristic primary mode WIV events noted at these lower wind speeds. It has been postulated that the reason the secondary modes (2 lobes per span) are not excited by vortex shedding is that they require a span-wise correlation of lift forces that is much more difficult to achieve than for the lower frequency primary modes (with 1 lobe per span). The higher frequency modes are also associated with higher wind speeds which occur less frequently and higher Reynolds numbers. However, for pipeline configurations with very low vibration frequencies and/or small (aerodynamic) diameters, it is possible that secondary modes can be excited because they are associated with wind speeds in the sub-critical Reynolds number regime. Alaskan Arctic North Slope oil and gas operators have employed successful mitigating measures (pipeline vibration dampers and tuned vibration absorbers) to prevent potential severe fatigue damage to pipeline welds caused by these lower wind speed events and the associated primary mode(s) of WIV. However, no protective measures have been routinely employed to prevent pipeline girth weld fatigue failures from secondary mode WIV based on the low likelihood of occurrence.

INTRODUCTION

In late 2004, a high cycle fatigue pipeline girth weld failure attributed to high frequency, low amplitude secondary mode WIV associated with higher wind speeds (30-35 mph) occurred. Analyses revealed high quality welds, with no significant weld defects or metallurgical flaws that would have caused this failure had it not been for the cyclical stresses caused by the WIV. Significant secondary mode WIV was not predicted to occur by the analytical models historically used to analyze WIV of North Slope pipelines. Such models have proven to reliably predict susceptibility to primary mode WIV, and mid-span installation of pipeline vibration dampers (PVDs) or tuned vibration absorbers (TVAs) on such pipeline segments has proven to be an effective mitigation measure for primary mode WIV. This failure was the first documented evidence of a secondary mode vibration failure under the broad-banded, multi-modal vortex shedding characteristics attributed to higher wind speeds. As a result, in-depth studies of this failure commenced and subsequent secondary mode WIV susceptibility screening procedures and enhanced modeling techniques are being developed to analyze these higher frequency secondary mode WIV events.

An overview of the results of the studies to date and the impact of high frequency WIV on Arctic pipeline systems will be discussed along with specific information regarding mitigating measures employed.

BACKGROUND

Dynamic Characteristics of Above Ground Pipeline Configurations

Typical arctic cross-country pipeline configurations consist of a longitudinal thermal anchor followed by 10 to 20 straight run spans with repeated span lengths ranging 40 to 65 feet, an expansion loop, then another 10 to 20 straight run spans and another anchor (Hart, 1992). In terms of the pipeline dynamic properties related to WIV, the most important feature of this structural configuration is the 10 to 20 straight run spans. Analytical and experimental investigations of these systems have identified useful patterns related to the vibration modes in the vertical plane of the pipeline, which are the modes excited by vortex shedding. The modal trends indicate that the behavior of multi-span systems is reasonably well-bounded by the behavior of a single span system. For example, in a 15 span run, the frequencies of the vertical modes will occur in “clumps” of 15 modes. Each clump of modes is distributed over a frequency range that is approximately bounded by the frequencies of a single span with pinned and fixed-end conditions, respectively. The bounding frequencies of the modes with pinned and fixed-end conditions are closely approximated by the closed-form equations for the corresponding frequencies of a single span beam.

Whereas for a 15 span run, the 15 modes in the first (“primary” mode) clump have shapes where there is essentially one lobe per span, the 15 modes in the second ("secondary" mode) clump have shapes where there are essentially two lobes within every span (or one lobe per half-span). The shapes of the higher frequency secondary modes become progressively more complex with the addition of one inflection point per mode, but the overall pattern is represented by essentially two lobes per span. For the lower frequency modes within the secondary mode group, the maximum bending stress is at a quarter-span or three-quarter-span location, while for the higher frequency modes within this group, the maximum bending stress is at a support location. To help illustrate the mode shape trends discussed above, Figure 1 provides a side-by-side comparison of the 5 primary mode shapes and the 5 secondary mode shapes for an example 5-span pipeline configuration.

