Modal analysis of fusion thermal-hydraulic systems using digital image correlation

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Abstract. Flow-induced vibrations are a potential life-limiting factor in thermal hydraulic systems for key fusion reactor components, such as the tritium breeding blanket. These components must be designed to avoid excitation of resonant frequencies in operation, and the models used to ensure this must be validated against experimental data. In this work we have used digital image correlation as a data-rich modal analysis technique for mock-up pipework components, in parallel with image deformation based on simulation data to provide thorough uncertainty quantification. We use this technique to investigate pipework mock-ups in free-free and fixed-free configurations, both with and without turbulent fluid-flow.

Introduction

Flow-induced vibration (FIV) can be a life-limiting factor in thermal-hydraulic systems, promoting high-cycle fatigue and fretting. When FIV frequencies match the resonant frequencies of components, the loading induced is significant and can lead to more rapid failure. The water-cooled lithium-lead test blanket module (WCLL-TBM) for ITER will use U-bend cantilever double-walled tubes (DWTs) immersed in liquid lithium-lead to carry cooling water. Resonant FIV could result in severe damage to the test module and prevent reactor operation. Modelling efforts are carried out to avoid resonant frequencies in component design, but these must be validated by experimental data.

Digital image correlation (DIC) enables non-contact tracking of component displacements at the surface, simulating the effect of a great number of accelerometers without the concomitant mass effects. However, the image-based technique introduces potential sources of error from image noise, speckle pattern quality, and subset smoothing. We have carried out modal analysis of a copper pipe mock-up in free-free and fixed-free configurations using DIC, in parallel with uncertainty quantification using finite element (FE) modelling and virtual image deformation to simulate experimental data.

Finite Element Modelling

The first 3 modes and associated frequency values were initially identified both analytically and through FE modelling in ANSYS (see Tab. 1 and Fig. 1), assuming a density of 7980 kg m^{-3}, elastic modulus of 117 GPa, inner diameter of 13.6 mm and a wall thickness of 0.65 mm. To account for uncertainty in these material and geometric parameters, the process was iterated within the measured uncertainty for density, internal diameter, and wall thickness, and with an estimated uncertainty of ±10% for the elastic modulus taken from literature. This produced a 95% confidence interval on the identified frequency values.

Mode	Analytic frequency [Hz]	FE Modal Analysis	
		Median frequency [Hz]	95% confidence interval [Hz]
1	45.3	45.5	±3.6
2	283.3	282.3	±22.5
3	794.4	779.8	±62.1

Table 1: First three fixed-free resonant frequencies for a straight pipe calculated analytically and in ANSYS

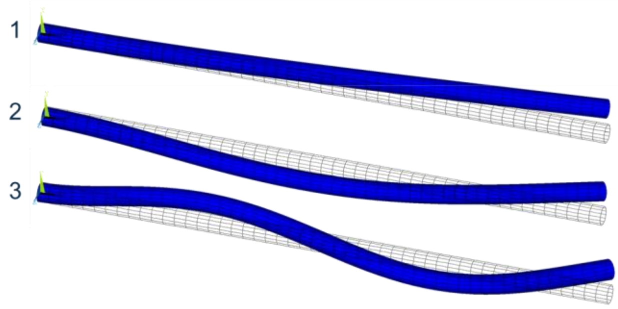

Figure 1: First three fixed-free mode shapes for a straight pipe calculated in ANSYS

Experimental Setup

A speckle pattern was applied to a 500 mm length of copper pipe using black paint sprayed through a template of 1.95 mm diameters dots over a base coat of white paint. The pipe was clamped to a table for the fixed-free configuration or suspended from a beam with a rubber band for the free-free configuration. The pipe was then tapped in-plane with a hammer at various points along the length to excite multiple resonant frequencies. A stereo-DIC setup using high speed cameras (Phantom Miro LAB110; 1280x800 px) was calibrated and used to image the vibrations at a rate of 5 kHz.

