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Short communication

On the quantification and visualization of transient periodic instabilities in pulsatile flows

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A B S T R A C T

Turbulent-like flows without cycle-to-cycle variations are more frequently being reported in studies of cardiovascular flows. The associated stimuli might be of mechanobiological relevance, but how to quantify them objectively is not obvious. Classical Reynolds decomposition, where the flow is separated into mean and fluctuating velocity components, is not applicable as the phase-average is zero. We therefore expanded on established techniques and present the idea, analogous to Reynolds decomposition, to decompose a flow with transient instabilities into low- versus high frequency components, respectively, to discriminate flow instabilities from the underlying cardiac pulsatility. Transient wall shear stress and velocity signals derived from computational fluid dynamic simulations were transferred to the frequency domain. A high-pass filter was applied to subtract the 99% most-energy-containing frequencies, which gave a cut-off frequency of 25 Hz. We introduce here the spectral power index, and compute the fluctuating kinetic energy, based on the high-pass filtered velocity components, both being frequency-based operators. The efficacy was evaluated in an aneurysm model for multiple flow rates demonstrating transition to turbulent-like flows. The frequency-based operators were found to better correlate with the qualitatively observed flow instabilities compared to conventional descriptors, like time-averaged wall shear stress or oscillatory shear index. We demonstrate how the high frequencies beyond the physiological range could be analyzed and/or transferred back to the time domain for quantification and visualization purposes. We have introduced general frequency-based operators, easily extendable to other cardiovascular territories based on a posteriori heuristic filtering that allows for separation, isolation, and quantification of cycle-invariant turbulent-like flows.
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1. Introduction

Hemodynamic forces, particularly wall shear stress (WSS), are thought to contribute to vessel wall adaption and remodeling (Malek et al., 1999; Morbiducci et al., 2016). Since direct measurements of these stresses are difficult, medical image-based computational fluid dynamics (CFD) (Taylor and Steinman, 2010) has been extensively used in the investigation of vascular pathology. Except for aortic flows with Reynolds numbers (*Re*) in the thousands (Nerem et al., 1972), cardiovascular flows have conventionally been considered laminar and stable; however, recent advances in imaging tools, as well as focus on numerical accuracy have highlighted the presence of transitional and turbulent-like flows (Valen-Sendstad et al., 2011, 2014; Chnafa et al., 2014; Zajac et al., 2015), consistent with experimental evidence (Roach et al., 1972; Yagi et al., 2013) and clinical observations (Ferguson, 1970, Kurokawa et al., 1994). The arterial stimuli from such turbulent-like flows have been linked, both *in vivo* (Fry, 1968) and *in vitro* (Davies et al., 1986), to adverse vascular remodeling. However, there appears to be no consensus in the literature on how to robustly quantify such turbulent-like flows.

While methods for decomposing the mean and transient parts of truly turbulent flows are well understood (Pope, 2000), for pulsatile flows this can only be applied in a phase-averaged sense, for flows with instabilities that vary from cycle to cycle (Chnafa et al., 2014; Poelma et al., 2015). Proper orthogonal decomposition (Grinberg et al., 2009) is an alternative method that allows for distinction between flow phenotypes and higher fluctuating components in cycle-invariant flows. However, the mechanobiological relevance of hemodynamic stresses reconstructed from

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high-mode velocity fields requires further investigation. Instead, initial ad hoc attempts in the biomedical literature have been focused on analyses or visualizations of 1D velocity–time traces from selected points (Valen-Sendstad et al., 2013; Bozzetto et al., 2015; Varble et al., 2016). However, these traces are subjectively placed, provide a limited amount of information, and do not allow for additional post-processing or make complete use of the available 3D flow field.