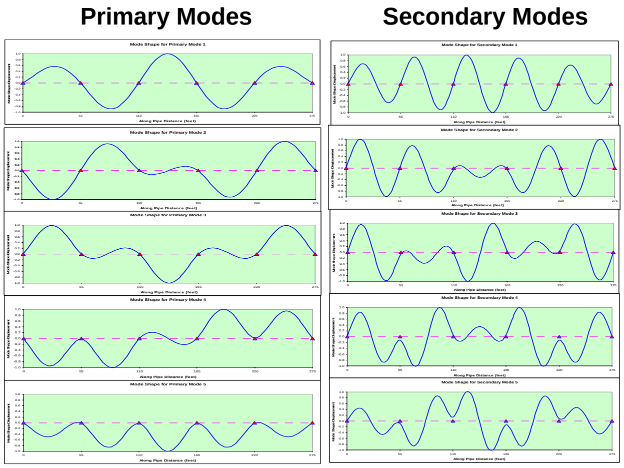

Figure 1: 5-Span Mode Shapes – Primary vs. Secondary

Based on the closed-form solutions for the frequencies of a single span (Blevins, 1990), it can be shown that the primary frequency with fixed-end conditions (at the high frequency end of the first clump) is about 2.3 times the primary frequency with pinned-end conditions (at the low frequency end of the first clump). The secondary frequency with fixed-end conditions (at the high frequency end of the second clump) is about 1.6 times the secondary frequency with pinned-end conditions (at the low frequency end of the second clump). The lowest secondary mode frequency is about 4 times higher than the lowest primary mode frequency and about 1.8 times higher than the highest primary mode frequency. This indicates that the frequencies of the primary and secondary mode clumps are well separated.

Perhaps the most important parameter for characterizing the stresses in multi-span pipeline configurations is the modal stress. The modal stress is defined as the zero-to-peak stress per inch of zero-to-peak amplitude in a given mode shape. It should be noted that the stresses discussed herein are nominal beam bending stresses (i.e., M/Z where M is the pipe bending moment and Z is the pipe section modulus). The modal stress can be extracted from the mode shapes of multi-span finite element models at locations of maximum stress (i.e., at mid-span and support locations for the primary modes and at ¼ , ¾ span and support locations for the secondary modes).

In order to estimate the WIV response of pipelines, it is necessary to assume a damping ratio for each of the vibration modes. Based on field test data obtained at Kuparuk, Alaska, it was determined that typical above-ground pipeline configurations are very lightly damped with modal damping ratios equal to less than 0.5% of critical. A "standard" value used for WIV analysis is 0.4% of critical [OMAE]. It can be shown that the amplitude of the steady-state response of the pipeline under resonant vibration conditions is inversely proportional to the damping ratio. Hence, doubling the pipeline damping ratio can reduce the resonant response amplitude by a factor of 2. Note that because the in-situ pipeline damping levels are so low, it does not take an excessive amount of additional energy dissipation to provide a substantial relative increase in the system damping.

WIV of Above Ground Pipeline Configurations

Recorded field data on pipelines at Kuparuk has indicated that WIV only occurred in the primary modes of the pipeline. No WIV events have ever been experimentally recorded which contained modes in the 2 lobe per span (secondary mode) category. It is postulated that the reason the secondary modes are not excited by vortex shedding is that they require a span-wise correlation of lift forces that is much more difficult to achieve than for the lower frequency primary modes (with 1 lobe per span). The higher frequency modes are also associated with higher and less frequently occurring wind speeds and higher Reynolds numbers. However, for very low frequency or small (aerodynamic) diameter pipeline systems, it is possible that secondary modes can be excited because they are associated with wind speeds in the sub-critical Reynolds number regime.

The WIV events measured over several months of field data monitoring at Kuparuk indicated that turbulent wind flow conditions, with average turbulence intensities (defined as the ratio of the RMS wind speed to the mean wind speed) of about 10%, are prevalent. However, there have been rare pipeline vibration events recorded on video tape and in visual observations with estimated vibration amplitudes large enough to indicate the possibility of laminar wind flow conditions. It was also observed that the typical pipeline response to wind-induced dynamic forces is bounded by two cases; narrow-banded (uni-modal) response and broad-banded (multi-modal) response. The largest measured displacements and stresses occurred when the pipeline was undergoing narrow-banded (resonant) vibration. The displacements and stresses were notably smaller during broad-banded vibration.

Aerodynamic Model for Pipeline WIV

Based on the field experimental work performed at Kuparuk, a WIV model was developed to estimate the steady-state, uni-modal dynamic response of multi-span pipelines due to narrow-banded vortex shedding. The model is implemented as a post-processor program that operates directly on the mode shapes and frequency results from multi-span AutoPIPE finite element models (AutoPIPE, 2004). The critical wind speeds (and the associated Reynold's Numbers) corresponding to the natural frequencies of the pipeline are computed based on the classical Strouhal Number relationship;

$$f_S = SU/D$$

where f_S is the vortex shedding frequency, U is the perpendicular wind speed, D is the aerodynamic (insulated) diameter, and S is the Strouhal Number, which can be regarded as a dimensionless frequency ($S = f_S D/U$). The Reynolds Number (R_e) is defined as;

$$R_e = UD/\upsilon$$

where υ is the temperature dependent kinematic viscosity of air.

