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Vibration Qualification of Piping Systems

David Olson
Sargent & Lundy, LLC

Abstract

A number of industry and U.S. Nuclear Regulatory Commission (NRC) requirements exist for the quantification and qualification of piping-system vibrations. An ASME Operating and Maintenance (OM) Standard was written to provide methods for obtaining piping vibration measurements and to define acceptance criteria for the evaluation and qualification of the vibrations. Described herein is an overview of this standard, ASME OM-3, “Vibration Testing of Piping Systems,” along with discussions of the acceptance criteria (Reference 1).

Industry and NRC Requirements

Section III of the ASME Boiler and Pressure Vessel (B&PV) Code for Class 1, 2, and 3 Piping and ASME B31.1, “Power Piping,” both contain requirements regarding piping vibration (References 2 and 3). Section III of the ASME B&PV Code uses the following wording to address steady-state vibration:

> Piping shall be arranged and supported so that vibration will be minimized. The designer shall be responsible by design and by observation under start-up or initial operating conditions, for ensuring that vibration of piping systems is within acceptable levels.

Requirements for dynamic transient vibration include the following:

> Impact—Impact forces caused by either external or internal loads shall be considered in the piping design.

ASME B31.1-2007 includes the following requirements regarding vibration:

> Vibration. Piping shall be arranged and supported with consideration of vibration

Nonmandatory Appendix V, “Recommended Practice for Operation, Maintenance, and Modification of Power Piping Systems,” of ASME B31.1 also contains recommended practices for completing visual surveys to address vibration.

Further requirements for nuclear power plants are delineated in NRC Regulatory Guide 1.68, “Initial Test Programs for Water-Cooled Nuclear Power Plants,” and

Section 3.9.2, “Dynamic Testing and Analysis of Systems, Structures, and Components,” of NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants” (References 4 and 5). These documents require most of the plant piping in a nuclear power plant to be tested during preoperational and startup testing for both steady-state and dynamic- transient vibrations. Regulatory Guide 1.20, “Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing,” also has requirements for piping-vibration testing (Reference 6).

ASME OM-3 Vibration Testing of Piping Systems

ASME OM-3 was published to address the vibration requirements included in the piping Codes and NRC Regulatory Guides and additionally addresses vibrations encountered during operation and as a result of modifications. OM-3 includes testing requirements and acceptance criteria for piping vibration. For pipe-vibration monitoring and testing, it includes a visual inspection method, a simplified method for qualifying piping systems, and a rigorous qualification method for steady-state and transient vibration. Instrumentation and measurement techniques are included and corrective action is discussed along with potential vibration sources.

The General Requirements section of OM-3 establishes a Vibration Monitoring Group (VMG) classification system. This classification system provides guidance for each VMG based on the degree of sophistication of the monitoring system and analysis methods used. Piping systems are classified into one of the three VMGs, ranging from the simplest, VMG-3, to the most detailed, VMG-1. OM-3 also divides piping vibrations into two vibration types, steady-state and dynamic-transient (e.g., water hammer). Each type of vibration is assigned to a VMG.

The VMG-3 classification relies to a large part on judgment and experience to qualify the vibrations. This includes walkdowns and visual inspections to witness vibration of the operating systems. Systems classified as VMG-3 are qualified on the basis of prior experience with the vibration of similar systems and judgment based on knowledge of acceptable levels of piping vibration for the systems.

The VMG-2 classification is a simplified qualification method intended to conservatively estimate piping-vibration stresses. VMG-2 uses vibration measurements and simplified calculations along with judgment and experience to qualify vibrations. This method is based on modeling a vibrating portion of the piping using a simple beam analogy and/or computer model and determining vibration limits in terms of displacement or velocity.

The VMG-1 classification relies on detailed measurements and calculations; this is a rigorous qualification method, requiring that the vibration stresses be determined with a high degree of accuracy. VMG-1 testing may also involve a detailed correlation between analytical and experimental results and/or instrumentation of the piping with a sufficient number of strain gauges to determine the magnitude of the highest stresses.

OM-3 leaves with the owners the responsibility of meeting industry requirements by determining what systems are to be monitored, what type(s) of vibration (steady-state and/or dynamic-transient) are to be monitored, and what vibration-monitoring group each system is to be classified in. These commitments would most likely be made in the plant Safety Analysis Reports (SARs) or other design-basis documents.

