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Research Paper

Unsteady flow behavior of a steam turbine control valve in the choked condition: Field measurement, detached eddy simulation and acoustic modal analysis

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HIGHLIGHTS

- Field test determined flow-induced vibration of the valve in the choked condition.
- Unsteady flow modeled using DES and POD analysis identified vibration causes.
- Axial & circumferential acoustic modes were found to coincide with pressure patterns.

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ABSTRACT

The unsteady flow behavior of a steam turbine control valve in the choked condition, which occurs during the warming-up process of a steam turbine, was studied through complementary techniques, including field measurements of the valve spindle's vibration behavior, detached eddy simulation (DES) of the unsteady flow field, and acoustic modal analysis of the valve chamber. Three peak frequencies at $St = 0.044$, $St = 0.17$, and $St = 0.59$ were identified from field measurements of the vibration behavior. Subsequently, the unsteady flow fields in the control valve were determined from DES and then analyzed using the state-of-the-art data-driven proper orthogonal decomposition (POD) method and cross-correlation analysis, which extracted the dominant unsteady flow behavior in relation to the valve spindle's vibrations. The findings demonstrated that the valve spindle's lateral force fluctuations at $St = 0.019$ occurred due to the alternating oscillations of the annular wall-attached jet, which resulted from the first two POD modes occupying 25% of the turbulent fluctuation energy. The valve spindle's axial force fluctuations at $St = 0.043$ were attributed to the synchronous oscillations of the annular wall-attached jet, which resulted from the third, fourth, and fifth POD modes occupying 15% of the turbulent fluctuation energy. Finally, through acoustic modal analysis that compared the pressure fluctuations extracted from the DES results, the axial acoustic mode in the valve's cavity at $St = 0.19$ was found to be associated with the valve spindle's axial force fluctuations at $St = 0.174$, while the first circumferential acoustic mode of the valve diffuser at $St = 0.61$ was found to be associated with the valve spindle's lateral force fluctuations at $St = 0.62$. This confirmed the potential coupling between the acoustic mode pattern and pressure fluctuation pattern. These complementary techniques were demonstrated to be effective methodologies for the flow-induced vibration behavior and intensive acoustics in valves.

1. Introduction

As the major flow control component, the steam turbine control valve, which is commonly placed between a boiler and steam turbine, operates in response to variations in the required power output; the control valve is mostly kept at a moderate or large opening ratio with an optimized minimum pressure drop. However, operation of the control valve at a very small opening ratio, which gives rise to choked flow with a supersonic jet, is practically needed for hours during the cold-state startup of the steam turbine, as it provides low-rate high-temperature steam to warm up the downstream steam turbine. Otherwise, a large volume flow of high-temperature steam results in the generation of unexpected

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List of symbols

Main symbols

L_v	lift displacement of the valve's spindle
D_{seat}	minimum diameter of the valve's seat
St	Strouhal number
a_{in}	local sound speed at the valve inlet
p^*_{in}	total pressure at the valve inlet
T^*_{in}	total temperature at the valve inlet
p_{out}	averaged static pressure at the valve outlet
y^+	non-dimensional wall distance
$\hat{p}$	root mean square of the pressure fluctuations
$\bar{p}$	time-averaged pressure
p'	pressure fluctuation
λ_i	acoustic or POD eigenvalues
A^i	POD eigenvectors
φ^i	POD modes
ρ_{pp}	cross-correlation coefficient of the pressure fluctuations
F_l	lateral force on the valve's spindle

Greek symbols

ε	opening ratio of the control valve
φ	pressure drop of the control valve
ξ	streamwise separation interval in cross-correlation
τ	time delay in cross-correlation

Abbreviations

DES	detached eddy simulation
POD	proper orthogonal decomposition
RANS	Reynolds-averaged Navier–Stokes
LES	large eddy simulation
SAS	scale-adaptive simulation
SAS-F	scale-adaptive simulation with an embedded forcing zone
FEM	finite element method
SST	shear stress transport
DEH	digital electric hydraulic control system
RMS	root mean square

thermal stress, which can contribute to structure damage of high-temperature components via low-cycle fatigue [1]. There is no doubt that choked flow through the narrow channel between the valve spindle and valve seat is extremely unstable, and results in intensive flow-induced vibration and flow noise. Accordingly, insight into the unsteady flow behavior in the choked condition is of great practical significance.