Experimental results indicate that for smooth flowing (laminar) wind, a definite flow transition begins to occur at wind velocities associated with a Reynold's Number of approximately 280,000. For turbulent wind flow, the transition occurs at Reynold's Numbers of approximately

200,000. This transition represents a change of the boundary layer between the bluff body (pipeline) and the fluid (air) from laminar to turbulent. The transition causes variations in the vortex-shedding frequency and a reduction in the amplitude of oscillating lift forces. In general, wind-induced vibration response below the critical R_e tends to be relatively large amplitude and narrow banded (or uni-modal) while above the critical R_e, the response tends to be relatively low amplitude and broad-banded (or multi-modal). Thus, the critical Reynold's Number defines a "random shedding threshold", above which resonant, uni-modal response will not typically occur.

Wind tunnel experiments indicate that for low values of R_e, the Strouhal Number is approximately 0.2, for R_e ranging from roughly 60,000 to 2,000,000, the Strouhal Number is variable and dependent on the degree of turbulence in the flow, and for R_e above 2,000,000 the Strouhal Number is near 0.25. These R_e "regimes" are often referred to as sub-critical, critical (or trans-critical) and supercritical, respectively. The experiments also indicate a reduction in fluctuating lift coefficient with increasing Reynolds Numbers for both laminar and turbulent flow conditions.

The WIV model is based on a range of published information and is qualitatively similar to models presented in (Harris, 1988) and (Simiu, 1986). The model uses the Fluctuating Lift Coefficient vs. Reynolds Number relationship presented in (Cheung, 1983) and assumes a Strouhal Number of 0.2 for all Reynolds Numbers. The model computes the response for each Y (vertical plane) mode of the pipeline system excited individually in resonant conditions. In order to bound the expected behavior, the response is estimated under both laminar and turbulent wind conditions. The response is computed essentially by scaling the mode shape by an appropriate laminar or turbulent lift coefficient which is a function of the Reynolds Number of the wind flow. The WIV model is a narrow-banded model that applies to uni-modal vibration events in the sub-critical Reynolds number regime. This model is not intended be applied directly to predict the response to broad-banded excitation in the trans-critical or supercritical regimes.

The model has been compared against field WIV data gathered on 8-inch diameter pipelines at Kuparuk. As previously noted, field test data indicates that turbulent wind conditions are prevalent on the North Slope (with turbulence intensities of about 10%) and the model estimates WIV amplitudes based on a fluctuating lift coefficient for turbulent wind conditions. However, since the WIV data was gathered over only a limited time period, it cannot be said for certain that the worst type of WIV events have been "captured". In fact, based on video observations of severe WIV events, it is believed that there are rare occurrences of "locked-in" WIV that are significantly more severe than those measured in the field or those predicted based on turbulent wind assumptions. For this reason, the WIV model also estimates the pipeline response amplitudes based on a fluctuating lift coefficient for laminar wind conditions (with turbulence intensities of less than 1%).

Pipeline Vibration Dampers (PVDs)

The Kuparuk pipeline studies lead to the development and field-wide implementation of PVDs at Kuparuk during the early 1990s (Hart, 1993). Since then, the PVDs have also been applied to WIV susceptible pipelines across the entire North Slope and have a well-established track record of successful mitigation performance. It is estimated that there are currently well over 30,000 PVDs currently installed on the North Slope. The conventional PVD design approach is to mitigate the primary modes of the pipeline using a family of three different PVD types. The three primary mode PVD types are each tuned to a different primary mode pipeline "target frequency". A low frequency or "L" device is tuned to the lowest primary mode frequency, a high frequency or "H" device is tuned to the highest primary mode frequency, and a medium frequency or "M" device is tuned to a frequency mid-way between the lowest and highest primary mode frequencies. A typical PVD device is shown in Figure 2. The frequency of a PVD device is obtained by selecting the number of elastomeric tiers in the PVD and the suspended PVD weight. Because the stiffness and damping ratio of the PVD elastomer material depends on the ambient temperature, PVDs are typically tuned at a design temperature of +10°F (approximately equal to the average annual North Slope temperature) and their performance is evaluated over a temperature range (typically from –45°F to +50°F). The primary mode PVDs are attached at the mid-spans of the pipeline within the straight runs between anchors and expansion loops. The PVDs are installed using an alternating H-L-M placement pattern to distribute a broad-banded mitigation throughout the run.

Figure 2: Typical Pipeline Vibration Damper (PVD) Device

Tuned Vibration Absorbers (TVAs)

Since the 1999 time frame, several new North Slope pipelines have had design restrictions that required a minimum clearance below the pipeline (e.g., a 5 foot minimum clearance) and in some cases, this restriction was taken to mean the clearance between the ground surface and the bottom of the PVD weights. Because this interpretation would require taller VSMs and hence significantly increased VSM costs, there was a motivation to develop a top-of-pipe vibration damper. In the 1999-2000 timeframe, LORD Corporation (the PVD vendor) developed a tuned vibration absorber (TVA) for pipeline application that could be installed on the top of the pipe as well as under the pipe. More details regarding TVAs can be found in (Norris, 2000). The TVAs have been designed as a direct replacement for the conventional under-pipe PVD devices. A typical top-of-pipe TVA device is shown in Figure 3.