OM-3 Acceptance Criteria

Flow-induced or mechanical-equipment-induced vibration conditions are frequently not known or well-defined during the design phase of a piping system and hence are typically not addressed by the design-basis stress report. Vibration walkdowns, examinations, and testing are usually performed during initial startup and operation. OM-3 guidance is intended to address the testing and acceptance criteria needed to determine the acceptability of the experienced vibrations.

The intent of the OM-3 acceptance criteria is to meet the allowable stress requirements of the ASME B&PV Code. The allowable stresses in OM-3 are based on the fatigue curves given in Section III of the ASME B&PV Code (Reference 2). Steady-state vibrations will most likely result in a large number of stress cycles; the standard therefore sets an allowable steady-state vibration stress equal to the “endurance limit” of the piping material, where the endurance limit is defined as a stress at which the piping can cycle for the life of the plant and not fail as a result of fatigue. If a lower number of cycles can be computed for steady-state vibrations, the allowable stress can be increased accordingly.

For dynamic transients, an equivalent number of full-range stress cycles is calculated and/or extrapolated from the recorded time-history traces; the equivalent cycles are used in conjunction with the fatigue curves to assess the effect of transients on the fatigue life of the piping. These transient stress cycles are considered with other cycling stresses (e.g., seismic) addressed in the design-basis report.

The OM-3 standard uses the alternating peak stress value at 1011 cycles as the endurance limit, i.e., the allowable stress for steady-state vibration. Appendix I of the ASME B&PV Code contains fatigue curves for both stainless and carbon steels.

The endurance limit based on a stress corresponding to 1011 cycles can be justified as follows. The value of 1011 cycles envelops a steady-state vibration with a frequency of more than 30 Hz occurring continuously for 60 years; see Figure 1. Therefore the alternating stress corresponding to 1011 cycles represents a practical endurance limit for power-plant piping. For stainless and carbon steels the AMSE B&PV has stress/failure

(SN) fatigue curves that extend out to 1011 cycles; therefore, the allowable stress can be obtained directly from these curves. These curves also flatten at 1011 cycles; i.e., the rate of decrease in allowable alternating stress is small as the number of cycles increase. From the ASME curves an endurance limit for stainless steel equals 93,770 kilopascal (kPa) [13,600 pounds per square inch (psi)]. Similar curves for carbon steel indicate the corresponding endurance limit for carbon steel equals 48,260 kPa [7,000 psi] (see Appendix I, “Design Fatigue Curves,” to Section III of the ASME B&PV Code for notes and details applicable to the use of the fatigue curves).

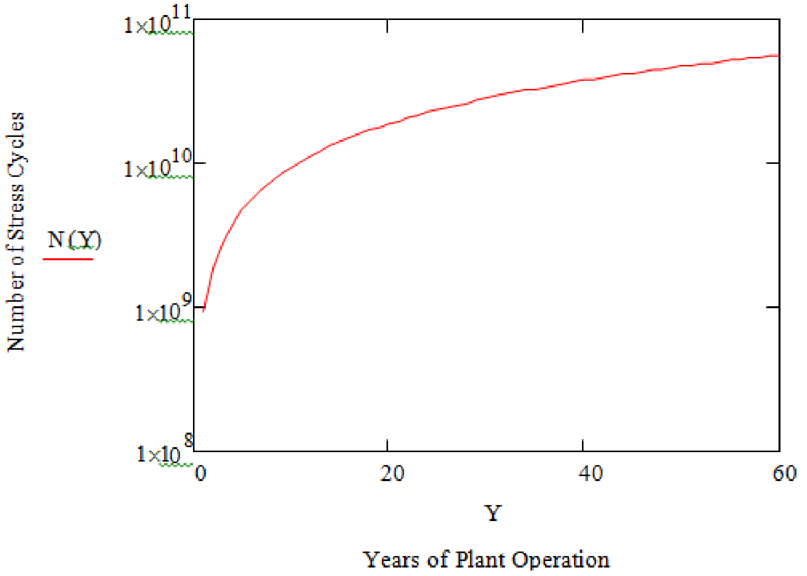

Figure 1: Accumulated Stress Cycles vs. Years of Operation

Use of Peak Stress

Peak vibration stresses are determined using methods in OM-3 and these stresses are compared to the allowable alternating peak stress at 1011 cycles from the ASME B&PV Code. For a given piping component, nominal pipe bending stress resulting from vibration is multiplied by the product of the stress indices C2 and K2 to convert it to peak stress. The C2 and K2 factors are from Section III of the ASME B&PV Code and represent stress indices that account for the configuration of a particular piping component (C2) and the peak stress resulting from local conditions (K2), such as a weld surface.

