Journal of Fluids and Structures 65 (2016) 355–380

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Characterizing fluid structure interactions of a helical coil in cross flow

W.R. Marcum*, P.L. Harmon

Oregon State University, Department of Nuclear Engineering and Radiation Health Physics, 116 Radiation Center, Corvallis OR 97330, United States

ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
1 June 2016
Accepted 13 June 2016
Available online 30 June 2016

Keywords:
Helical coil
Cross-flow
Fluidelastic instability

ABSTRACT

Mechanical vibrations compromise the integrity of key components of thermal power plants. Without careful design, strong resonances during steady state operation can wear these components to the point of failure, leading to an unsafe situation that may force a plant to shut down. The purpose of this research is to further the understanding of the vibrations induced in a helical coil subject to steady fluid flow. A helical coil steam generator, such as that found in most integral pressurized water reactors, appears to eliminate many flow-induced vibration concerns when compared to traditional steam generators; however this has yet to be clearly demonstrated experimentally. The objective of this study is to detail and demonstrate a new method to quantify the motion of a helical coil in an annulus subject to external axial flow of water and further characterizing the influence of pitch-to-diameter ratio on the fluidelastic instability of a helical coil. This is accomplished by observing the motion of a helical coil mounted to an inner opaque cylinder through an outer glass tube using a high speed video camera. A mirrored image-pair is used to observe this structure from two perspectives simultaneously, allowing for three-dimensional characterization of the coil motion. The experimental facility is described in detail. The method developed herein for identifying specific points on the coil from images and mapping them to the coil location using the law of refraction is described. An uncertainty analysis of the coil position measurement is conducted based on geometry and refractive index which can be readily applied to measurements obtained using this method. The outcome of empirical observations shows these helical coils to hold a slightly higher resonance frequency than that of cylinders in cross flow, their mechanical stiffness approximated through analytical means shows to produce relatively accurate natural frequencies when compared to the empirical data – 14.1 Hz and 12.5 Hz, respectively for first mode vibration. This study"s contributions present a new method for metering fluid structure interactions with high-fidelity, provide new empirical data which has not previously been produced, and make observations to the response of a helical coil which are new to the field of fluid-structure interactions.

Published by Elsevier Ltd.

* Corresponding author.
E-mail address: marcumw@engr.orst.edu (W.R. Marcum).

http://dx.doi.org/10.1016/j.jfluidstructs.2016.06.008
0889-9746/Published by Elsevier Ltd.

1. Introduction

Mechanical vibrations compromise the integrity of key components of thermal power plants, such as heat exchangers and emission control systems. These structures have high length to width aspect ratios which make them susceptible to mechanical vibrations. They are often designed to maximize heat transfer and generation, reduce footprint or increase particulate sequestration. Flow typically passes through or around these elements at a rapid rate, causing periodic pressure changes that induce vortices and structural oscillations. Without careful design, it is plausible for strong resonances during steady state operation to wear these components to the point of failure, leading to hazardous conditions and potential shutdowns.

Boilers, condensers, and steam generators are examples of power plant components sensitive to mechanical vibrations. Their heat exchanging elements often include hundreds of long tubes bundled together inside pressure vessels. These are commonly inaccessible to repair after installation without prohibitive cost. Also, emissions control systems in coal-fired plants, such as electro-static precipitators and selective catalytic reduction systems, have large parallel-plate arrangements that are regularly vibrated to remove particulate build-up. Finally, vibration or bowing of precisely spaced cylinders or parallel plates in a reactor core increases high temperature peaks which affect the determination of plant power rating.

For example, the pressurized water reactor (PWR) at San Onofre, California is currently being decommissioned due to leakage of primary coolant through ruptured tubes in its steam generator. Changes in the steam generator design as well as manufacturing and handling issues exacerbated the response of the steam generator tubes when vibrating during steady state operation due to flow-induced vibration (FIV). This led to fretting of the pipes and their rapid deterioration. This power plant was forced to close permanently, incurring heavy expenses to its parent company, the manufacturer of the failed components and the rate-payers in the area. This event underscores the need for careful consideration of flow-induced vibrations of high aspect ratio heat exchanging elements relevant to current power plant design as a necessary feature for safe and continuous plant function.

Problems with steam generator vibrations in nuclear power plants are not new. The Enrico Fermi Atomic Power (EFAP) Plant, which operated from 1963 to 1972, was a fast breeder reactor operating next to Lake Erie (February 2006). As a sodium-cooled reactor, the plant had a mechanically complex steam generator. Designers had to account for the possible reaction of sodium with water while providing an efficient transfer of heat. Flow of sodium at the steam generator inlet of the EFAP Plant induced excessive vibrations in its serpentine tubes. Wearing between the tubes and their restraints allowed water to leak into the sodium coolant, incurring extensive damage. Shin and Wambsganss (Shin and Wambsganss, 1977) identify two general causes for this wear. First, there was insufficient restraint of tubes near the inlets of the sodium coolant, where the flow velocity was high and the failures observed. Also, there was insufficient baffling at these inlets to reduce flow velocity.

Sandusky et al. (2013) noted that steam generators for most integral reactor designs, which have helical coil geometry, are less susceptible to flow-induced vibrations than traditional designs. However, this has not been verified experimentally, and further study is needed to confirm this assumption. Study in this area is complicated by a number of factors. The compression of the structure due to the pressure gradient from fluid flow parallel to the coil axis, or axial flow, around its exterior affects the coil's natural frequency. When the coil is in close proximity to a solid surface, as when the coil windings are spaced less than their width apart or near a cylindrical wall, it may resonate with a different frequency. Predicting failure is difficult partly because the structural vibration of helical coils under steady fluid flow is currently not well understood.

The purpose of this study is to further the understanding of the vibrations induced in a helical coil subject to steady bulk fluid flow. A helical coil coaxial with an inner and outer cylinder is proposed as a simplified geometry of a heat exchanging element. In this configuration the flow of external coolant over the coil windings promotes heat transfer. The thinnest fluid channels are formed in the gaps between each loop of the coil and between the coil and the cylinder walls. With supports constraining motion only at its ends, the flexibility of the coil's central windings will allow for observable motion from flow-induced vibrations.

The objective of this study is to detail and demonstrate a new method to quantify the motion of a helical coil in an annulus subject to external axial flow of water and further characterizing the influence of pitch-to-diameter ratio on the fluidelastic instability of a helical coil. Separate effects experiments have been conducted by observing and quantifying coil motion while varying flow rates and coil pitch over ranges of interest.

2. Survey of literature

There is an abundance of literature on vibrations induced in blunt bodies subject to fluid flow, modal analysis of helical coils, and position tracking through image processing. However, the application of all these disciplines to the analysis of motion of a helical coil in external axial fluid flow is unique. Flow induced vibration mechanisms have been well researched by a variety of numerical and experimental methods. Numerous experimental techniques have been applied to the modal analysis of structures in fluid flow, but most of these techniques were developed before the wide adoption of high speed digital imaging devices. Recent developments in large dataset analysis using computer programs have also made image-based measurement more feasible. This study applies this knowledge and these tools to the analysis of a flexible helical coil using a high speed camera to observe the structure's motion when mounted in a clear cylinder and subject to FIV.