Application to the 20th ERCOFTAC da Vinci Competition

Title of the PhD thesis: The transitional regime of pulsatile pipe flow

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Brief Summary

Cardiovascular diseases are among the leading health risks today. To prevent them, it's essential to understand their causes. One cause is the friction forces exerted by blood flow on our blood vessels. When these forces become too strong, they can damage the delicate cells in vessels like the aorta, leading to injuries and potentially serious conditions such as aneurysms.

But when do these harmful forces arise? Think of water flowing in your sink. If you open the tap just slightly, the water flows smoothly in straight lines—this is called laminar flow. If you touch the stream, you'll feel a gentle, steady friction force. Now, open the tap further. The water starts to swirl and move chaotically. This is turbulent flow, and the friction you feel on your hand becomes much stronger and rapidly changes direction.

Blood flow can also be either laminar or turbulent. Turbulent blood flow is associated with stronger, rapidly varying friction forces, and it is not the type of flow we want when it comes to cardiovascular health. However, we still do not fully understand when and why blood becomes turbulent. Measuring blood flow accurately is extremely complex because it is influenced by many factors: body posture, movement, and especially the heart pulsation.

In my thesis, I focused on the effect of cardiac pulsation alone. I studied an idealized model of the aorta as a straight pipe, with a fluid driven by a pulsating force — what is known as pulsatile pipe flow. Assuming the flow starts off as laminar, I used advanced computer simulations to investigate how it transitions to turbulence. I found that pulsatile pipe flow is highly susceptible to becoming turbulent—even small disturbances can grow significantly and trigger turbulence. Through simulations, I explored how turbulence behaves in pulsatile flow and identified potential mechanisms for controlling it.

Overall, my thesis provides a detailed examination of how pulsation relates to turbulence—how it can trigger the transition from laminar to turbulent flow, and how turbulence behaves under pulsating conditions. My findings offer strong evidence that cardiac pulsation alone can be enough to initiate and sustain turbulent blood flow.

Scientific Summary

Cardiovascular flows are influenced by many complex characteristics: like complex geometries, non-Newtonian fluid effects or compliant vessel walls. My thesis focused on the effect of one of these complex features alone: the pulsatile driving of our heart. The objective was to extensively study the effect the pulsation alone has on the transition to turbulence. Therefore, I considered the flow in a rigid pipe with circular cross section, what is known as pulsatile pipe flow. Pulsatile flows are not exclusive to biological flows, and are also found in industrial applications. Therefore my analysis considered a vast parametric regime of pulsatile pipe flows, including cases that are relevant to cardiovascular flows, and others that are not. The key parameters are: the Reynolds number (ratio of inertial and viscous time scales); the Womersley number (ratio of the pulsation and viscous time scales) and the waveform of the pulsation. I tried to answer two questions: how do pulsatile pipe flows transition to turbulence?; and, how does turbulence behave once triggered?

1: Transition to turbulence in pulsatile pipe flow

Experimental studies reported a novel transition mechanism of pulsatile pipe flows, not observed in the steady driven case. Small geometric imperfections at the wall suddenly triggered helical patterns in the flow that quickly collapsed and triggered turbulence. Researchers numerically investigated the transition in pulsatile pipe flow using transient growth analysis, i.e. they computed the perturbations that can grow the most on top of the laminar pulsatile pipe flow profile. They identified a family of helical perturbations that transiently and exponentially grow on top of the laminar profile. However they could not identify the causes of their growth.