Figure 3: Top-of-Pipe Tuned Vibration Absorber (TVA) Device

The device tuning is accomplished essentially by varying three design parameters; the stiffness of the TVA base configuration, the amount of dynamic mass on the lever arm and, the distance from the center of mass to the center of rotation on the lever arm. Side-by-side laboratory and field testing of TVAs and PVDs has illustrated that, in terms of mitigation performance, a given TVA significantly outperforms the corresponding PVD.

Secondary Mode WIV Mitigation

In recent years, a handful of North Slope pipelines have required both primary mode and secondary mode vibration dampers (i.e., PVDs or TVAs). Each of these pipelines has had some exceptional characteristic that made it different from "typical" above-ground North Slope pipeline configurations. These characteristics resulted in either very low pipeline frequencies or very low Reynolds Numbers, or both. In each case, the Reynolds Numbers for at least some of the secondary modes dropped below the "critical" cutoff Reynolds Number such that narrow-banded vortex shedding could be predicted in secondary modes. For these configurations, the standard design approach is used to develop the primary mode PVDs or TVAs. For the secondary mode PVDs or TVAs, the design approach is similar. A family of three secondary mode damper types is used to mitigate the secondary modes with each damper type tuned to a different secondary mode pipeline "target frequency". A low frequency or "L_S" device is tuned to the lowest secondary mode frequency, a high frequency or "H_S" device is tuned to the highest secondary mode frequency, and a medium frequency or "M_S" device is tuned to a frequency mid-way between the lowest and highest secondary mode frequencies (note that the "S" subscript is used to denote secondary modes). The secondary mode dampers are attached at the ¼ spans of the pipeline within the straight runs between anchors and expansion loops. As with the primary mode dampers, the secondary mode dampers are installed in adjacent spans within the multi-span run using an alternating H_S-L_S-M_S placement pattern. The end result is a pipeline with two dampers per span, one primary mode device at the mid-span location and one secondary mode device at the quarter span location.

DISCUSSION

Secondary Mode WIV Girth Weld Failure

On December 17, 2004, an 8-inch diameter gas lift (GL) pipeline between Kuparuk Central Processing Facility 3 (CPF3) and Drill Site 3I (DS3I) experienced a failure at a pipeline girth weld located at approximately ¼-span. Subsequent field investigation of this pipeline revealed a second girth weld failure 5 spans downstream, once again at approximately ¼-span and along the same directional azimuth. The support system design for this line consists of 55 foot long spans between pipe supports (Vertical Support Members, or "VSMs"), and carries several parallel lines in addition to the failed GL line in a typical North Slope "pipe rack" type installation. The failed line was on the outside edge of the pipe rack. At the time of failure, the wind was blowing from the East, nearly perpendicular to the pipeline alignment, with a relatively steady wind speed of between 35 mph and 40 mph from an angle between 95^o and 104^o clockwise from north. This put the subject 8-inch GL line on the leading edge of the wind relative to other parallel pipelines on the pipe rack. The perpendicular wind speed was fairly uniform and within the secondary mode wind speed range of the 8-inch GL line for several hours prior to and after the time of the failure. These conditions were favorable for the occurrence of secondary mode WIV. Subsequent analysis clearly established that the girth weld failure was the result of high-cycle fatigue and occurred during a secondary mode wind-induced-vibration (WIV) event.

Table 1 details the DS3I GL pipeline characteristics. The 8 inch GL line was placed into service in 1986. Initially, there were no WIV dampers installed on the line as the WIV phenomenon was not recognized when the initial design was developed and installed. From 1986 to 1991, it is likely that the line experienced both primary and secondary mode WIV events. As a result of these WIV events, load cycles no doubt accumulated in the GL line girth welds. It is well-established that even high quality welds are susceptible to fatigue cracking when subject to sufficiently high cyclic stress levels. Also, based on their inherent stress concentration factors, welds tend to be the weak link in a piping system subject to cyclic loading conditions, and therefore will develop fatigue cracks from fewer applied stress cycles than the parent pipe material.

Table 1: Failed Pipeline Characteristics

Pipeline Size	8.625 inch OD
Wall Thickness	0.277 inch
Insulation Thickness	3 inch
Sheet Metal Jacket Thickness	0.028 inch
Pipe Material	API 5L-X65 – Arctic Grade
Contents	Artificial Lift Gas
Content Density	4.9 pcf
Support Span	55 feet
Construction Date	1985-1986
Construction Code	API 1104
Pipeline Azimuth	N2.1°W

