# Uncertainty quantification on the frequency response of fusion thermal-hydraulic components using digital image correlation

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**Abstract.** Flow-induced vibrations (FIV) leading to high-cycle fatigue and fretting could limit the operating life of thermal-hydraulic systems for key fusion reactor components, particularly if resonant frequencies of the components are activated. We used high-speed digital image correlation (DIC) with a simplified experimental mock-up to capture the physics of pipe vibration when immersed in a fluid or excited by an internal turbulent flow. We replicated our experiments with the same finite element techniques used to simulate the proposed components to validate the accuracy of the models. The output of these simulations was used to artificially deform images which were then processed with DIC, enabling us to rigorously investigate the effects of uncertainty in experimental and simulation parameters and perform a quantitative comparison between them.

**Possible Sessions**

<u>7.</u> Dynamic Behaviour of Materials, <u>14.</u> Model Validation, <u>18.</u> Nuclear Applications: Fusion

**Introduction.** ITER, a test fusion reactor, will trial a water-cooled lithium lead blanket module circulating cooling water through u-bend cantilever double-walled tubes immersed in liquid lead-lithium (Pb-Li). Any damage to these tubes could damage the module and reactor operation. Flow-induced vibration (FIV) in double-walled tubes could promote high-cycle fatigue and fretting, especially if resonant frequencies are excited. Finite element simulations have been developed to investigate the likelihood of this, but a rigorous uncertainty quantification procedure, comparing data from both simulations and experiments, is needed for these simulations to be trusted for design decisions.

We used digital image correlation (DIC) to measure the frequency response of a simplified mock-up component in experimental cases corresponding to simulations of increasing complexity, capturing different aspects of the relevant physics. This provides a rich quantity of surface displacement data which can be compared with the simulation output. As a non-contact method, DIC does not affect the frequency response and can be used for components fully immersed in water [1,2]. Previous work on DIC for modal analysis has shown good agreement with traditional vibration measurement techniques, though typically with greater error on out-of-plane vibration and limitations on sampling rate [3-5]. Additionally, DIC can create new sources of error, such as frequencies from lighting flicker and active cooling systems for the high-speed cameras [1]. Difficulty in correcting for temporal aliasing with high-speed cameras has also been noted [5].

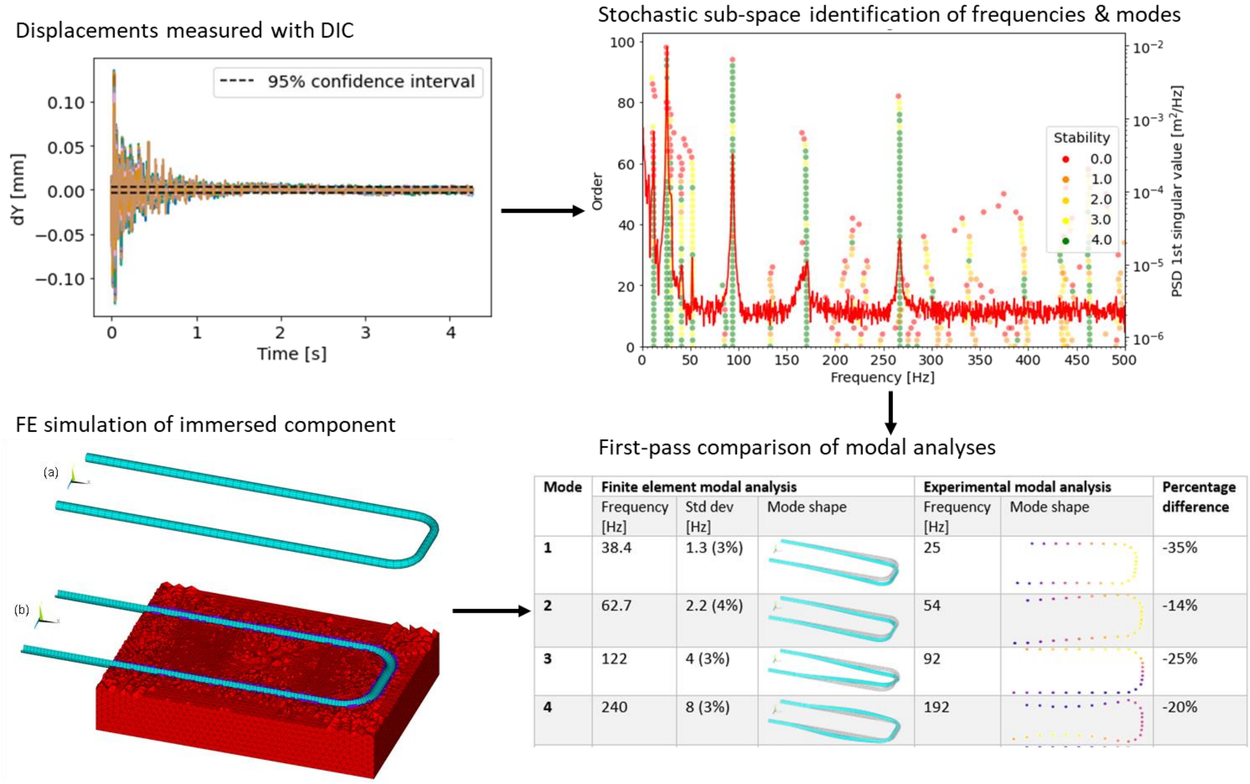
**Finite Element Simulation.** We constructed a finite element (FE) model of the u-bend cantilever mock-up in ANSYS (Mechanical 2021 R2). This was used to replicate cases of impact testing in air and immersed in water, without fluid flow. A one-way coupled CFD and FE simulation was used to model the effects of internal turbulent water flow. In all these cases, geometric and material parameters were varied stochastically to quantify the effects of uncertainty in these parameters on frequency response.

