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## Identification and Prediction of Piping System Noise

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### ABSTRACT

In a power plant environment, the piping systems form a network that extends throughout the facility. Various components in a piping system can be major sources of in-plant and community noise, both the pipe and the contained fluid can be propagation paths, and radiation can occur from the external surface of the pipe. Though the basics of these phenomena are often understood, the translation into workable predictive tools has been slow. Too often, source, propagation, and radiation effects are treated as separate entities without allowing for the interactions that exist. The spectral characteristics of the sources will govern the type of response by the system. Pipe transmission loss models will change in pipe to duct transition areas. The status of these concepts will be reviewed with a discussion of current and possible future efforts to improve predictive tools.

### 1. INTRODUCTION

Whether evaluating whole piping systems, (i.e. turbine bypass, duct burner, soot blower, heater drain, vent/flare, etc.) or individual components in a system, (i.e. pumps, compressors, valves, tees, etc.) there are basic phenomenon which must be considered. In an ideal sense, noise generated by any component or source will propagate in the fluid and cause the pipe wall to vibrate, with subsequent radiation from the outer surface to an observation point. In reality there also can be a direct structureborne path from the source to the pipe which adds to both the vibration level and to the radiated noise. Also, noise generated in the piping and inaccuracies in the prediction methods give rise to discrepancies between predicted and measured external noise levels. Ultimately noise propagating in the fluid may enter other systems, manifolds, tanks, or be vented. All of these scenarios fit into the overall heading of piping system noise through a variety of acoustic, hydrodynamic, and structural phenomena.

### 2. EXTENT OF THE PROBLEM

Noise prediction for piping system components used to be accomplished with graphs, tables, and at most some algebraic equations. With the ever increasing availability of computing power the work has gone in two directions. First the old methods were programmed, with special care taken to develop a convenient user interface for data entry. This didn't improve accuracy, however, it did allow virtually anyone to make a calculation without knowing the assumptions behind it or how to interpret the results. Secondly, highly sophisticated computational methods were developed for research and subsequently used on very specialized applications. Along the way there has been a steady stream of improved technology in all phases of acoustics and

vibrations. The problem is that industry has a poor history of translating the improved technology into methods that can be used on a day-to-day basis. For a variety of reasons, noise requirements have become more difficult as service conditions become more severe, and it is imperative that we find ways to utilize the most appropriate level of technology possible.

### 3. INCOMPRESSIBLE FLOW

Generally liquid noise is not a problem unless cavitation occurs somewhere in a system. Since the noise from cavitation is an indicator of potential damage to piping and equipment, it has been more important to develop guidelines to prevent cavitation than to develop methods to predict the level of the noise. Prediction methods that do exist should be treated as estimates since the true vapor condition of the fluid is rarely known for certain, which has a major effect on the acoustic impedance. Also, the proximity of the bubble collapse zone to the inner pipe surface will be dependent on the component and system geometries.

The remainder of this paper will concentrate on compressible flow applications.

### 4. COMPRESSIBLE FLOW SOURCES

Compressors, valves, orifices, area expansions, spargers, etc, are all potential sources of high level broadband noise, as well as tones.

Usually flow generated tones only become a problem if they can couple to a supportive resonance in the system. If low frequency pulsations are able to couple well with acoustic and/or structural resonances, then large scale vibrations are expected, since beam modes of the piping can be excited. Generally, structural resonances would be checked in the system design phase, however, acoustic resonances may not be. A fix is either to eliminate or change the frequency of the source tone or to decouple the resonance, whichever is most efficient and/or effective. Broadband noise can also excite system resonances which makes decoupling more difficult. Reducing the source noise levels are the main option. Predicting all potential tone problems during either the system or component design phase is nearly impossible. Increased use of computational methods are certainly helping and will continue to improve our understanding of system response as shown in Eberhart et. al. [1].

#### A. Flow Noise - Pipe

The real concern when predicting noise levels for components in a piping system is broadband noise. In an imaginary piping system where all the components are perfectly quiet, there would still be a base noise level associated with fully developed turbulent flow in the pipe. All flow disturbances, whether pipe fittings, valves, or compressors, add to the intensity of the turbulence and therefore increase the noise levels above the base. Undisturbed pipe flow noise levels are generated by turbulence which develops as a result of the shearing action near the wall. This turbulence is continually decaying and reforming as the flow moves down the pipe. There are two fluctuating pressure fields at the inner wall of the pipe. One is the fluctuating turbulent fluid itself, and the second is the acoustic field produced by the fluid fluctuations. The turbulent field will move downstream at the velocity of the fluid and decay as it goes, while the acoustic field will propagate with less decay at the speed of sound. This discussion of turbulent flow applies to a long constant area pipe. Though often discussed as a noise problem, it rarely produces controlling noise levels as shown in Norton & Bull [2].