Hindsight

By 1991, WIV was recognized as an issue and primary mode PVDs were installed at the mid-spans of selected pipelines throughout the Kuparuk field, including the subject DS3I GL pipeline, as its orientation relative to the prevailing wind direction rendered it susceptible to WIV. PVDs are expected to provide an infinite life for primary mode vibration as long as no pre-existing girth weld cracks are present prior to PVD installation. If cracks pre-exist, the PVDs either entirely remediate crack growth or dampen crack growth such that fatigue failure will be delayed, perhaps by several years. Approximately 918 field welds located near mid-spans and supports were inspected prior to installation of the PVDs and two (2) of the welds clearly revealed fatigue cracks. As previously noted, the highest stress for primary mode vibration is either at the mid-spans or at the VSMs, depending on the vibration frequency. For secondary mode vibration, the highest stresses are either at the ¼ span and the ¾ span locations, or at the VSMs, depending on the vibration frequency. It is well established that mid-span installation PVD designs focus solely on primary mode WIV mitigation and thus have no secondary mode WIV mitigating effects.

While excessive primary mode WIV was addressed by the installation of mid-span PVDs, the pipelines were not protected from potential secondary mode WIV. As a result of continuing secondary mode WIV in the years following installation of the primary mode PVDs, it is likely that at least some cracks in welds unknowingly initiated and/or propagated. No inspections were completed at the ¼ and ¾ span welds in the years leading up to the failure as the problem was not anticipated. In gathering information from those who were involved in the decision to install PVDs in 1991, it is clear that secondary mode WIV was considered not to be a significant issue. There were four specific reasons for this:

1. A WIV susceptible pipeline was extensively instrumented and monitored for two months and showed no evidence of secondary mode WIV;
2. Field observations showed no evidence of secondary mode WIV (although it is acknowledged that it might be difficult to visually observe secondary mode WIV);
3. A literature search and analytical modeling indicated that high amplitude secondary mode WIV is unlikely, since higher wind speeds make narrow-banded, highly organized vortex shedding difficult to achieve; and
4. Based on historical North Slope wind speed and direction statistics, the higher wind speeds associated with secondary mode WIV have a significantly lower frequency of occurrence than the low wind speeds associated with primary mode WIV.

Based on this information, secondary mode WIV was not predicted to be a major threat for weld fatigue damage.

The DS3I GL line girth weld failure was caused by high-cycle fatigue as a result of secondary mode WIV. Analyses revealed quality welds with no significant weld defects or metallurgical flaws that would have caused this failure had it not been for the cyclical stresses caused by the WIV.

ANALYSIS

AutoPIPE Model of DS 3I 8-inch GL Pipeline

Based on the initial weld failure report, a multi-span AutoPIPE model was developed to represent the section of the pipeline containing the failed welds. Modal analysis was performed to extract all of the primary and secondary modes in the vertical plane of the pipeline. The following observations were made based on the modal analysis results:

1. The primary mode frequencies range from 2 to 4 Hz (a frequency range of about 2 Hz).
2. The modal stresses for the primary modes range from 3 to 8 ksi.
3. The secondary mode frequencies range from 7.4 to 11.2 Hz (a frequency range of almost 4 Hz).
4. The modal stresses for the secondary modes range from 12 ksi to 22 ksi.
5. The modal stresses for the secondary modes are 3 to 4 times larger than the corresponding modal stresses for the primary modes.

Figure 4 presents a plot of the modal stress vs. frequency for all of the primary and secondary modes of the model. The difference between the frequencies and modal stresses of the primary and secondary is readily apparent in this figure.

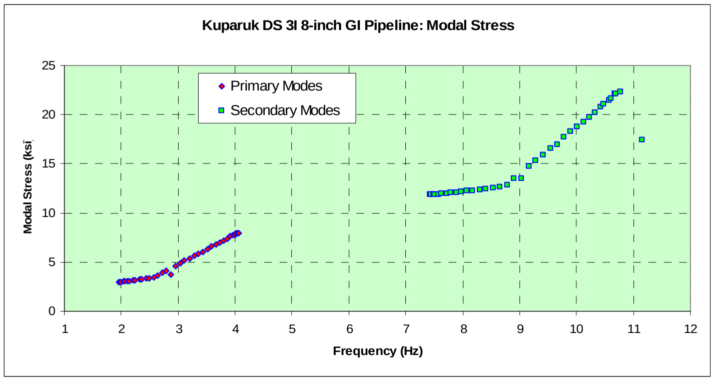

Figure 4: Modal Stress vs. Frequency

The model of the DS 3I 8-inch GL pipeline was modified to include the existing primary mode PVDs and to include the secondary mode TVAs which were designed and installed after the fatigue failure. At an ambient temperature of -7^{o}F (the estimated temperature at the time of the failure), the equivalent damping ratio of the PVD/TVA elastomer material is about 7.2% of critical. Assuming a basic damping ratio of 0.4% of critical in the pipeline without PVDs/TVAs, it is possible to compute estimates of the total modal damping ratio in the pipeline with PVDs/TVAs based on energy methods (Zhang, 1989). Figure 5 presents the estimated total modal damping ratio as a function of frequency for this pipeline with the added primary mode PVDs and secondary mode TVAs at an ambient temperature of -7^{o}F. Note that the distinct peaks in the damping ratio plot correspond to the frequencies of the L, M and H PVD frequencies and the L_S, M_S and H_S TVA frequencies. The troughs between these peaks correspond to the minimum damping ratios for the pipeline with PVDs and TVAs. The energy calculations indicated that the primary mode PVDs provided negligible added damping for the secondary modes and that secondary mode TVAs provided negligible added damping for the primary modes.

