

NON-DESTRUCTIVE TESTING AND ASSESSMENT OF DYNAMIC INCOMPATIBILITY BETWEEN 3rd PARTY PIPING AND DRAIN VALVE SYSTEMS: AN INDUSTRIAL CASE STUDY

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Non-destructive Testing and Assessment of Dynamic Incompatibility between 3rd Party Piping and Drain Valve Systems: An Industrial Case Study

This paper presents the outcome of an industrial case study that involved condition monitoring of piping system that showed signs of excess fatigue due to flow induced vibration. Due to operational requirements a novel non-destructive assessment stratagem was adopted using different vibration analysis techniques – such as Experimental Modal Analysis (EMA) and Operating Deflection Shapes (ODS) – and complemented by visual inspection. Modal analysis performed near a drain valve showed a dynamic weakness problem (several high frequency flow induced vibration frequency peaks) hence Condition Based Monitoring (CBM) was used. This could easily be linked to design problem associated with the dynamic incompatibility due to dissimilar stiffness between two 3rd party supplied pipe and valve systems. It was concluded that this is the main cause for these problem types especially when systems are supplied by third parties, but assembled locally, a major cause of dynamic incompatibility. It is the local assembler's responsibility to develop skills and expertise needed to sustain the operation of these plants. This paper shows the technique used as result of one such initiative. Since high amplitude, low frequency displacement can cause low cycle fatigue, attention must be paid to ensure flow remains as steady-state as possible. The ability to assess the level of design incompatibility and the level of modification required using non-destructive testing is vital if these systems are to work continuously.

Keywords: modal analysis; non-destructive testing; ODS; pipe; stress; vibrations

1. Introduction

Vibration loading, typically mechanical or flow-induced, is the most common cause of high cycle fatigue [1]. In a recent survey [2] pipe cracking was identified as the most frequently recurring problem, the most significant cause of which was determined to be piping vibration. Mechanical vibration was one of the major causes of all reportable occurrences involving pipes and fittings [2]. Failure of piping systems can have disastrous effects, leading to injuries and even fatalities as well as creating a

substantial additional cost to industry and the environment. Piping vibration problems in operating plants have resulted in costly unscheduled outages [3]. Piping vibration failures have been one of the major causes of downtime, fires and explosions in industrial plant over the past 30 years. For example, one piping failure at a petrochemical plant in 1974 caused over \$114,000,000 in property damage due to an explosion [4]. In nuclear pressurised water reactor power plants, over 80 cases of cracks or leaks occurred in the piping systems of charging pumps over a two year period [5]. Therefore, it is vitally important that piping vibration amplitudes in a system be evaluated to determine if the levels are acceptable. If the vibrations levels are judged to be excessive, the piping configuration, support structure, span length or material may have to be modified to make the system acceptable [6-8].

Detecting, monitoring and predicting vibration [9] is an important and cost effective way to identify issues associated with structures such as general wear and tear, possible imbalance problems or incompatible structural stiffness. However, vibration monitoring can only pinpoint the root causes of failures which are usually triggered by poor design, poor assembly, miss-alignment or imbalance of whole structure of associated components. This incompatible structural stiffness is usually due to the presence of sub-optimal structures that lacks dynamic compatibility due to non-uniform mass distribution or miss-match stiffness such as fluid momentum greater than the stiffness of the pipe. In such cases, the overall dynamic response is no longer the expected one and the system behaves in a completely different or unpredictable manner.

One of the main causes of the unpredictable behaviour of pipes is the induced vibrations due to the interaction between the structure (walls of the pipe as well as the pipe supports) and the fluid flowing through the pipe. Generally the fluid behaves as a turbulent flow and exerts random pressures on the pipe walls [10]. Due to the fluid

structure interaction including flow turbulent fluctuations and unsteady pressure on the pipe walls a random response will be induced to the pipe structure which may result in resonant vibrations. The pipe response can be unstable undergoing large structural vibrations once a critical threshold value is exceeded by the turbulent flow. It has been proved that the fluid-structure interaction phenomenon induces a significant response of the structure [11] and alters the fluid force acting on the walls. The fluid-induced vibration of simply supported and clamped pipelines was studied in [12], where parameters such as liquid mass density to pipe-wall mass density ratio, pipe radius to pipe-wall thickness ratio, fluid velocity and fluid pressure are considered. A vibration analysis of a 3-dimensional piping system composed of curved and straight sections is performed in [13] using the wave approach while the obtained results are compared with the ones obtained from a FEM formulation.

Other causes of the unpredictable behaviour of pipes is the fluid high internal velocity which can induce buckling on a pipe supported at both ends and high instability at on a pipe supported at one end. A structured and systematic assessment approach of the vibration of pipes was considered in [14]. The study conveys that some of main problems in the existing vibrating piping systems are due to poor supporting systems.