Nodal displacements over time for each case were exported and used alongside a calibration file to virtually deform a set of images of the component in MatchID (2022.2.1) [6]. These deformed images were processed with DIC in the same way as real experimental images to produce displacement maps over time. This allowed us to replicate sources of uncertainty in the experimental output (by artificially adding systematic and random errors) and processing parameters, enabling us to quantify the combined effects of uncertainty from simulation and processing parameters on the agreement between simulations and experiments.

**Experimental Method.** We focused first on validating natural frequencies from modal analysis for the simplest cases, with a simplified copper u-bend component mock-up in free-free and fixed-free configurations in air, without internal fluid flow or immersion. A stereo-DIC setup with two high-speed cameras (Phantom Miro LAB110) was used, recording the component at 1 kHz as it was impacted with an instrumented hammer to induce vibration. A similar setup was used to record the frequency and mechanical response of a component connected to a flow loop of room temperature water, with turbulent flow induced by a water pump. Finally, impact hammer testing was performed again with most of the component immersed in water. DIC was performed on the captured images for all experimental cases using MatchID [6].

Each of these tests was carried out with and without accelerometers attached to the component, so that we could verify the accuracy of DIC vibration analysis while having access to results unaffected by the additional mass. The noise floor for each case was evaluated by recording images without applied excitation loads, and processing these with DIC, taking the standard deviation on each displacement component as the noise floor.

**Results.** We used the covariance-driven stochastic sub-space algorithm (SSI) to identify excited frequencies and reconstruct mode shapes from in-plane and out-of-plane displacement maps [7][8]. In the free-free case, the first eight natural frequencies were all within the uncertainty in simulation parameters, while in the fixed-free case the first natural frequency was outside the simulation uncertainty. This bias was attributed to compliance in the fixed support. The immersed case showed a systematic bias of at least 15% across all natural frequencies, most likely due to support compliance or errors in the measurement of the unsupported or immersed length (both of which strongly affected the simulation). Transient analysis of the pipe excited by turbulent fluid flow showed small displacements, with most of the excitation in the first two vibration modes, and very little activation of higher modes, which agreed with our simulation results. The work to fully link the experimental and simulation results into a full uncertainty quantification procedure has not yet been completed but will be presented at the conference.




| Mode | Finite element modal analysis | | | Experimental modal analysis | | Percentage difference |
|---|---|---|---|---|---|---|
| | Frequency [Hz] | Std dev [Hz] | Mode shape | Frequency [Hz] | Mode shape | |
| 1 | 38.4 | 1.3 (3%) | | 25 | | -35% |
| 2 | 62.7 | 2.2 (4%) | | 54 | | -14% |
| 3 | 122 | 4 (3%) | | 92 | | -25% |
| 4 | 240 | 8 (3%) | | 192 | | -20% |

Figure 1: Process of simulation comparison to DIC for modal analysis of the component mock-up

**Summary and Future Work.** We successfully used DIC to carry out modal analysis of a mock-up thermal-hydraulic component and investigate the mechanical response due to internal turbulent flow. We used these results to validate our finite element simulations and implemented an uncertainty quantification procedure to measure the combined effect of uncertainty in simulation and experimental parameters on output agreement.

We found that inaccuracy in boundary conditions was a key reason for disagreement between experimental and simulated frequency response. This is a source of error which is difficult to simulate accurately, or to remove in experiments, and work remains to be done to resolve this. The simulation of the water-immersed condition was especially sensitive to small changes in compliance and unsupported length. This is concerning given suggestions to alter the geometry of DWT components to be longer and with greater mass at the free end, which could result in greater risk of FIV and resulting damage to critical components.

## References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