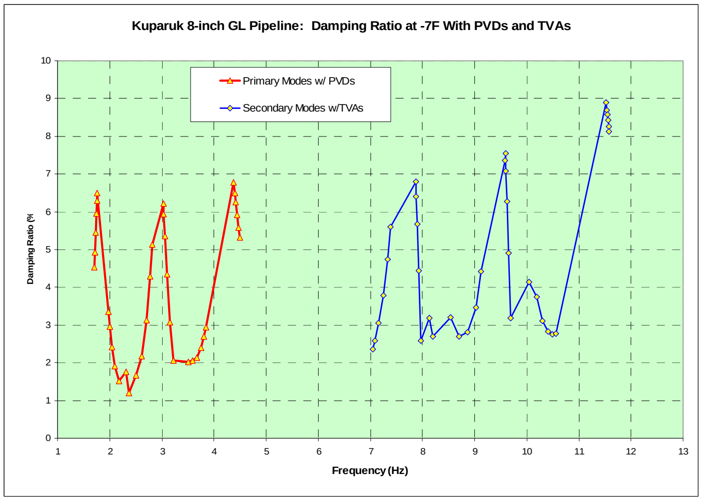

Figure 5: Modal Damping Ratio vs. Frequency

WIV Analysis of DS 3I 8-inch GL Pipeline

The WIV model was used to estimate the uni-modal (narrow-banded) WIV response of the DS 3I 8-inch GL pipeline with and without PVDs/TVAs at an ambient temperature of -7^{o}F. The results of these analyses include the vibration frequencies, estimates of the critical wind speeds, Reynolds Numbers (Re), wind-induced (zero-to-peak) displacements, and the (peak-to-peak) maximum stress ranges under both laminar and turbulent wind conditions, and a “random shedding” threshold associated with the critical “cutoff” Reynolds Number (200,000 for turbulent conditions, and 280,000 for laminar wind conditions). Although the WIV model processes all of the vertical modes, only the modes found to be below the “random shedding” threshold are likely to be exposed to narrow-banded vortex shedding which can lead to uni-modal WIV. These modes are referred herein as “sub-critical” modes.

Figure 6 presents a plot of the estimated maximum laminar WIV stress range as a function of perpendicular wind speed for the model with and without PVDs/TVAs. The vertical line shown in this figure corresponds to the random shedding cutoff Reynolds Numbers for laminar

(Re=280,000) conditions. The following observations can be made:

1. The estimated critical perpendicular wind speeds for the primary vibration modes range from about 8 to 17 mph. The estimated critical perpendicular wind speeds for the secondary vibration modes range from about 31 to 46 mph.
2. For laminar wind conditions, the cutoff wind speed corresponding to Re=280,000 is about 19 mph. All of the primary modes are associated with wind speeds below this cutoff while all of the secondary modes are associated with wind speeds above this cutoff.
3. Under laminar wind conditions in the sub-critical modes, the largest predicted WIV displacement is about 2.7 inches, zero-to-peak and the largest stress range is almost 16 ksi.
4. These results indicate that this pipeline (without PVDs/TVAs) can be predicted to experience narrow-banded vortex shedding and uni-modal (resonant) response in the primary modes.
5. The addition of primary mode PVDs and secondary mode TVAs provides a substantial mitigation benefit. The largest predicted WIV displacement for primary modes in the “with PVDs” configuration is about 0.9 inches, zero-to-peak and the largest stress range is about 6.3 ksi. Both of these maxima occur for a single mode with a wind speed just above 10 mph. The maximum displacements and stress ranges for all of the remaining primary modes are less than about 0.5 inches, zero-to-peak and 3.5 ksi, respectively. The largest calculated WIV displacement for secondary modes in the “with TVAs” configuration is about 0.1 inches, zero-to-peak and the largest stress range is about 2.6 ksi.