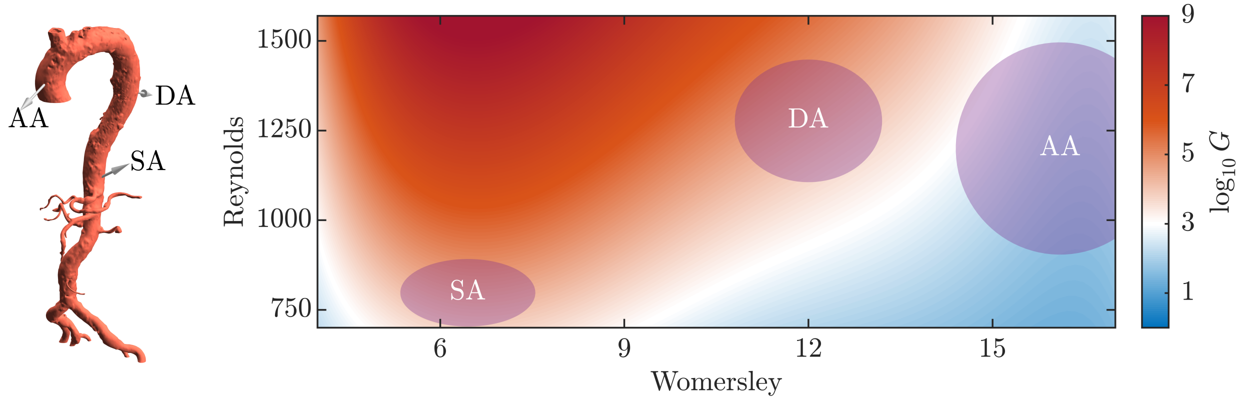

Figure 1: (left) Visualization of a human aorta (right) Energy growth G (as the ratio of maximum and initial energy) of infinitesimally small helical perturbations computed at the corresponding flow parameters, for a pulsatile pipe flow driven with a physiological waveform. I denote with bubbles the typical flow parameters measured at different sections of interest of the aorta: ascending aorta AA, descending aorta DA and supraceliac aorta SA.

In my thesis I extended these transient growth analyses, and proposed a different method to study transition of unsteady laminar profiles [2]. The idea is that, at certain flow parameters (low Womersley numbers), the laminar profile changes at a much slower rate than the flow perturbations. Here, the perturbations see the laminar profile as if it was frozen (quasi-steady). I performed linear stability analysis of pulsatile pipe flow, by treating the instantaneous laminar profile, at several phases of the period, as if it was quasi-steady. At the flow parameters where helical perturbations are susceptible to grow, the laminar profile is instantaneously unstable. I identified that this instantaneous instability is ultimately caused by the inflectional shape of the laminar profile. I show that, at certain flow parameters, transient growth analysis is not needed in order to determine the stability of the flow, and that the 'simpler' linear stability analysis suffices.

I performed transient growth and my proposed stability analysis, to explore a vast parametric space of pulsatile pipe flows. I identified what characteristics make certain waveforms more susceptible to transition than others. I observed that triangular waveforms, with a fast acceleration, followed by a slow deceleration, are the most susceptible to the growth of perturbations. Interestingly, the pulsation waveforms observed in the blood flow at the largest arteries, are very similar to this triangular waveform. In fact, I observed outstanding energy growth G (as the ratio between maximum and initial energy) of perturbations on top of pulsatile pipe flows driven with a physiologically inspired waveform, and at flow parameters measured at different sections of the aorta, see fig. 1.

I explored how turbulence is triggered with the use of direct numerical simulations. I perturbed laminar pulsatile pipe flows with the helical perturbation or with body forces localized close to the wall [1]. I observed that the helical perturbations, and the ones triggered by the body force, are able to quickly grow and trigger non-linear dynamics in the flow, see fig. 2. I showed that, in order to trigger long-lived turbulence structures, the perturbations must be localized. Additionally, waveform characteristics that make pulsatile pipe flows more susceptible to transition, like fast acceleration phases, are detrimental for turbulence survival.

2: Turbulence in the transitional regime of pulsatile pipe flow

Once triggered, turbulence in the regime of interest takes the form of localized turbulent patches (known as turbulent puffs) that show a rich variety of dynamics in the parametric space of interest [3]. A large number of high fidelity and long direct numerical simulations is needed in order to correctly characterize the behavior of puffs in the vast parametric regime. Therefore, as part of my thesis, I developed a new CUDA code, that runs entirely in GPUs and that outperforms state of the art CPU codes in terms of simulation time and cost-efficiency [4].

I found that puffs behave in four distinct ways in the transitional regime of pulsatile pipe flow: at some parameters they decay deterministically at certain phases of the period while at others stochastically; at others they remain localized, modulated by the pulsation in length and magnitude; and at others they split and proliferate increasing the turbulent fraction in the pipe, see fig. 2b. The dynamics one observes depend non-linearly on the flow parameters. For instance, while puffs tend to survive longer and proliferate at higher Reynolds numbers and pulsation amplitudes, at the same Reynolds and Womersley numbers, an increase in the pulsation amplitude can actually negatively affect turbulence survivability.