Stresses caused by steady-state vibration that are within the acceptance limits are assumed not to affect the fatigue life of the piping and components because the allowable stresses are less than the endurance limit and therefore should not reduce the fatigue life of the piping and components.

Because peak stresses are the basis of the acceptance criteria, the use of instrumentation, data-acquisition, and data-reduction equipment must result in the determination of peak vibration measurements. Most piping vibration will not be purely sinusoidal or harmonic; it will be quasi-random. Much of the available instrumentation measures the root mean square (rms) of a vibration signal. The rms reading for a purely sinusoidal vibration can be easily converted to peak amplitude by multiplying the rms measurement by 1.414. For vibration that is not composed of a purely sinusoidal motion, this simple relationship is not applicable and significant error can result if it is used.

True peak and peak-to-peak vibration measurements are required. These can best be obtained by using instrumentation that directly senses true peak values. It is possible to statistically convert rms measurements to peak values if the properties of the measured vibration time histories are used. The instrumentation requirements in OM-3 provide guidance for obtaining the relevant peak vibration measurements.

Qualitative Evaluations

OM-3 also requires the completion of Qualitative Evaluations. Piping system response must be acceptable based on qualitative evaluations, in addition to meeting the quantitative acceptance discussed above. Qualitative evaluations are based on observed responses of the piping that address potentially detrimental conditions not explicitly quantified by the stress-based acceptance criteria. Judgments on the acceptability of the observed responses consider comparisons to known acceptable responses.

Vibrations that can affect the functionality, operability, and structural capability of sensitive equipment are qualitatively evaluated as part of the piping vibration qualification walkdowns. If the vibrations are determined to be potentially excessive based on qualitative evaluations, more detailed evaluations (or modifications) would be implemented.

Piping vibration can adversely affect associated equipment such as pumps, valves, and piping restraints. Inline instrumentation can also be adversely affected. Qualitative evaluations are intended to address the potential for vibration damage that results in addition to pipe stress. For example, the effects of cavitation on support wear, pipe erosion, and pitting of the internal surface of valves are considered as part of the qualitative evaluations. Therefore, the presence of significant cavitation, typically accompanied by continual or intermittent loud noise, indicates that the vibration is not acceptable according to the qualitative evaluation, even if the quantitative evaluation indicates acceptable pipe stress.

Transient Vibration

For piping systems that experience transient vibration conditions, transients could play a significant role in fatigue failure and/or support damage. System alignment or operating condition changes, e.g., changes in valve position, sometimes cause transient vibration in piping systems. Some observed transient vibration conditions (such as water hammer and cavitation) are frequently not known during the design phase and hence are not covered by the Design Specification nor analyzed in the stress report.

For systems in which transients are expected and for which the stress report includes an analysis of the transient, the objective is to verify that the transient vibration is within the values analyzed in the design-basis stress report. For transients not considered in the design bases, the fatigue and stress limits of the applicable ASME B&PV Code or other design bases limitations must be met.

If the transient peak stresses can be demonstrated to be below those allowed for steady-state vibration, it is assumed that there will be no effect on the fatigue life of the piping and components, which are considered to be qualified similarly to how they would be for steady-state vibration. If the peak stresses are larger than the steady-state vibration limits, the transient stresses shall be combined with other applicable design-basis stresses and evaluated in accordance with the applicable ASME B&PV Code of record.

Simplified Vibration Qualification Methods (VMG-2)

A considerable portion of OM-3 addresses the use of simplified methodologies for qualifying piping vibration (i.e., VMG-2 methods). The objective of simplified vibration qualification methods is to provide efficient and effective means of screening piping vibration. Because virtually all piping in a power plant will experience some amount of vibration, effective means of quickly screening the vibration are needed. The acceptance criteria defined for VMG 2 are essentially screening limits used to separate vibrations that are not detrimental from those that are potentially excessive.

Vibration limits calculated using the simplified methods defined in VMG 2 are intended to be a screening tool. The simplified methods are intended to conservatively determine the stresses in the vibrating section of piping. If the vibrations exceed the limits determined through these simplified methods, the vibrations should be investigated further. This could involve either reducing or eliminating the vibrations or completing more detailed evaluations to eliminate conservatism from the calculated vibration limits. The flowchart in Figure 2 depicts the steps that are completed for a system walkdown to qualify vibrations in accordance with VMG-2 criteria. These steps are described in detail in OM-3.