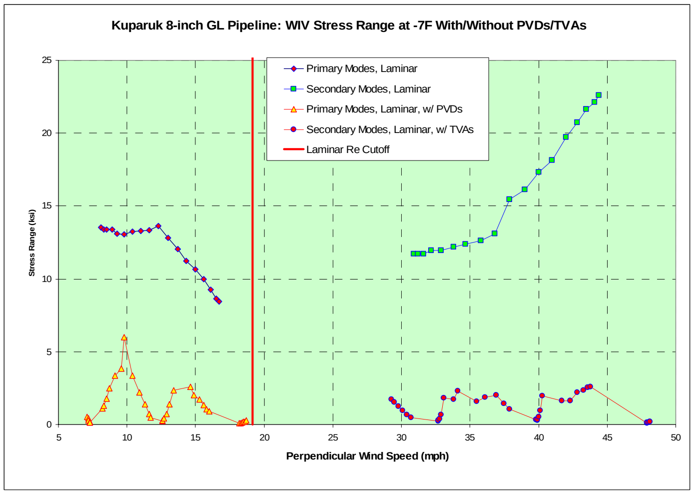

Figure 6: WIV Stress Range vs. Perpendicular Wind Speed

Synthesis of Analysis of the DS 3I 8-inch GL Pipeline Failure

The follow up investigation provided information describing the dynamic properties and WIV response of the DS3I 8-inch GL pipeline for the ~5 year time period before the PVDs were installed and for the ~13 year time period since the PVDs were installed. Several important observations and findings are summarized as follows:

1. The orientation of the section of the line containing the failures is very close to perpendicular to prevailing North Slope wind directions.
2. The wind speed range of the primary vibration modes (from about 8 to 17 mph) straddles the mean North Slope wind speed of approximately 11 mph.
3. The maximum predicted stress range for the primary modes in uni-modal (resonant) vibration due to narrow-banded vortex shedding corresponds to a high potential for girth weld fatigue damage, even for a high quality girth weld.
4. Based on experience, informal classification of the potential for fatigue damage at pipeline girth welds based on stress range demand relative to a high-cycle fatigue endurance limit can be made. A stress range demand below 6 ksi is considered to be essentially benign (e.g., a “green light condition”). A stress range demand between 6 ksi and 10 ksi, can be considered as potentially damaging, depending on the quality of the girth weld (e.g., a “yellow light condition”). A stress range demand of 10 ksi or more can be considered to have a high potential for fatigue damage, even for a high quality girth weld (e.g., a “red light condition”).
5. Based on these observations, this pipeline without PVDs would be considered to be *highly susceptible* to WIV and fatigue damage in the primary modes.
6. The welds that failed certainly could have accumulated fatigue damage due to primary mode vibration during the “unprotected” years of service. These welds were not inspected prior to installation of the PVDs.
7. Addition of the primary mode PVDs to this pipeline provided a substantial mitigation benefit for the primary modes resulting in stress ranges unlikely to result in girth weld fatigue damage except for in the case of a girth weld with a significant pre-existing crack or flaw.
8. The primary mode PVDs are not tuned or positioned to mitigate secondary mode WIV and the analysis results indicates that the added primary mode PVDs provide virtual zero mitigation benefit for the secondary modes.
9. The WIV analysis results indicate that none of the secondary modes can be predicted to experience narrow-banded vortex shedding and uni-modal WIV (i.e., these modes are all associated with Reynolds Numbers well above the random shedding cutoff). This means that if WIV were to occur in the secondary modes, it would be expected to be due to broad-banded vortex shedding, and that several modes would participate in the response (multi-modal, non-resonant conditions). Experience indicates that multi-modal vibration due to broad-banded vortex shedding is typically associated with low amplitude pipe motions.
10. Even though WIV due to well-organized vortex shedding is not predicted or expected for the secondary modes of this pipeline, there is significant evidence indicating that secondary mode WIV played a role in the observed girth weld fatigue failures. The evidence includes the occurrence of relatively steady perpendicular wind speeds directly within the secondary mode wind speed range in the hours prior to and after the failure, and the two girth weld failures occurred very near to ¼ or ¾ span locations where the lower frequency secondary modes experience the high stress.
11. In the absence of a well-developed model for predicting multi-modal vibration due to broad-banded vortex shedding, the results predicted by the WIV model for modes above the cutoff Reynolds Number were used as a reference load case. Using this approach for this pipeline, the results at a perpendicular wind speed in the range of 36 to 37 mph (observed prior to the failure) show zero-to-peak displacements of approximately 0.55 inches with a maximum stress range of approximately 14 ksi. This level of secondary mode WIV would clearly be source of concern for fatigue damage even for a high quality girth weld. This approach does not address possible “beating” (cancellation) effects associated with multi-modal vibration for modes with closely-spaced frequencies.
12. If secondary mode vibration were to occur, the high modal stress (stress per inch of pipe motion) and high vibration frequency

combine to make it a cause for concern for potential fatigue damage.