The general stability problem of vibrating pipes conveying fluid has been studied extensively in [10] and [15]. The nonlinear dynamics of a pulsatile pipe conveying fluid was studied in [16] while the nonlinear dynamics of a curved pipe conveying fluid subject harmonic excitation was studied in [17].

The phase shift effects of resonant vibrating pipes due to various imperfections are discussed in [18, 19] and their dynamic structural response in [20]. The perturbation analysis used provides direct insight into how the non-uniform mass, stiffness, the non-proportional damping, or weak imperfections affect the phase shift. The post-buckling

effect in vibrating pipes which permit axial sliding and don't deflect transversely was discussed in [21]. Traditionally, modal parameters, such the ones presented above, are extracted by conducting experimental modal analysis on a static pipe structure. However sometimes extracting modal parameters while the system is in operation is highly desirable. A method named Operational Modal Analysis (OMA) has been introduced in order analyse structures subjected to excitation generated by their own operation [22]. System identification methods are efficient OMA tools to estimate modal parameters from ambient vibrations. A review of in operation identification for modal analysis that is Stochastic System Identification (SSI) has been fully reviewed in [40]. The method described in [23] was successfully used to identify damages during the operation of the pipes of a gas compressor due to operating equipment as well as the flowing fluid. When classical condition monitoring is not possible, in-service Operating Deflection Shape (ODS), a non-invasive and non-destructive approach to monitor and visualise the motion of the system while in operation [24-29], can be successfully used.

To assess possible structural damage, fatigue crack initiation, growth behavior and resistance of cracked pipes under cyclic loading have been studied in [30]. A failure analysis of a hydraulic pipe due to resonance condition as a form of energy dissipation resulting from viscous friction has been presented in [31], where a crack structural damage was assessed due to the corrosion of the pipe and the reach of maximal admissible stress. A failure analysis of a natural gas pipe adjacent to a source of vibration, based on pipe material characterisation, dynamic stress, modal analysis and metallurgical assessment was studied in [32]. The main factor leading to failure (a crack was initiated) was considered the huge energy level due to an increase in the amplitude of a vibrating valve leading to the development of the pipe dynamic stress.

This paper presents the outcome of an industrial case study that involved condition monitoring of a piping system that showed signs of excess fatigue due to flow induced vibration. Due to operational requirement a novel non-destructive assessment stratagem was adopted using different vibration analysis techniques – such as Experimental Modal Analysis (EMA) and Operation Deflection Shapes (ODS) – and complemented by visual inspection. Modal analysis performed near a drain valve showed a dynamics weakness problem (several high frequency flow induced vibration frequency peaks) hence initiated Condition Based Monitoring (CBM). The analysis reveals a dynamic weakness problem of a drain valve along the piping system, due to a design problem and dynamic incompatibility of the supplied pipe and valve systems. This could easily be linked to design problem associated with the dynamic incompatibility due to dissimilar stiffness between two 3rd party supplied pipe and valve systems. It was concluded that this is the main cause for these types problem especially when systems are supplied by third parties and assembled locally.

2. Problem Formulation

Condition monitoring of an industrial piping system shown in Figure 1 is considered in this section. Due to the operational requirements, a non-destructive assessment stratagem to carry out a vibration diagnostic & analysis was considered using the Experimental Modal Analysis (EMA) and Operating Deflection Shapes (ODS) analysis techniques described below.

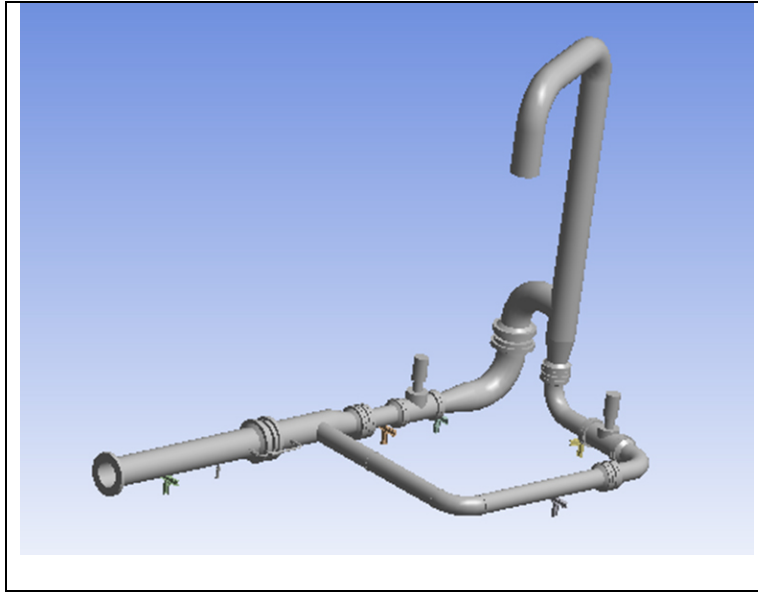


Figure 1. Industrial piping system

The non-destructive technique is based on a measurement procedure and vibration criteria to evaluate whether or not the high recorded vibrations of the industrial piping system introduced highly vibratory stress into the piping by its running conditions.