Results

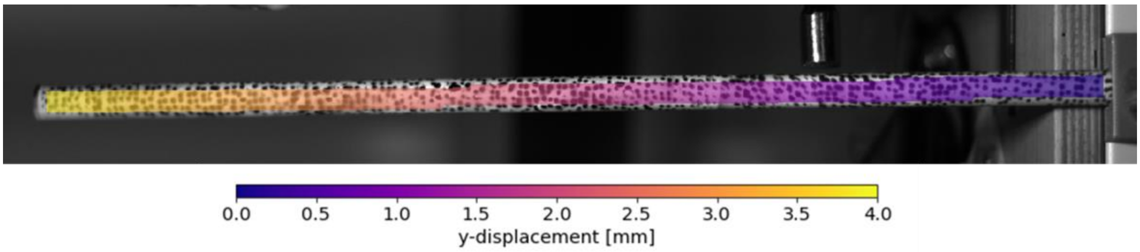

Figure 2: Map of displacement in the loading direction, overlaid on the component in the fixed-free configuration

The correlation procedure was performed in MatchID with a typical maximum displacement map shown in Fig. 2 (subset 15 px, step 5 px). The enhanced frequency domain decomposition (EFDD) algorithm and the covariance-driven stochastic sub-space identification (SSI) algorithm were used to investigate the resonant frequencies and associated mode shapes from the displacement data along the pipe length [1,2]. The first two resonant frequencies could be clearly identified within the uncertainty of those calculated in ANSYS, as could the normalised mode shapes.

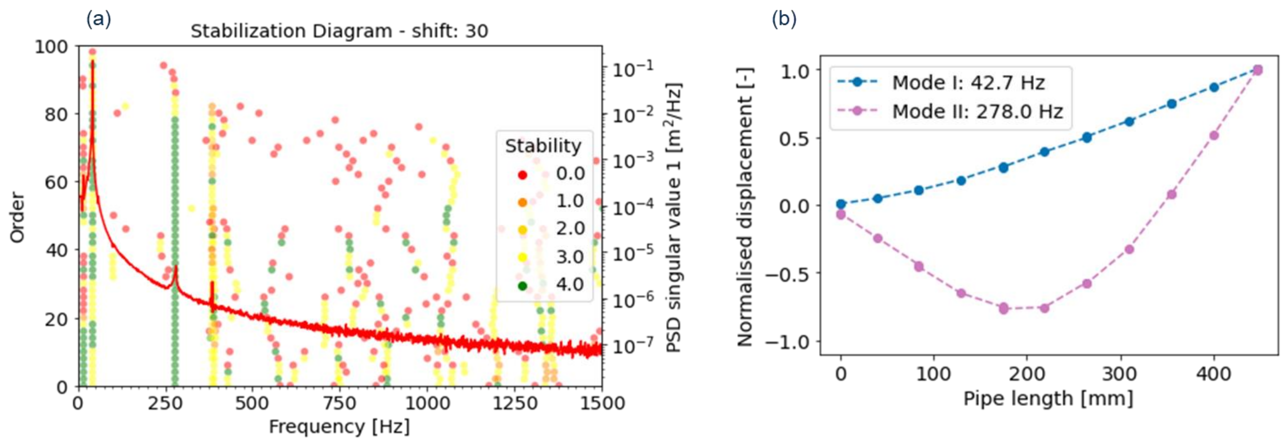

Figure 3: (a) Covariance-driven stabilization diagram overlaid with the first set of power spectral density (PSD) singular values; (b) Normalised mode shape displacement at the first two resonant frequencies

Summary and Future Work

We have demonstrated the use of high-speed imaging to capture the frequency response of mock-up fusion thermal-hydraulic systems. The extracted natural frequencies compare well to the finite element model and validate the first two natural frequencies within the bounds of uncertainty for the experiment and simulation. We are currently in the process of performing a thorough uncertainty quantification using the synthetic image deformation tool in MatchID [3,4] which will allow us to optimise the DIC parameters to minimise errors. This tool will also allow us to investigate and mitigate the effects of aliasing of high order modes which is a drawback of using DIC modal analysis [5]. Finally, the use of high-speed imaging will allow us to assess the performance of fusion thermal-hydraulic systems under turbulent fluid excitation. At the conference we will present our latest results showing the transient vibration response of a breeder blanket cooling tube excited by turbulent fluid flow, with thorough uncertainty quantification.

References

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