13. It should be pointed out that secondary mode WIV has *never* been observed or recorded during field experiments on typical, insulated above ground pipelines. However, considering the small fraction of time that most pipelines are actually observed relative to the length of their service lifetime and the relatively short duration of formal experimental pipeline monitoring programs compared to the service lifetimes of these pipelines, the possibility of secondary mode WIV cannot be dismissed. However, it would be expected that if/when secondary mode WIV does occur, it is both infrequent and characterized by relatively low amplitude pipe motions.
14. Figure 7 provides a useful illustration that supports the expected low frequency of occurrence of conditions that are favorable for potential secondary mode WIV of the DS 3I GL pipeline. This figure is a histogram of component of wind speed resolved perpendicular to the DS 3I GL pipeline alignment based on a 20 year database of North Slope wind speed and direction observations. The red vertical lines denote the primary mode wind speed range (from about 8 to 17 mph) and the blue vertical lines denote the secondary mode wind speed range (from about 31 to 46 mph). Summation of the bins (or portions of bins) of this histogram that fall within the primary and secondary mode wind speed ranges indicates that about 35.7% of the perpendicular wind speed component occurrences fall within the primary mode range while only 0.75% of the occurrences fall within the secondary mode wind speed range.
15. Prior to this failure, secondary mode vibration dampers have been designed for a handful of North Slope pipelines. Each of these pipelines has had some exceptional, non-standard characteristic that made it different from “typical” above-ground North Slope pipeline configurations. These characteristics resulted in either very low pipeline frequencies or very low Reynolds Numbers, or both. In each case, the Reynolds Numbers for at least some of the secondary modes dropped below the “critical” cutoff Reynolds Number such that narrow-banded vortex shedding could be predicted in secondary modes. Hence, secondary mode vibration dampers were designed for these lines.

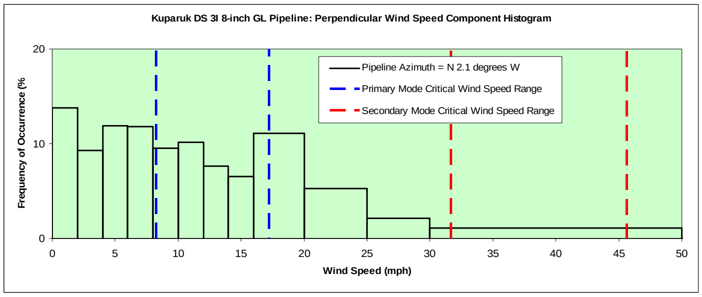

Figure 7: Perpendicular Wind Speed Histogram

CONCLUSIONS

Alaskan Arctic North Slope oil and gas operators have employed successful mitigating measures (PVDs and TVAs) to prevent potential severe fatigue damage to pipeline welds caused by lower wind speed events (8-18 mph) and the associated primary mode(s) of WIV. However, in general, no protective measures have been employed to prevent pipeline girth weld fatigue failures from secondary mode WIV based on the low likelihood of occurrence and the fact that significant secondary mode WIV was not predicted to occur. It has been postulated that the secondary modes require a span-wise correlation of lift forces that is much more difficult to achieve than for the lower frequency primary modes. The higher frequency modes are also associated with higher wind speeds, which occur less frequently, and higher Reynolds numbers. Furthermore, this failure was the first documented evidence of a higher mode vibration failure under broad-banded, multi-modal vortex shedding characteristics attributed to these higher wind speeds.

A significant amount of evidence indicates that secondary mode WIV played a role in the observed girth weld fatigue failures, including the occurrence of relatively steady perpendicular wind speeds directly within the secondary mode wind speed range (35-40 mph) in the hours prior to and after the failure, and the two (2) girth weld failures occurred very near to ¼ or ¾ span locations where the lower frequency secondary modes experience the high stress. In the absence of a well-developed model for predicting multi-modal vibration due to broad-banded vortex shedding, application of the results predicted by the model for modes that are above the cutoff Reynolds Number were used as a reference load case, revealing secondary mode WIV to clearly be source of concern for fatigue damage even for a high quality girth weld.

As a result of this work, several strategy changes are being implemented for WIV assessment of North Slope pipelines, starting with the pipelines in the Kuparuk oil field. The following programs are currently being pursued at Kuparuk:

1. The field-wide inventory of pipelines is being screened for relative susceptibility to secondary mode WIV. The screening criteria includes the pipe diameter, density of contents and span length and the corresponding secondary mode frequency, wind speed and Reynold’s Number ranges, the orientation of each segment of the pipeline, the age of the pipeline, the location of the pipeline on the pipe-rack (e.g., leading edge or shielded), etc.
2. Pipelines that are flagged by the screening as highly susceptible to secondary mode WIV are selected for additional action, including more refined analysis of secondary mode WIV and/or application of secondary mode WIV mitigation (using PVDs or TVAs).
3. The WIV model is being extended to consider broad-banded, multi-modal WIV as a basis for better ranking pipelines based on potential fatigue damage due to secondary mode WIV.
4. The traditional WIV mitigation “fan” (a swath of pipeline azimuths typically considered most susceptible to WIV) is being considered for widening. This is important because of the trend for extended service lives (e.g. from 20 to 30+ years).

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