A literature survey shows that many efforts have been made to determine the unsteady flow behavior inside steam turbine control valves. By measuring the pressure fluctuations in combination with Reynolds-averaged Navier–Stokes (RANS) simulation of the steam flow, Hardin [2] attributed the failure of stream turbine control valves to flow-induced vibration. Zaryankin [3] measured pressure fluctuations in a steam turbine control valve, and showed a strong correlation between the valve's vibration and the pressure fluctuations. Large eddy simulation (LES) of the flow in a steam turbine control valve by Morita [4] showed the asymmetric flow structures attached to the valve's spindle, which resulted in rotating pressure fluctuations and corresponding valve vibration. Scale-adaptive simulations (SAS) of the unsteady flow behavior in a steam turbine control valve by Zanazzi [5] demonstrated that the strong unbalanced force on the valve resulted from the interaction of the asymmetric supersonic jets between the valve spindle and the downstream diffuser. Detached eddy simulations (DES) of the flow in a steam turbine control valve conducted by Zeng et al. [6] indicated that the unstable flow along with the moving high-pressure region induced the low-frequency intermittent vibration of the valve spindle. Domnick et al. [7] numerically simulated the unsteady flow field of steam turbine control valves using SAS with an embedded forcing zone (SAS-F), and identified three flow topologies in the valve's diffuser section in response to variations in the opening ratio and the pressure ratio, i.e., the full diffuser flow, the wall-attached jet flow and the wall-detached jet flow. The wall-attached jet flow and the wall-detached jet flow in the choked condition gave rise to a large vibration in the valve spindle.

Very recently, further analysis of unsteady flow behavior has been complemented by acoustic modal analysis to identify the potential coupling mechanism between unsteady flow behavior and intensified acoustics. Barannyk [8] numerically determined the diametral acoustic modes in a steam control gate valve using the finite element method (FEM) and taking into account the experimentally measured pressure fluctuations inside the valve chamber, and established the dependency of the diametral and longitudinal acoustic modes on the inflow velocity. Using the SAS method, Musch [9] numerically simulated the unsteady flow in a steam turbine's emergency stop and control valve in the a choked condition, demonstrating that the pressure fluctuation pattern related to the vortex shedding process superimposed on the supersonic wall jet was spatially similar to that of the acoustic mode distribution around the valve seat; in a similar way, the circumferential acoustic mode was found to be coupled with a periodical switch of the wall jet between the supersonic and subsonic statuses. Using the SAS-F turbulence model, Domnick [7] captured the fluctuating aerodynamic force on the spindle of a steam turbine control valve, showing that the axial acoustic mode in the valve's cavity was closely related to the axial force fluctuations at the large opening ratio, while the first circumferential acoustic mode featured in the valve's diffuser was related to the lateral force fluctuations at the moderate opening ratio. However, in terms of the authors' knowledge, understanding of the unsteady flow behavior and its complementarity with the acoustic modes is far less than enough for choked flow when the steam turbine control valve operates at an extremely small opening ratio, which is again a required process before the cold-state startup of a steam turbine.

In the present study, attention is focused on a complementary analysis of the unsteady behavior of choked steam flow through a steam turbine control valve and the spatial and spectral features of acoustical modes. A field test was performed during the warming-up process of a steam turbine to determine the peak frequencies of the control valve structure's intensive vibration. Subsequently, DES simulation and acoustic modal analysis were conducted separately to explore the potential coupling between the unsteady flow behavior and intensified acoustics. Using the state-of-the-art data-driven proper orthogonal decomposition (POD) method, the energetic flow structures in the highly unsteady flow were extracted from the very large numerical database. Subsequently, a cross-correlation analysis of the pressure fluctuations in the control valve was conducted to delineate the convective features of the vortex structures.

2. Field measurements of valve vibration

A steam turbine control valve placed in a thermal power plant was forced to operate at an extremely small opening ratio of 2% ($\varepsilon = 0.02$), providing a small volume of steam flow to warm up the downstream steam turbine components. Here, the opening