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EXPERIMENTAL INVESTIGATION OF TRANSITIONAL FLOW IN CEREBRAL ANEURYSMS

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SUMMARY

The onset of transitional flow in cerebral aneurysms has previously been demonstrated in numerical simulations but it remains to be seen if this phenomenon is present *in vivo* as the detection of such flow fluctuations is difficult with the resolution of modern imaging. Here, we experimentally investigate the presence of transitional flow in physical models of aneurysms previously studied in numerical simulations. We detect the presence of transition in aneurysms through wall vibrations recordable by a microphone, and correlate it with the flow fluctuations detected in numerical simulations.

Key words: *aneurysm, transitional flow*

1 INTRODUCTION

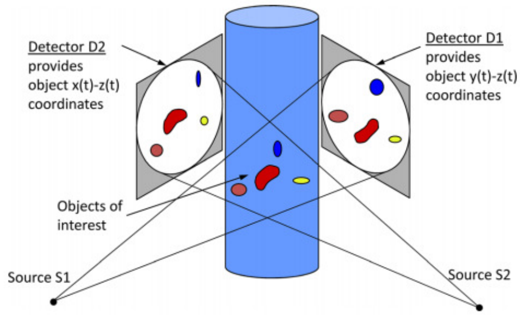
Computational fluid dynamics (CFD) has demonstrated its ability to discriminate cerebral aneurysms based on their rupture status by computing flow dependent forces that act in aneurysms [1]. Recent CFD simulations have predicted the presence of a flow regime in aneurysms that, in spite of the low Reynolds number in the parent artery, is not laminar but exhibits high frequency fluctuations which resemble transitional flow [6]. The presence of such a flow regime in aneurysms *in vivo*, however, can only be ensured by extensive validations. Recent comparisons of CFD and phase contrast magnetic resonance (PC-MR) imaging [4] depict a close resemblance between PC-MR and CFD for aneurysms in which numerical simulations predict laminar flow, while vivid differences are reported for aneurysms with transitional flow. Such studies improve the confidence in the accuracy of CFD and suggest the requirement of high resolutions in simulations for the capture of such a flow.

In the study at hand, we aimed to investigate the presence of transitional flow by conducting experiments on the physical models of the same aneurysms that were previously studied in numerical simulations [6, 2], and to check whether the flow fluctuations were detectable through a microphone (ie. via pseudo-sound produced by aneurysm wall-vibrations) and X-ray PTV measurement, and if so, whether the intensity of flow fluctuations correspond to previous numerical simulation studies.

2 METHODOLOGY

Two previously studied aneurysms, one with transitional flow shown in figure 1a, and another with laminar flow were developed in multiple sizes and materials. We denote them as Model A and Model B following [2]. All models were rigid but the roughness varied among the models. From a previous direct numerical simulation study, which was conducted using a lattice Boltzmann method [2, 5], it was known that the flow inside the aneurysm transitioned to a weakly turbulent regime at Re=351 in one of the aneurysms while it remained laminar up to at least Re=650 in the second model. These findings were under stationary inflow conditions, and the simulations resolved the smallest scales that can appear in a turbulent flow, namely the Kolmogorov micro-scales [2, 5].

(a) Physical models of the aneurysm that exhibited transitional flow (Model A)



(b) Block diagram of the stereographic X-ray setup

In the present experiments, the flow was gravity driven and consisted of a 10 litre container elevated roughly 2 metres above the aneurysm model, with a 3 litre container used to catch the water. Although other driving mechanisms e.g. pumps were considered, the gravity driven flow was given precedence for its simplicity, and to avoid spurious noise in the acoustic measurement.

Data acquisition for the acoustic method was performed using a National Instruments myDAQ and an in-house built amplifier previously determined to be linear. The amplifier included an analog second order low pass filter, limiting measured frequencies to less than 4096 Hz, and the sampling frequency was set to 16384 Hz. Welchs periodogram method was used to estimate the Power Spectral Densities (PSDs) and 2^{18} data points were found sufficient.

A block diagram of the stereographic X-ray setup can be seen in figure 1b. The distance from the origin to the detector 1 and 2 was 110mm and 100mm, respectively. The distance from source 1 to detector 1 and source 2 to detector 2 was 636 mm and 552 mm, respectively. Two 400W X-ray sources were used, with a voltage range of 20-100kV and current range of 0.5-10mA, resulting in X-rays emitted in a cone shaped beam from a 0.5mm focal spot. The X-ray generator settings were set to 40kV and 4mA in the FlowCapture software that controlled the X-ray machine.