2.1. Experimental Modal Analysis (EMA) and Operating Deflection Shapes (ODS) analysis

Experimental Modal Analysis (EMA) – It is an investigation on vibration characteristics of elastic structures. EMA requires the system to be in a complete ‘shutdown’ state; which means no unaccounted excitation force induced into the system. Measurable impacts or random forces are used to excite the system. The responses of the system are cross-correlated with the measured inputs. Transfer functions are later obtained by considering the Fourier transform of the cross-correlated functions. This procedure is repeated with a discrete set of geometrical positions which are sufficient to describe the structure. Various curve-fitting algorithms are then used to extract the three parameters; namely natural frequencies, mode shapes and modal damping.

EMA with SISO, SIMO and MIMO modal identification algorithms in time, frequency and spatial domain, has been widely used in troubleshooting, Structural Dynamic Modification (SDM), analytical model updating, optimal dynamic design, passive and active vibration control, as well as vibration-based structural health monitoring in aerospace, mechanical and civil engineering. In applications, the extracted modal parameters from EMA have been widely used to detect damage on beams and beam-like structures [33-37] as well as rotor systems [38, 39]. These are the methods used for damage detection based on dynamic characteristics of structures such as natural frequencies, dynamic mode shapes, and structural damping. These methods have taken advantage of the present day development of modal analysis techniques with accurate measurements of modal parameters. When damage event occurs, the structural dynamic characteristics changes and this may be used as an indicator of damage.

Operating Deflection Shapes (ODS) analysis – A very attractive solution named Operating Deflection Shape (ODS) can measure the deflection of structures while in-service. Generally, an operating deflection shape can be defined as “any forced motion of two or more points on a structure”^[24] and can be planar, orbital or three dimensional. Since ODS represents a linear combination of the mode shapes of a structure, ODS measurement should be performed under constant and stable operating conditions in order to obtain accurate results. The measurement should be performed in such a way so the measurement equipment does not affect the answer of the system, that is, a high signal to noise ratio. In the measurement process the constant and stable operating condition depends on the system complexity and whether all DOFs are measured simultaneous or not, while the “simultaneous” condition depends on the number of data acquisition channels and DOFs to be measured.

There are basically three types of operating deflection shape named Time ODS which measures the vibration of a structure as a function of time, or Spectral ODS and Run-up/down ODS which measure the vibration pattern of an equipment (typically a rotating machinery) at a discrete operating frequency. For a pipe operating structure when no rotating equipment is employed along the pipe, the measured time signal obtained from the ODS can be processed to show the pipe behavior over time.

2.2. Measurement procedure description

A non-invasive measurement and evaluation procedure applied to a piping system that showed signs of excess fatigue was considered based on the “need to know” whether or not and how the stress induced into the piping by its running conditions, i.e. flow induced high amplitude vibrations, affect the overall structural integrity of the piping system. The measurement and evaluation procedure have been devised using a state of the art MDT-Q2 data acquisition system based on a 4 channels real-time machinery analyser, tri-axial (measurement locations were taken in the principal directions) and uni-axis accelerometers, modally tuned impact hammer and related equipment and ME’scope software used to analyse the motion and the excessive vibration levels of the piping system. It has been observed that the flow induced vibrations may not cause excessive stresses in the main pipe but to the adjacent systems that are attached to the vibrating pipe.

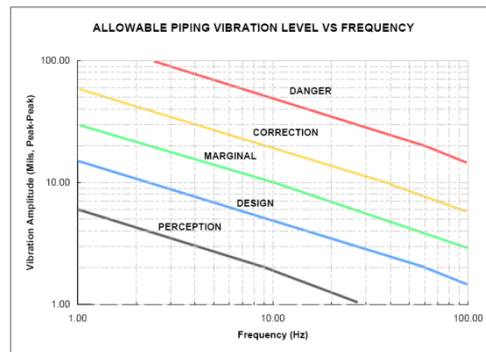


Figure 2. Allowable Piping Vibration Level versus Frequency

As a part of the non-invasive measurement and evaluation procedure, the evaluation part has been based on the allowable levels of piping vibration versus the associated frequencies criteria shown in Figure 2. The criteria states that for the cases when piping vibration amplitudes at the measured frequencies are greater than the danger line (the red line in Figure 2) then piping failures are considered to be typical occurrences, and for the cases when the vibration level were below the design line (blue line shown in Figure 2), very few failures may occur. It was considered that vibrations level versus frequency criteria can serve as a good starting point in assessing piping vibrations and to screen systems that need further analysis [7].