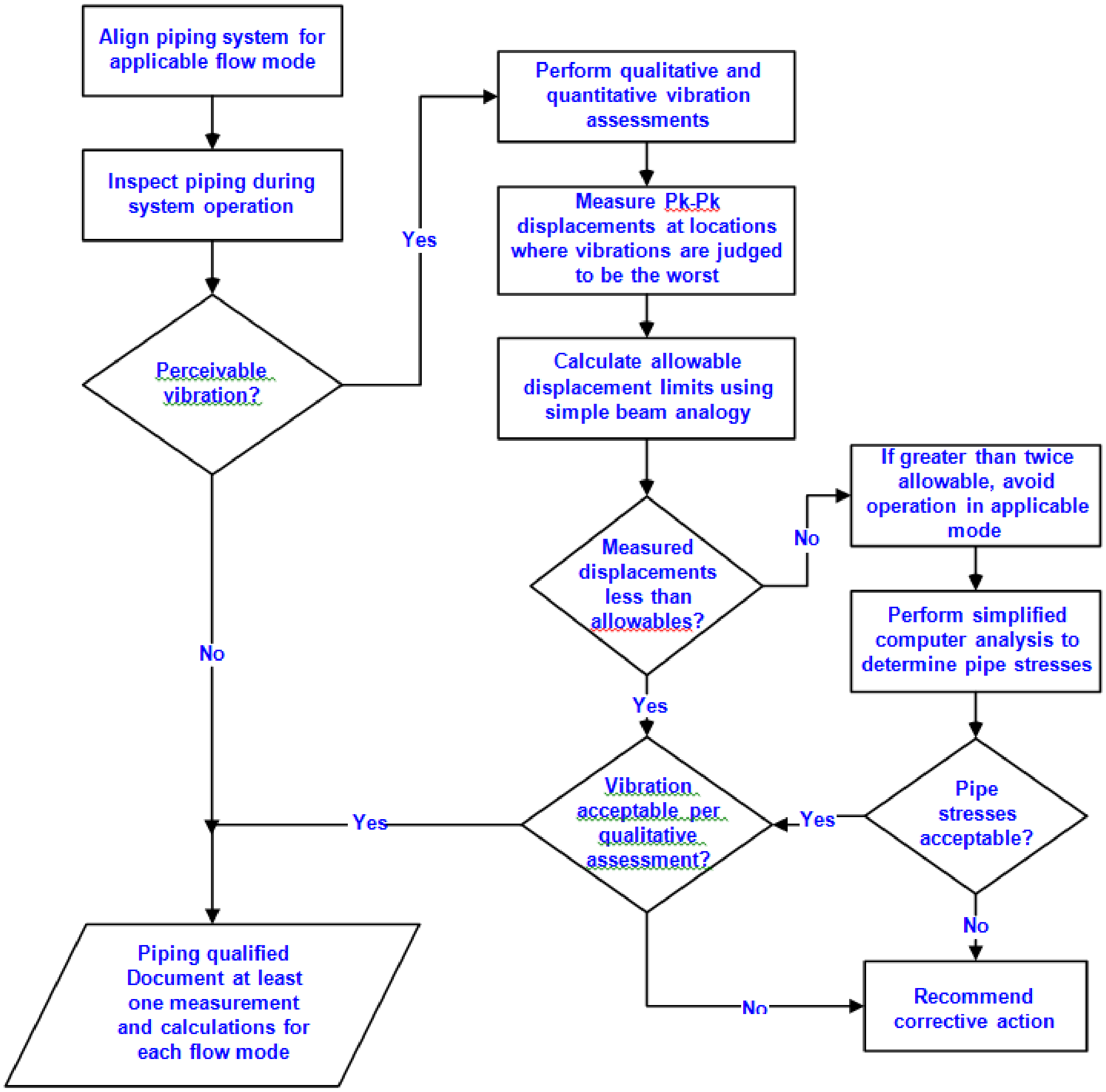

Figure 2: Walkdown Qualification Procedure for Piping Steady-State Vibration

The simplified VMG-2 qualification methods break the vibrating piping system down into smaller segments that can be conservatively represented by simple beam models. These beam models would assume conservative end (restraint) conditions and/or lengths in such a way that if the measured vibrational displacements or velocities were imposed on these models, the resulting bending stress would provide a conservative indication of the actual vibration bending stress in the piping system. A sample simple beam model is shown in Figure 3. Note that the use of simple beam models for qualifying vibrations is not applicable to high-frequency shell-wall vibrations. Shell-wall vibrations are discussed separately in OM-3.