#### B. Flow Noise - Fittings

When a pipe expands to a larger size or terminates in a manifold or vessel the noise generation may increase dramatically. Area expansion causes the exiting wall flow to accelerate rapidly,

creating an intense shear region in the larger area. As flow velocity increases in the smaller pipe, the noise contribution can be significant. Even though the excess turbulence will rapidly decay, the internal acoustic field produced will propagate down the pipe. Velocity limits for compressible flow are often expressed in terms of Mach number. Setting the Mach number equal to .3 is a commonly used criteria for quiet operation. However, this allows the limit to be met with pipe velocities ranging from 100 – 225 m/s depending on the fluid. In power plants a common fluid is high temperature steam, which will allow over twice the velocity as compared to room temperature air at the same mach number. Reasonable external noise predictions can be made since the internal power spectra are known from measurements, however, these methods have not been made industry friendly. An excellent discussion and presentation of internal data concerning noise from flow through pipe and normal fittings is found in Norton & Karczub [3] and Norton & Bull [2]. Additional information on piping tees can be found in Karczub et. al. [4], and Scott & Ziada [5].

### C. Equipment Noise

Compressors, valves, orifices, area expansions, spargers, etc. usually control noise levels in pipelines. Currently, valve manufacturers provide noise prediction based on experience, field or lab testing, theoretical models, or a combination of these. There needs to be a more concerted effort to obtain internal spectra for these sources under a variety of conditions, since this ultimately controls the external spectra and therefore the overall levels. Other piping system components don't have a noise prediction method, for lack of either sufficient empirical data, or an appropriate model to describe the noise generating process. Many of these components have multiple sources that need to be understood before extrapolating to conditions beyond what can be tested. As an example, a valve can have jets, interacting jets, impinging jets, jets with crossflow, and highly turbulent flow in the outlet. They may or may not all be present at the same time, however, the possibility needs to be understood. It is unlikely that these various sources can be treated individually, however, an awareness that they exist should prevent overly simplified models from being used. Au-Yang [6] gives a description of many flow-induced vibration sources in a piping system

## 5. INTERNAL PROPAGATION AND COUPLING

The spectral characteristics of various sources in a pipeline are important because they dictate how the internal noise propagates and how it couples to the pipe or other structures

There are four important frequencies that establish approximate ranges for various types of transmission loss behavior.

- 1) Ring frequency -  $f_r$  - the frequency at which the longitudinal wavelength is equal to the circumference of the pipe.
- 2) Acoustic cut-off frequency - the lowest frequency at which transverse modes of propagation can exist in the internal fluid.
- 3) Internal coincidence frequency -  $f_o$  - the frequency at which the axial bending wave speed in the pipe is equal to the axial propagation velocity in the fluid for a given circumferential mode.
- 4) External coincidence frequency -  $f_g$  - the frequency at which the external acoustic wave speed is equal to the velocity of a bending wave in the pipe wall.

Early work by Cremer [7] established that above the ring frequency the pipe responds as a flat plate of the same thickness as the pipe wall, that is, the effect of curvature of the pipe wall is negligible. The effects of stiffening cause by curvature of the pipe wall predominant below this frequency. These results allowed later research to concentrate on effects below the ring

frequency. For most industrial piping, the frequencies of maximum radiation are dictated by strong coupling between higher order internal acoustic modes and bending modes of the pipe wall. Below the cut-off frequency sound propagates only as a plane wave moving through the fluid, however, above this frequency sound can propagate in more complex higher order modes which tend to travel with a spiral or helical motion. At the cut-off frequency the sound wave spins circumferentially, and as frequency increases an axial component is added which causes propagation through the fluid in a spiral motion. The same circumferential modes are present in the pipe wall and also develop an axial component as frequency increases. These propagate as helical bending waves of the pipe wall at a velocity which is frequency dependent. For each circumferential mode order there is a frequency at which the axial bending wave speed in the pipe is equal to the axial propagation velocity in the fluid which is called the internal coincidence frequency. It is at these frequencies that maximum coupling occurs. The above discussion is only for the shell modes of the pipe.

The coupling mechanism between the pipe wall and the fluid changes in the turbulent region near the source where the fluctuating pressure field rapidly decays. There is a different coincidence effect based on the fluid velocity instead of the axial acoustic wave speed as described by White [8]. Further downstream the propagating acoustic field dominates. When evaluating piping system noise, however, this is rarely taken into account, because it is time consuming and there isn't a standard way to approach it.