3. Results

Modal analysis was performed during non-operating condition to obtain the natural frequencies of industrial piping system and structure. Figure 3 show the results for different locations.

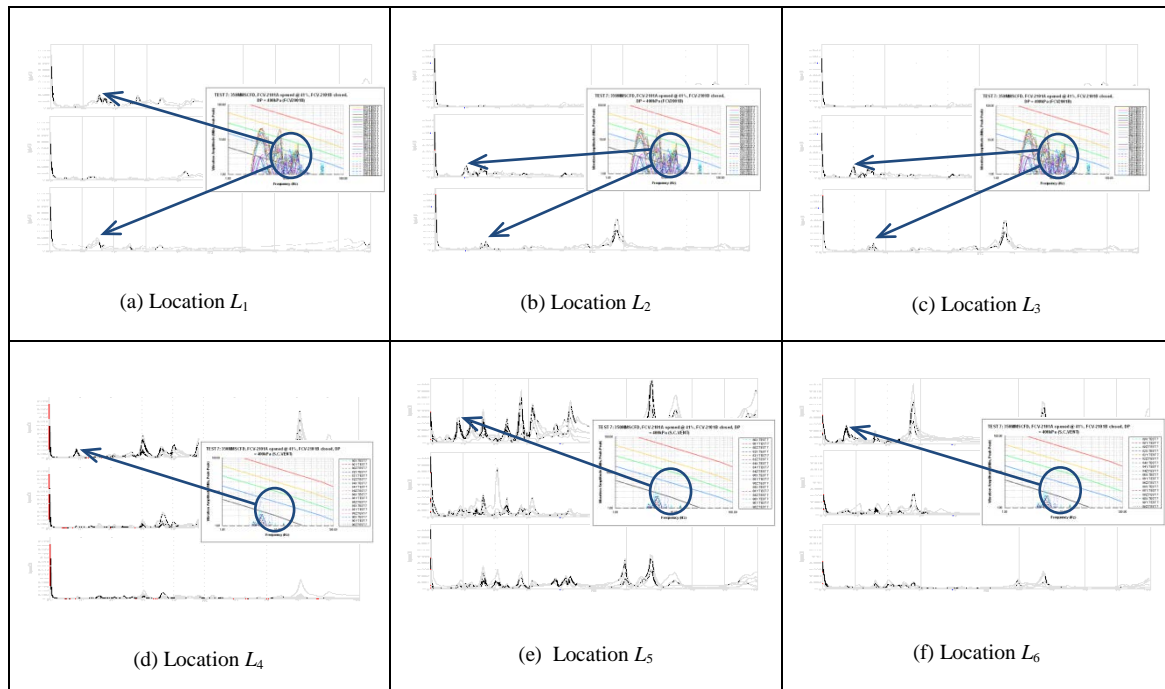


Figure 3. Modal Analysis on Locations L_1 - L_6 are Shown in (a) – (f)

Modal analysis performed on the structure does not show any peak at the flow-induced frequencies region (5-15Hz). All the vibration measurements on the structure are low compared to the vibration level of the pipe. This indicates that there is no structure dynamics weakness issue of the structure.

The pipe dynamics weakness situation was assessed along the pipe. The details locations are described as below: modal analysis along the pipes show some natural frequencies at 5-15Hz region which might indicate pipe dynamics weakness for 6 locations named L_1 , L_2 , ..., L_6 . Cracks have been observed at the connections L_3 , L_5 and L_6 (between the drain valve and main pipe) and high vibrations were recorded at those locations. It was also observed that vibration level increase when increasing the flow rate. Since cyclic excitation (and not random vibration) generates resonance situation, it was supposed that the high vibration of the pipe was probably due to flow-induced excitation which is a stiffness controlled situation rather than a pipe dynamics

weakness. As a result it was concluded that the high vibration of the pipe are probably due to the process and design problem.

The evaluation of whether or not the high vibration levels represent a problem has to be based primarily on the vibratory stresses introduced into the piping. Many times apparently high vibration may not cause excessive stresses in the piping, but could cause excessive stresses to piping system that are attached to the vibrating pipe. Since cracks were found at the connection between the drain valve and main pipe, vibration measurement have been performed on the Kicker Line Drain Valve shown in Figure 4a in order to assess the vibrations levels. The recorded vibrations for Kicker Line Drain Valve are shown in Figure 4b with the high vibration level dominant frequency at 47Hz in X-axis caused mainly by the unsuitable design or selection of the drain valve.