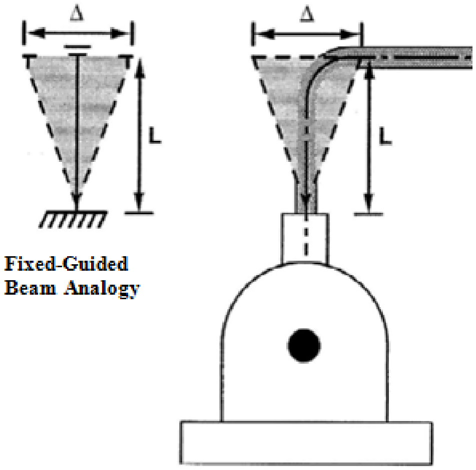

Figure 3: Example of Simple Beam Analogy

Two simplified methods are defined for determining whether the amplitudes of vibration are acceptable; one method provides acceptable displacement limits and the other method provides acceptable velocity limits. Both methods have been used in the industry and have proven to be effective tools for evaluating piping vibration. Formulae are provided for determining allowable displacement and velocity limits.

A benefit of using the velocity method is that velocity limits are theoretically independent of the characteristic span length and pipe diameter. However, a disadvantage of using the velocity method for determining the acceptability of vibration of piping spans is that the velocity limits depend on the assumption that the piping span is vibrating in resonance in its fundamental beam mode. If this is not the case, correction factors must be used considering the actual vibration beam mode frequencies of the piping segments and the measured vibration frequencies. The effort to determine whether the span is vibrating in resonance can involve determining the fundamental vibration mode frequency of the as-built piping span, including determining actual stiffness values of the restraints and anchors. Therefore, the correct application of this method may be significantly more cumbersome than using the displacement method.

Use of the displacement method has several advantages. Displacement of the piping is directly proportional to the acceptance criteria, which is a limit on peak bending stress. The piping system can readily be divided into smaller piping spans with conservative boundary conditions for use with the displacement limit calculations. There are no inherent assumptions concerning resonance and there is no need to determine the natural vibrational frequencies of the as-built pipe spans (as is required by the velocity method). The individuals completing the testing can often, through experience, gain an intuitive feel for the magnitude and severity of vibrational displacements, which is hard to develop when dealing with velocity.

In OM-3 the allowable deflection limit, “Δallow,” for a characteristic span is defined as a function of the configuration coefficient K, endurance limit S_{el}, peak stress index C2K2, span length L, and pipe outside diameter D_o. OM-3 provides examples of characteristic spans and their associated configuration coefficients for common pipe configurations. The nominal deflection limit Δn is obtained for a given span configuration, span length, and pipe diameter based on a nominal vibration stress of 68,950 kPa [10,000 psi] and stress index equal to 1.0. The nominal deflection limit is adjusted to account for the relevant peak stress index and allowable stress limit to obtain the allowable deflection limit.

Conclusion

Most piping will experience some amount of vibration during operation. Because of the myriad of potential vibration sources and effects, piping vibration is difficult to accurately predict and evaluate during design. The most effective and practical means of qualifying vibration is to witness and evaluate it during system operation.

The piping vibration testing and qualification methods defined in OM-3 were developed to meet the requirements for quantifying and qualifying vibration experienced by operating piping systems. These methods have been proven effective through their use in preoperational and startup test programs at nuclear power plants. They have also been effectively used to evaluate power uprates and plant modifications as well as operating problems in fossil and petrochemical plants. The methods are based on pragmatic and proven methods for measuring and evaluating piping vibration.

References

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2. ASME, “Metallic Components,” Division 1 of “Rules for Construction of Nuclear Facility Components,” Section III of the *Boiler and Pressure Vessel Code* (specifically Paragraphs NB-3622, NC-3622, and ND-3622 and Appendix I), New York, NY, July 1, 2013.

3. ASME, “Power Piping,” B31.1-2012, New York, NY.

4. U.S. Nuclear Regulatory Commission (NRC), “Initial Test Programs for Water-Cooled Nuclear Power Plants,” Regulatory Guide (RG) 1.68, Rev. 3, March 2007.

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6. NRC, “Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing,” RG 1.20, Rev. 3, March 2007.