Puffs at certain flow parameters need to remain localized in order to survive the low velocity phases of the pulsation. With the use of a (Granger) causal analysis I demonstrated that this is because puffs actively make use

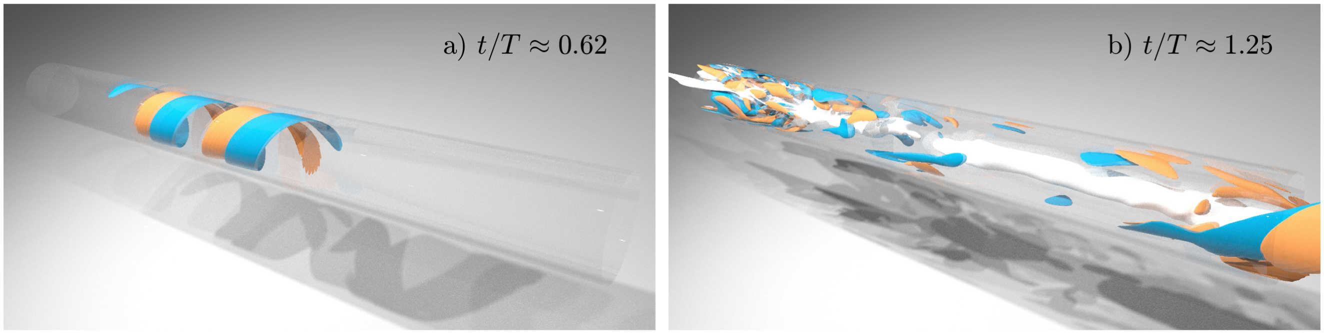

Figure 2: From a helical perturbation to a turbulent puff. Two instants, at two different phases of the period T, of a direct numerical simulation of a single harmonic pulsatile pipe flow, with Reynolds= 2400, Womersley= 11 and pulsation amplitude $A = 1.4$. Grey denotes low velocity streaks, while red/blue positive/negative axial vorticity. The simulation is initialized at $t/T = 0.5$ with a helical perturbation with an initial energy of 10^{-4} the flow energy. a) shows the initial perturbation, after it initially grows. b) the resultant turbulent puff after the perturbation growth and saturation.

of the instantaneous instabilities in the laminar profile behind them to survive the pulsation [3]. I use this knowledge to extend a reduced order model of puffs in steady driven pipe flow (by Prof. Dwight Barkley), to pulsatile pipe flow. With a pair of one dimensional advection-diffusion-reaction stochastic differential equations, I qualitatively capture the four dynamical regimes described above.

Conclusions

My thesis presents a comprehensive analysis on the impact of pulsation on turbulence transition and turbulence survival in pipe flow. My analysis serves as a foundation to study cardiovascular flows, and can be combined with studies on the effect of compliant walls [5]; complex geometries or other characteristics of cardiovascular flows.

My thesis shows that pulsatile pipe flows driven with a physiological waveform are particularly susceptible to turbulence transition [2]. In fact, for these flows, tiny geometric defects can trigger bursts of turbulence at certain phases of the period [1]. For the case of cardiovascular flows, this means that, even if turbulence is not able to survive the whole pulsation cycle, it will be likely triggered at particular locations and particular phases of the period, posing a threat to cardiovascular vessels.

My thesis also investigates the behavior of turbulence in pulsatile pipe flows, and includes a thorough analysis of the causes by which at some flow parameters turbulence survives, and at others it does not [3]. Future analyses can take advantage of these causes, and my reduced order model, to design optimal strategies to control turbulence in these flows. As a by-product of my thesis, I have developed a new numerical GPU code to simulate pipe flow [4] (publicly available in this Github).

The results shown in my thesis provide a deeper knowledge on the transition mechanism of unsteady driven flows. It establishes a very convincing link between classic turbulence transition theory and state of the art flow experiments. Moreover, it introduces novel tools to investigate the causes of transition and turbulence survival in this type of flows.

Selected publications

[1] Feldmann, D., **Morón, D.**, & Avila, M. (2020). Spatiotemporal intermittency in pulsatile pipe flow. Entropy, 23(1), 46.

[2] **Morón, D.**, Feldmann, D., & Avila, M. (2022). Effect of waveform on turbulence transition in pulsatile pipe flow. Journal of Fluid Mechanics, 948, A20.

[3] **Morón, D.**, & Avila, M. (2024). Turbulent puffs in transitional pulsatile pipe flow at moderate pulsation amplitudes. Physical Review Fluids, 9(2), 024601.

[4] **Morón, D.**, Vela-Martín, A., & Avila, M. (2024). Predictability of decay events in transitional wall-bounded flows. In Journal of Physics: Conference Series (Vol. 2753, No. 1, p. 012009). IOP Publishing.

[5] Zeugin, T., Keuchel, P., **Morón, D.**, Coulter, F. B., Halic, M. M. N., Heil, M., Avila, M., and Holzner, M. (2025). Fluid structure interaction in pulsatile flow through an elastic pipe segment. *Accepted in Physical Review Fluids*, DOI:https://doi.org/10.1103/ymqr-dbsw