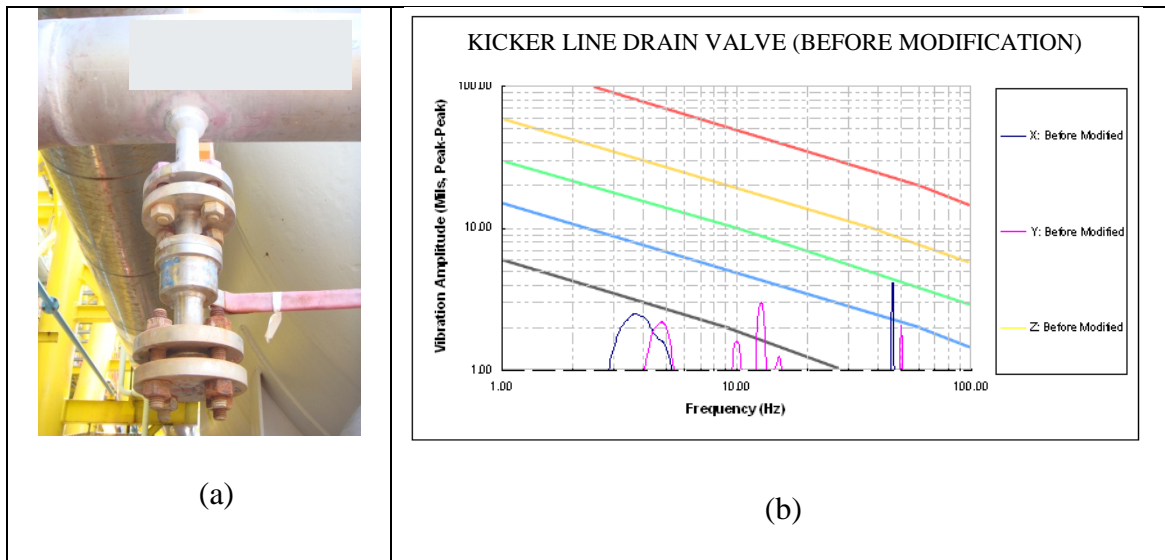


Figure 4. Before Modification (a) Kicker Line Drain Valve, and (b) Valve Vibration Level vs. Frequency

(note that the location of figure 4 has been replaced after the text mentioning it)

In order to observe if there is any excessive stress in the piping caused by the valve, the effect of the valve on the vibrations levels by vibration measurement was analysed after removing the valve as shown in Figure 5a. It can be observed that 47Hz component have been eliminated as shown in Figure 5b.

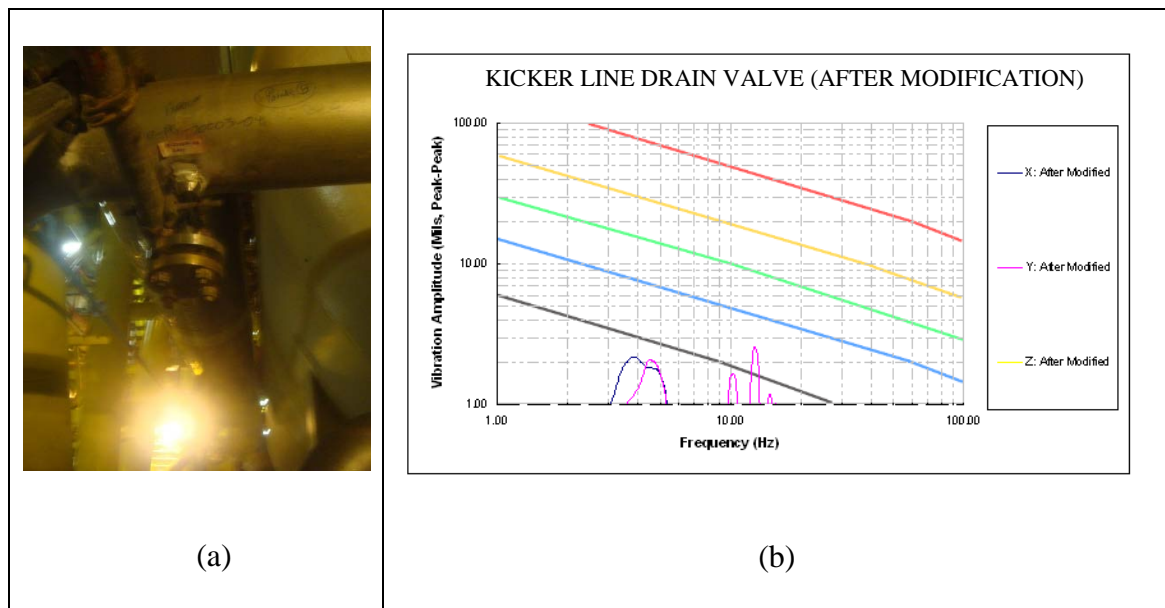


Figure 5. After Modification (a) Kicker Line Drain Valve, and (b) Valve Vibration Level vs. Frequency

The cracks in kicker drain valve have proved that the improper design and unsuitable drain valve location affect the piping system. In this case the designed drain valves are too long and heavy therefore fatigue failure is easily to occur for this kind of design. To evaluate the vibration of the pipe due to operation condition and the risk of apparently high vibration which may induce excessive stress to piping system that are attached to the vibrating pipe, an ODS analysis have been performed for different testing conditions (decided based on the pipe operating conditions) as shown in Figure 6.

