Flow-induced vibration analysis of a helical coil steam generator experiment using large eddy simulation

Haomin Yuan\textsuperscript{a,⁎}, Jerome Solberg\textsuperscript{b}, Elia Merzari\textsuperscript{b,c}, Adam Kraus\textsuperscript{b}, Iulian Grindeanu\textsuperscript{c}

\textsuperscript{a} Nuclear Engineering Division, Argonne National Laboratory, Lemont, IL, USA
\textsuperscript{b} Lawrence Livermore National Laboratory, Livermore, CA, USA
\textsuperscript{c} Mathematics and Computer Science Division, Argonne National Laboratory, Lemont, IL, USA

ARTICLE INFO

Keywords:
Nek5000
DIABLO
SHARP
CFD
Flow-induced vibration (FIV)
Large eddy simulation (LES)
Helical coil steam generator
Spectral-element method

ABSTRACT

This paper describes a numerical study of flow-induced vibration in a helical coil steam generator experiment conducted at Argonne National Laboratory in the 1980 s. In the experiment, a half-scale sector model of a steam generator helical coil tube bank was subjected to still and flowing air and water, and the vibrational characteristics were recorded. The research detailed in this document utilizes the multi-physics simulation toolkit SHARP developed at Argonne National Laboratory, in cooperation with Lawrence Livermore National Laboratory, to simulate the experiment. SHARP uses the spectral element code Nek5000 for fluid dynamics analysis and the finite element code DIABLO for structural analysis. The flow around the coil tubes is modeled in Nek5000 by using a large eddy simulation turbulence model. Transient pressure data on the tube surfaces is sampled and transferred to DIABLO for the structural simulation. The structural response is simulated in DIABLO via an implicit time-marching algorithm and a combination of continuum elements and structural shells. Tube vibration data (acceleration and frequency) are sampled and compared with the experimental data. Currently, only one-way coupling is used, which means that pressure loads from the fluid simulation are transferred to the structural simulation but the resulting structural displacements are not fed back to the fluid simulation.

1. Introduction

The reliability of the steam generator (SG) is one of the most significant safety issues in nuclear power plants. In the operating history of nuclear power plants, a significant number of steam generators failed or were found to be defective and removed from service or repaired each year (MacDonald et al., 1996). A large fraction of the failures were due to tube rupture, which usually caused complex plant transients and induced damage to the whole system. The most important driver of tube rupture is flow-induced vibration (FIV) inside SGs. FIV leads to both fretting-wear and fatigue, both of which lead to the growth of pre-existing flaws that eventually result in severe tube failures (Jo and Jhung, 2008). Therefore, the improved safety and operating performance of nuclear power plants depend on the ability to assess a particular SG design for reliability, especially with regard to the tube rupture problem. Simple design changes that minimize flow-induced vibration, such as decreased span length, larger tubes, thicker walls, and greater tube spacing, also decrease the steam generator efficiency and increase the plant cost and footprint. If the lifetime of a steam generator can be predicted, preventive measures and/or design changes can be implemented to decrease the possibility or severity of tube rupture failure. Since the leading driver of tube rupture is flow-induced vibration, a complete FIV analysis for the tubes in SGs must be performed.

The FIV problem has been studied for decades, with a special emphasis on steam generators and other heat exchangers incorporating tube arrays. The authors Paidoussis (1980, 1982), Pettigrew et al. (1998), Pettigrew and Taylor (2003a,b), Lowdon et al. (1990), Chen et al. (1983), Chen (1989), Tanaka and Takahara (1980, 1981), and Weaver and Grover (1978) all did comprehensive work studying this problem. However, the methodology used in those papers is primarily a mix of analytical and empirical methods.

Regarding the numerical approach, most of the researchers used CFD/FEM method to coupled CFD and FEM code to simulate the response of structure under flow condition. Jo and Jhung (2008) performed a numerical simulation of helical coil steam generator using CFX. He simulated flow in both primary side and secondary side considering a single tube. Kuehler et al. (2008) studied the FIV problem for a tube bank, a single tube, and a hydrofoil in cross flow using FLUENT with RNG k-epsilon model and a dynamic subgrid LES model. His numerical simulation considered a full scaled coupled CFD/FEA FSI analysis, but limited again to a single unit cell.
The methodology is valid only when the displacements calculated by the structural simulation are both small. As flow velocity increases, tube displacement is enhanced; and at the same time the structural motion starts to affect the flow significantly. As the flow rate increases, the one-way coupling method becomes less and less accurate, finally becoming completely invalid at the onset of fluid-elastic instability.

In the 1980s, Chen et al. (1983) performed an experiment on a half-scale sector model of a steam generator helical coil tube tank at Argonne National Laboratory. This test was designed to study the structural motion of the whole tube bundle under the conditions of still and flowing air and water. Details of the experiment are discussed in section 1.1. Data from this test is used to validate SHARP (Yu et al., 2016), which is an advanced modeling and simulation toolkit for the analysis of nuclear reactors (Yu et al., 2016). Results demonstrate that for low velocity, where the one-way coupling assumption is likely to hold, SHARP can be used successfully to simulate flow-induced vibrations.

SHARP’s thermal-hydraulic code Nek5000 (Fish et al., 2008) is used to simulate the flow using large-eddy simulation (LES) for turbulence modeling. Lai et al. (2016) performed a study applying LES to models of a helical coil steam generator using Nek5000. Even though that study was based on one subsection of a tube bank, the simulation results are in excellent agreement with the experimental data, confirming LES’s applicability to this problem. Fig. 1 shows the computational domain used in the Nek5000 fluid simulation for the helical steam generator tested in Chen’s experiment. The Nek5000 simulation setup and results are discussed with more detail in Section 2. We also discuss turbulence modeling approaches and justify the need for a large eddy simulation approach in this context and highlight the need of further research in RANS and hybrid modeling approaches.

SHARP’s structural mechanics code DIABLO (Solberg et al., 2014) is used to simulate the response of the tube bank subjected to surface loadings predicted by fluid simulation. Fig. 2 presents the geometry in the DIABLO simulation with a magnified tube displacement. The DIABLO simulation setup and results are discussed in more detail in Section 3.
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