Conventional hemodynamic WSS-based descriptors like time-averaged WSS and oscillatory shear index (OSI) were originally developed for unsteady laminar flow regimes, and thus are not necessarily adequate descriptors of turbulent-like flow stimuli. The aim of the current study was to investigate a robust approach to quantify and visualize these turbulent-like flows. We propose frequency-based operators, which, analogous to Reynolds decomposition, decompose a signal into low- and high-frequency components. We demonstrate how this method can be applied to detect, characterize, quantify, and visualize high-frequency instabilities of volumetric and surface quantities, focusing on a cerebral aneurysm as a representative example.

2. Methods

We took advantage of methods frequently used, e.g., in turbulence research (Pope, 2000), where any signal can be transferred from the time domain to the frequency domain. Taking this approach, any heuristic filter can be applied to analyze the low versus high frequency components, and (potentially) transfer the harmonics back to the time domain for additional analyses and visualization purposes. Analogous to Reynolds decomposition, the signal reconstructed from low- versus high-frequencies are comparable to the phase-average versus fluctuating components, respectively.

Fig. 1 illustrates this principle where the 1D time–velocity trace in red was decomposed using a high pass filter. The low frequency physiological 'carrier' signal is shown in black, while the high frequency residual is shown in blue, reflecting the 'unphysiological' fluctuating components. We emphasize that this applies to any 1D signal, like velocity, pressure, or WSS trace, but can also be assembled to surface and volumetric quantities, respectively.

Inspired by the harmonic index defined as the fraction of harmonic amplitude spectrum arising from pulsatile flow component (Gelfand et al., 2006), we defined

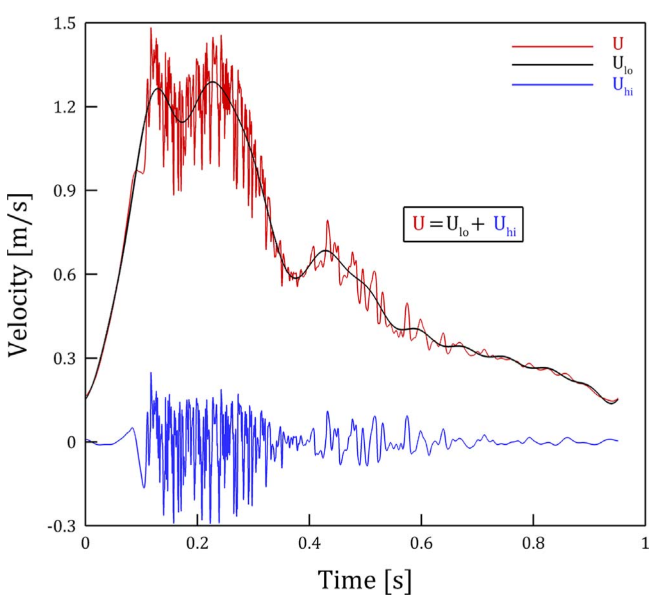

Fig. 1. Fourier decomposition of a cycle-invariant velocity signal (red line) into low (black line) and high (blue line) frequency components. The inset equation shows the analogy to Reynolds decomposition where U_{lo} is equivalent of the phase-average while U_{hi} is equivalent of the fluctuating component. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

the spectral power index (SPI) as:

$$\mathrm{SPI} = \frac{\sum_{n=n_c}^{+\infty} |Y[n\omega_0]|^2}{\sum_{n=1}^{+\infty} |Y[n\omega_0]|^2} \tag{1}$$

where $|Y[n\omega_0]|$ is the magnitude of the Fourier-transformed signal, ω_0 is the fundamental angular frequency of the periodic signal, n_c is the harmonic corresponding to the cut-off frequency. To objectively determine n_c in order to exclude frequencies in the normal physiological range, we subtracted harmonics that contained 99% of the energy in the driving flow rate waveform, which resulted in a cut-off frequency of n_c=25 Hz. We emphasize two key differences from the harmonic index by Gelfand et al. (2006): (i) SPI does not include the pulsatile waveform mean in the denominator, such that summation begins from the first harmonic and (ii) SPI is based on the power of the signal instead of the energy, to better highlight energy content at higher frequencies. SPI is, therefore, a normalized quantity having the desirable property of being on the interval $[0-1]$; zero meaning that there are no flow instabilities while the scalar value 1 would reflect a completely unstable flow. Analogous to turbulence kinetic energy (TKE), we also computed the time-averaged fluctuating kinetic energy (FKE), defined as:

$$\mathrm{FKE} = \frac{1}{2}\left(\overline{u_{hi}^2} + \overline{v_{hi}^2} + \overline{w_{hi}^2}\right) \tag{2}$$

In contrast to Varble et al. (2016) who used a steady inflow, we here applied Eq. (2) to a pulsatile waveform where u_{hi}, v_{hi} and w_{hi} are the high-pass filtered velocity components and the overline refers to the time average. To evaluate the efficacy of frequency based operators, we chose an aneurysm model from the open-source Aneurisk database (Aneurisk-Team, 2012). We specified a fully developed Womersley velocity profile at the inlet, with a cross sectional mean velocity of 0.27 m/s (Valen-Sendstad et al., 2015) giving a base flow rate of Q=5.37 mL/s with a period of 0.951 s. The flow rate was also reduced to 0.75Q, 0.5Q, and 0.25Q to demonstrate the onset of flow instabilities. The Vascular Modeling ToolKit (Antiga et al., 2008) was used to generate a mesh with four boundary layers that consisted of three million tetrahedron cells, equivalent in spatial resolution to the 'medium' (HR5) simulations in Khan et al. (2015), previously demonstrated to be sufficient to resolve WSS and OSI.

Pulsatile CFD simulations were performed using the CFD solver *Oasis*, taking 10,000 time steps per cycle. *Oasis* uses a projection scheme where special care has been taken to maintain a second-order accuracy in space and time (Simo and Armero, 1994) to obtain a solution that preserves kinetic energy while minimizes numerical dispersion and diffusion errors. For details regarding the implementation and order-optimal convergence results, we refer to Mortensen and Valen-Sendstad (2015). Post-processing was based on 2500 time steps, corresponding to Nyquist limit of 1314 Hz. SPI applied to WSS-time traces (SPI_{WSS}) and FKE were then compared against nominal descriptors like the WSS normalized to the parent artery (TAWSS) and OSI.

3. Results

Fig. 2(a) shows the chosen model and velocity magnitude traces in the carotid siphon, middle cerebral artery and the aneurysmal sac for 0.25Q, 0.5Q, 0.75Q and Q. While traces for 0.25Q and 0.5Q do not feature evident high-frequency fluctuations, the complexity of the traces for 0.75Q and Q are indicative of a turbulent-like flow, especially in the aneurysm sac.

From the corresponding qualitative maps shown in Fig. 2(b), we note only a modest increase in the parent artery normalized TAWSS maps with increasing flow rates. Regions of elevated OSI were found for relatively stable flows 0.251Q and 0.5Q, but also for turbulent-like flows, 0.75Q and Q. This is reflected through the inset traces showing the WSS magnitudes recorded at a location on the sac dome marked with a circle. In short, locations of high OSI are relatively unaffected by flow rate; what is affected is their extent, but approximately linearly with flow rate. Broadly, these maps indicate that both TAWSS and OSI are unable to discriminate laminar from turbulent-like flow stimuli.

On the other hand, a distinct increase in SPI_{WSS} was observed between 0.5Q and 0.75Q, consistent with the appearance of higher-frequencies observed in filtered WSS time-magnitude traces, cf., inset figure. Evident from these plots is that SPI_{WSS} is sensitive to flow destabilization and is able to discriminate between stable and unstable stimuli. Similar trends were observed for cycle-averaged volumetric FKE maps; no FKE is observed for 0.25Q and 0.5Q. However, distinct regions of FKE were observed

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