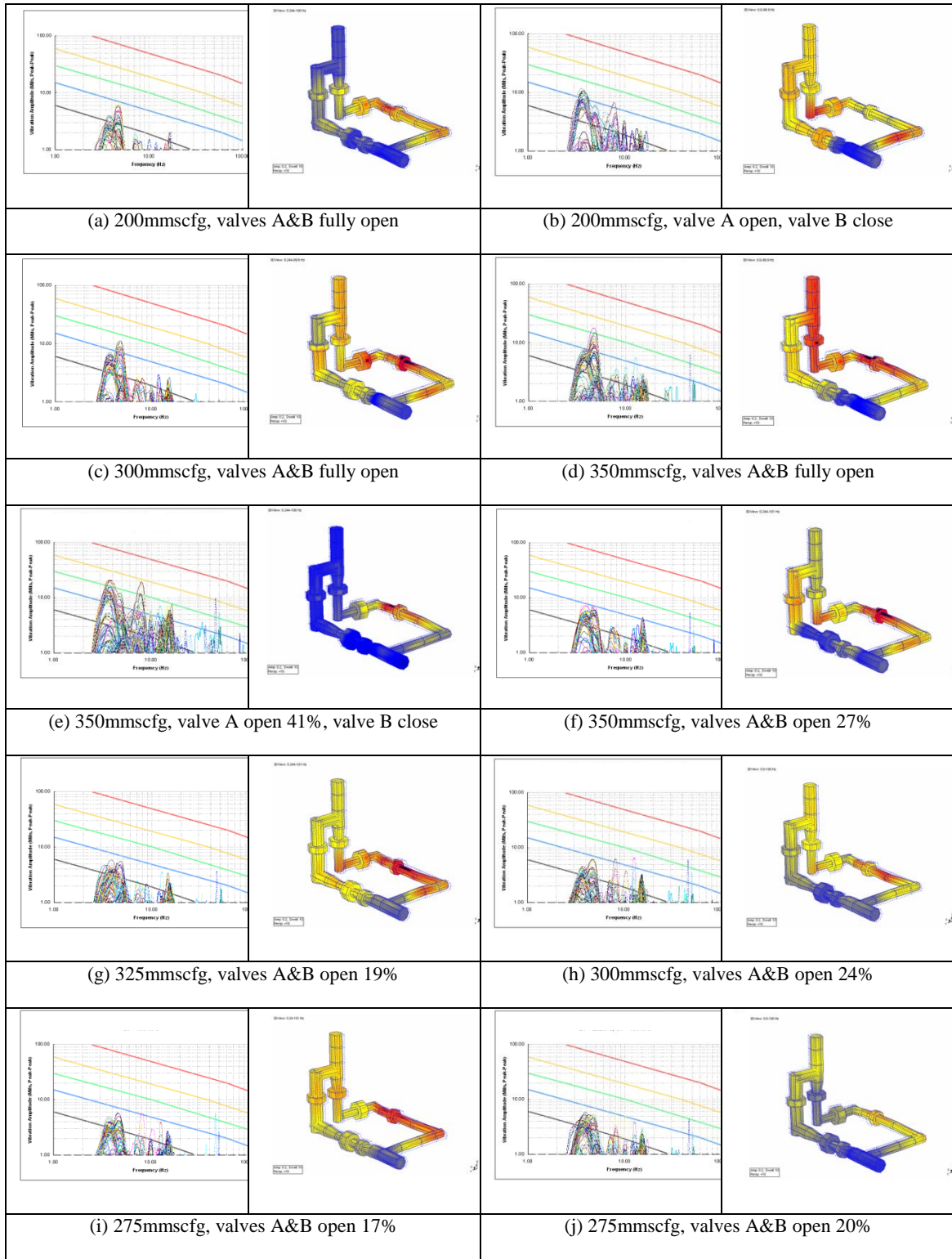


Figure 6. ODS Analysis for the Pipe for Different Testing Conditions

Referring to Figures 2 and 6, it can be observed that the vibration amplitudes of the pipe at the measured frequencies do not overlay the danger line and therefore no failures of

the pipe are expected. However, two vibration tests performed at a maximal flow rate (350mmscfd) show highest vibration levels for the pipe and a possible contribution in increasing the levels of stress to piping system that are attached to the vibrating pipe, especially when, as resulting from the modal analyses, these system which are supplied by third parties and assembled locally, suffer from dynamic incompatibility. Therefore, these vibrations versus frequency criteria can serve as a good starting point in evaluating piping vibrations in screening those systems that need further analysis.