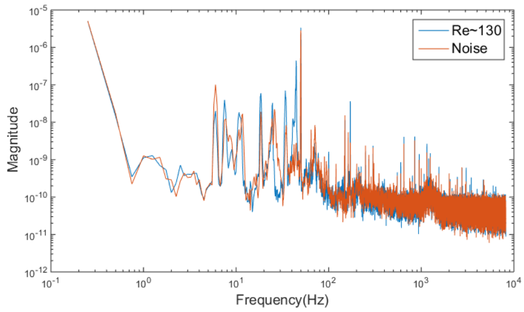
3 RESULTS

The acoustic signal was found to be independent of the position, model and run. The acoustic measurements were similar to the noise that was present at no flow for aneurysm model A up to Re=300, and up to Re=600 for model B. Figures 1a–1d show the power spectral density with respect to frequency for various Reynolds numbers, for the aneurysm with transitional flow [2]. The signature of the power spectrum of the fluctuations at Re=130 matches the power spectrum of the noise. At Re=300 (figure 1b), there is a tendency of higher magnitudes in the fluctuations (shown in blue) at frequencies of a few hundred Hertz. This tendency is amplified at Re=400 (figure 1c), and here there is a clear separation between the two curves in the frequency range 20-600 Hz.

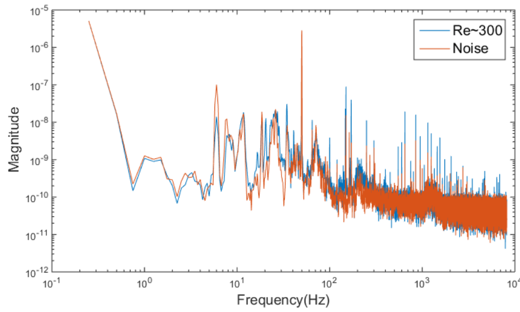
The wall vibrations are caused by pressure fluctuations in the flow, which for fully developed turbulence should should scale as $f^{-7/3}$, where f is the frequency. In Figure 1d, the power spectra at various Reynolds numbers are shown overlaid on each other to demonstrate the tendency of increased vibrations more clearly. Even though transitional effects seems to occur already at Re=300, fully developed turbulence seems not to be present before between Re=1500 or Re=3200. A corresponding plot from the previous DNS [2] is shown in figure 1e.

4 CONCLUSIONS

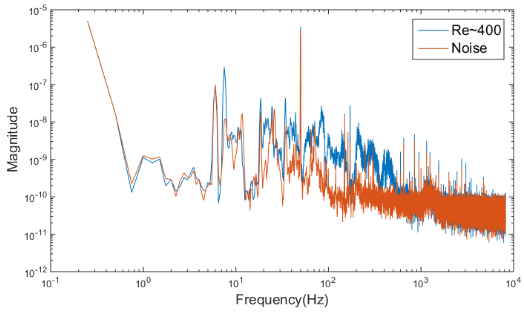
The experimental study on physical models depicts the onset of transitional flow in aneurysms at nearly the same Reynolds numbers as in previous numerical simulation studies [2, 5]. The analysis of the power spectral densities was possible by recording sounds from off-the-shelves microphones. X-ray PTV measurements failed to identify the transition, most likely due to the usage of particles that were too big to follow the flow at sufficiently low Reynolds numbers.



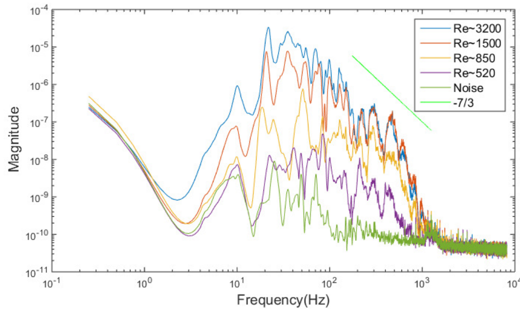
(a) Re=130



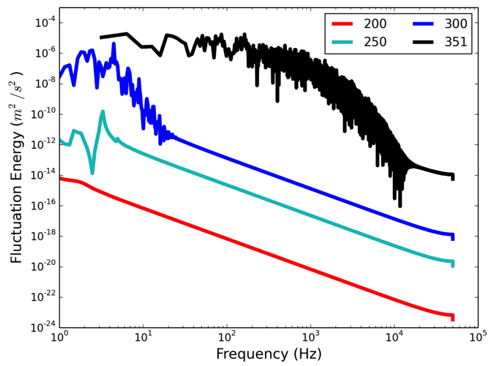
(b) Re=300



(c) Re=400



(d) Model A



(e) DNS (Model A)

Figure 1 Power spectrum of recorded wall vibrations for various Reynolds numbers and power spectrum of turbulent kinetic energy in a DNS simulations.

A direct comparison to DNS studies is not possible due to the detailed flow features that were captured by that study. This study validates the presence of transitional like phenomena in aneurysms.

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