SEA has been used by Fagerlund & Chou [9] and others to calculate the pipe wall transmission loss (TL) in the frequency range where higher modes dominate. This is effective because of the high number of modes per frequency band which is a criteria for SEA. At lower frequencies, and especially below the first cut-off frequency the mode count is low which makes the extrapolation of the TL into this region inappropriate. Research continues concerning TL as reported in Karczub [10].

Many rules of thumb have been used over the years with the usual form of (X dB) per (unit length). ISO 15665 [11] gives a method which doesn't take into account the internal acoustic mode decoupling at area transitions or structural mode decoupling at flanges or other discontinuities. In the audio frequency range the corrections are mainly useful for long welded transmission lines, rather than plant design. The transfer of energy between the pipe and the contained fluid at discontinuities can give misleading results.

## 6. EXTERNAL PIPELINE RADIATION

External shell mode radiation may be considered as a statement of the pipe surface boundary condition, where the particle velocity of the fluid adjacent to the surface is equal to the velocity of surface vibration. From this the acoustic pressure and subsequently the ideal radiated acoustic power can be calculated using the acoustic impedance of the fluid. The actual acoustic power radiated from the pipe can be calculated based on sound pressure level measurements at a point away from the pipe surface. A radiation efficiency term can then be defined as the ratio of the actual to the ideal acoustic power. An early study by Fahy [12] indicated that the radiation efficiency is equal to unity above the external coincident frequency, and is directly proportional to the frequency below coincidence. Fagerlund [13] used this to develop a method for converting pipe wall vibrations into equivalent sound pressure levels. Though the procedure is

quite simple, it works well because the spectral implications of the external radiation efficiency are addressed.

For large diameter thin wall cylinders (i.e. turbine exhaust ducts) the external coincidence frequency can be greater than the ring frequency. Most standard and heavy wall piping will push the external coincidence frequency below the ring frequency. These differences will change the expected spectral shape of the TL, which in turn would change the external levels. This points out again why the spectra associated with internal source levels and for TL need to be a part of overall pipeline noise prediction.

Practical system noise studies on multiple valves discharging into a manifold are being carried out as reported by Karczub et. al. [14]. This ongoing work is trying to address some of the needs pointed out in this paper.

VDI 3733 [15] is a compendium of information on the noise generated by piping systems. The influence of piping components as well as piping configurations are examined and presented in a quick calculation style without having to work through a detailed explanation of the phenomenon involved. It's broad subject coverage makes it a unique reference.

## **7. ACOUSTIC FATIGUE**

Acoustic fatigue refers to structural fatigue of the pipe-wall resulting from very high amplitude vibration of the pipe-wall excited by broad-band piping system noise. Acoustic fatigue is generally not a concern for external noise levels below 110dB for unlagged piping (acoustically insulating the pipe to reduce noise levels below 110dB will not reduce the fatigue risk since the pipe is still vibrating with the same amplitude). Structural failure of a pipeline due to acoustic fatigue can occur in several hours due to the high-frequency nature of the vibration, and is therefore a concern even if noise levels only exceed 110dB occasionally, such as during plant startup and shutdown or pressurization operations. Acoustic fatigue predictions are based on many of the same valve sound power and TL calculations as used for piping system noise predictions as shown by Karczub & Fagerlund [16], and are more critically dependent on the accuracy of these predictions due to the linear scale of vibration level and dynamic stress. Improvements in control valve internal noise predictions and TL models are therefore of importance to acoustic fatigue assessments, or at least an appreciation of the inherent uncertainties.

## **8. RECOMMENDATIONS FOR FUTURE WORK**

- 1.** The role of velocity and mach number in predictions and as limits needs to be better defined.
- 2** – Internal spectra are often inferred from external measurements and approximate TL models. Further progress on prediction methods will be difficult unless there is an increase in internal measurements to define the spectral characteristics of many sources
- 3** – Currently there is little beneficial testing under realistic conditions of higher pressure and temperature. Perhaps more cooperative work is needed.
- 4** – Workable methods need to show how the direct near field excitation should be taken into account along with the propagating acoustic field.

- 5** – Structureborne noise is not a part of most prediction methods. A definition of this and an assessment of the implications of energy sharing with the fluid needs to be developed.
- 6** – Industry has done a poor job of translating technical improvements into practical methods for day-to-day use. This needs to be improved.
- 7** – Transmission loss models need to be used in a spectral sense without trying to reduce it to a single number.
- 8** – Data based methods for predicting attenuation with distance along a pipeline need to be documented.
- 9** - Work is required to confirm the appropriate dynamic stress limits based on structural fatigue of piping materials for high-frequency random vibration

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