4. Conclusions

In this paper an investigation into the application of non-destructive evaluation of in-service pipe has been presented. The modal analyses applied to the piping structure do not show any indication of a structural dynamics weakness issue. Modal analysis along the pipes show there are few natural frequencies at 5-15Hz region which may be an indication of the pipes dynamics weakness. Some of the modal analyses which have been performed near a drain valve showed a design problem due to dissimilar stiffness – dynamic incompatibility - between the supplied pipe and valve systems.

It was concluded that this was the main cause for these types of problem especially when these systems are supplied by third parties, but assembled locally. Moreover, since the high vibration response of the pipe was mainly due to the flow-induced excitation as shown by the ODS analysis, a combined further analysis on the pipe design and flow (including a dynamical stress analysis and fluid-structure interaction (FSI)) is needed in order to (a) understand the process flow inside the pipe, (b) understand the flow-induced vibration/stresses for the entire system, (c) optimise piping production, and (d) to run the system under allowable endurance stress limit and safe condition.

References

- [1] Agency, O. N. E.: Nuclear Power Plant Operating Experiences from the IAEA/NEA Incident Reporting System 2002-2005. 2006, 1-56
- [2] Kustu, O., & Scholl, R.: Research Needs for Resolving the Significant Problems of Light-Water Reactor Piping Systems. 1980
- [3] Olson, D. E.: Pipe Vibration Testing and Analysis *Companion Guide to the ASME Boiler & Pressure Vessel Code* (Vol. Chapter 37). New York: ASME PRESS, 2002
- [4] Garison. W.G.: Major Fires and Explosions Analyzed for 30-Year Period, Hydrocarbon Processing, 1988
- [5] Olson, D. E.: Piping Vibration Experience in Power Plants, Pressure Vessel and Piping Technology, A Decade of Progress, Book No. H0030, ASME, 1985
- [6] Wachel, J.C., Morton, S.J., and Atkins, K. E.: Piping Vibration Analysis, *19th Turbomachinery Symposium*, Texas A&M University, September, 1990.
- [7] Wachel, J.C., Piping Vibration and Stress, Vibration Institute, Machinery Vibration Monitoring and Analysis Seminar, New Orleans, LA, April, 1981, 1-20
- [8] Wachel, J.C., "Displacement Method For Determining Acceptable Piping Vibration Amplitudes", PVP-Vol. 313-2, International Pressure Vessels and Piping Codes and Standards: Volume 2, ASME, 1995.
- [9] Rao S.S.: *Mechanical Vibration*, SI Edition, Prentice Hall, 2005.
- [10] Blevins R.D.: Flow induced vibration. 2nd ed. New York: Van Nostrand Reinhold, 1990. Chen S.S.: Flow-induced vibration of circular cylindrical structures, Washington: Hemisphere Publishing Corporation, 1987.
- [11] Dai H.L., Wang L., Qian Q., Gan J.: Vibration analysis of three-dimensional pipes conveying fluid with consideration of steady combined force by transfer matrix method, *Applied Mathematics and Computation* (Article in Press)
- [12] Zou G.P., Cheraghi N., Taheri F., Fluid-induced vibration of composite natural gas pipelines, *International Journal of Solids and Structures* 42, 2005, 1253–1268
- [13] Koo G.H., Park Y.S.: Vibration analysis of a 3-dimensional piping system conveying fluid by wave approach, *International Journal of Pressure Vessels and Piping* 67, 1996, 249-256.
- [14] Sukaih N.: A practical, systematic and structured approach to piping vibration assessment,

International Journal of Pressure Vessels and Piping 79, 2002, 597–609

- [15] Chen S.S.: Flow-induced vibration of circular cylindrical structures, Washington: Hemisphere Publishing Corporation, 1987.
- [16] Panda L.N., Kar R.C.: Nonlinear dynamics of a pipe conveying pulsating fluid with combination, principal parametric and internal resonances, *Journal of Sound and Vibration* 309, 2008, 375–406
- [17] Lin W., Qiao N., Yuying H., Dynamical behaviours of a fluid-conveying curved pipe subjected to motion constraints and harmonic excitation, *Journal of Sound and Vibration* 306, 2007, 955–967
- [18] Enz S., Thomsen J.J.: Predicting phase shift effects for vibrating fluid-conveying pipes due to Coriolis forces and fluid pulsation, *Journal of Sound and Vibration* 330, 2011, 5096–5113
- [19] Thomsen J. J., Dahl J.: Analytical predictions for vibration phase shifts along fluid-conveying pipes due to Coriolis forces and imperfections, *Journal of Sound and Vibration* 329, 2010, 3065–3081
- [20] Semke W.H., Bibel G.D., Jerath S., Gurav S.B., Webster A.L.: Efficient dynamic structural response modelling of bolted flange piping systems, *International Journal of Pressure Vessels and Piping* 83, 2006, 767–776
- [21] Plaut R.H.: Postbuckling and vibration of end-supported elastica pipes conveying fluid and columns under follower loads, *Journal of Sound and Vibration* 289, 2006, 264–277
- [22] Mohanty P., Rixen D.J.: A modified Ibrahim time domain algorithm for operational modal analysis including harmonic excitation, *Journal of Sound and Vibration* 275(1–2), 2004, 375–390.
- [23] Trebuňa F., Šimčák F., Huňady R., Pástor M., Identification of pipes damages on gas compressor stations by modal analysis methods, *Engineering Failure Analysis*, 27, 2013, 213–224
- [24] Devriendt C., Steenackers G., DeSitter G., Guillaume P.: From operating deflection shapes towards mode shapes using transmissibility measurements, *Mechanical Systems and Signal Processing*, 24, 2010, 665-677
- [25] Dossing O., Staker C.H.: Operational deflection shapes: background, measurement and applications, 5th International Modal Analysis Conference, London, UK, 1987, 1372–1378.
- [26] Marscher W.D.: Jen C.W.: *Use of operating deflection and mode shapes for machinery diagnostics*, Proceedings of 17th International Modal Analysis Conference, 1999, 65–71.
- [27] McHargue P.L., Richardson M.H.: *Operating detection shapes from time versus frequency domain measurements*, The 11th International Modal Analysis Conference, Kissimmee, USA, 1993, 581-587.
- [28] Pascual R., Golinval J.C., Razeto M.: *On-line damage assessment using operating detection shapes*,

- Proceedings of 17th International Modal Analysis Conference, 1999. 238–243.
- [29] Tongue B.H.: *Principles of Vibration*, Oxford University Press, 2nd ed., 2002.
- [30] Singha P.K., Vazea K.K., Bhasina V., Kushwahaa H.S., Gandhib P., Ramachandra Murthy D.S.: Crack initiation and growth behaviour of circumferentially cracked pipes under cyclic and monotonic loading, *International Journal of Pressure Vessels and Piping*, 80, 2003, 629–640
- [31] Rouabeh K., Schmitt C., Elaoud S., Hadj-Taïeb E., Pluvinage G.: Failure of grey cast iron water pipe due to resonance phenomenon, *Engineering Failure Analysis*, 26, 2012, 120-128
- [32] Ashrafizadeh H., Karimi M., Ashrafizadeh F.: Failure analysis of a high pressure natural gas pipe under split tee by computer simulations and metallurgical assessment, *Engineering Failure Analysis*, 32, 2013, 188-201
- [33] Fayyadh M.M., Razak H.A., and Ismail Z.: Combined modal parameters-based index for damage identification in a beamlike structure: theoretical development and verification, *Archives of Civil and Mechanical Engineering*, 11, 2011, 587-609.
- [34] Ismail Z. and Ong Z.C.: Honeycomb damage detection in a reinforced concrete beam using frequency mode shape regression, *Measurement*, 45, 2012, 950-959.
- [35] Ismail Z.: Application of residuals from regression of experimental mode shapes to locate multiple crack damage in a simply supported reinforced concrete beam, *Measurement*. 45(6), 2012, 1455–1461.
- [36] Ismail Z., Ibrahim Z., Ong A.Z.C., Rahman A.G.A.: Approach to Reduce the Limitations of Modal Identification in Damage Detection Using Limited Field Data for Nondestructive Structural Health Monitoring of a Cable-Stayed Concrete Bridge, *Journal of Bridge Engineering*, 17(6), 2012, 867-875.
- [37] Dilena M. and Morassi A.: Experimental modal analysis of steel concrete composite beams with partially damaged connection, *Journal of Vibration and Control*, 10(6), 2004, 897-913.
- [38] Ong Z.C., Rahman A.G.A., and Ismail Z.: Determination of Damage Severity on Rotor Shaft Due to Crack Using Damage Index Derived From Experimental Modal Data, *Experimental Techniques*, 2012 (In Press).
- [39] Rahman A.G.A., Ismail Z., Noroozi S., Ong Z.C.: Study of open crack in rotor shaft using changes in phase of Frequency Response Function (FRF), *International Journal of Damage Mechanics*, 2012 (In Press).

- [40] Peeters B., De Roeck G., Stochastic System Identification for Operational Modal Analysis: A Review, *Journal Dyn. Sys., Meas., Control*, 123(4) 659-667, 2001