Focus on Fluids
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The inside view of an oscillating pipe

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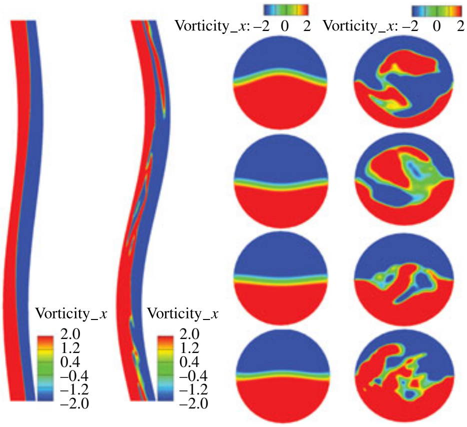

A pipe conveying fluid is a model problem in fluid–structure interactions and nonlinear dynamics. Several experimental and theoretical studies exist on this problem and very rich nonlinear dynamics have been observed including super- and subcritical instabilities as well as various routes to chaos. Despite all the existing studies, we had not yet seen the fluid inside an oscillating pipe as the pipe undergoes different types of flow-induced instabilities. But the wait is over.

Key words: flow–structure interactions, nonlinear dynamical systems

1. Introduction

When we water flowers with a garden hose, we hold an example of fluid–structure interactions in our hand. If we let the hose free on the grass with the valve wide open (i.e. high flow velocity), the hose exhibits a rather complicated motion. The motion might seem to be too complicated to explain. If we want to delve deeper into understanding what the hose does, we need to simplify the problem. We can make the pipe shorter, hang it vertically, and make sure that nothing is attached to it, so that the complicated interaction with its surroundings is removed. In that case, with no flowing water, the pipe will of course remain in its initial position, hanging. As we open the valve and increase the flow velocity, the pipe starts to oscillate beyond a critical velocity. We observe a limit cycle oscillation, which could be planar or three-dimensional, depending on the system parameters, but always with a single frequency. This is far simpler than the motion we found when the hose was lying on the grass. These simplifications may have been too extensive. We can model the interaction with the ground by adding a spring somewhere along the length of the pipe and represent the nozzle attached to the hose by an added mass at the free end of the pipe. In these configurations we can reconstruct the complicated dynamics that we observed in the

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garden hose. As we increase the flow velocity beyond the range of single-frequency limit-cycle oscillation, period-doubling bifurcations may occur, resulting in period-2, period-4 and period-n oscillations. We may also observe quasiperiodic oscillations, and at higher flow velocities, chaos. It is as simple as this: attach a mass to the free end of a hanging pipe, open the valve and impose a high flow velocity to get chaos at home!

The apparent simplicity of this system has made it a paradigm both in nonlinear dynamics and fluid–structure interactions. There have been several studies to understand the details of the pipe's behaviour. How will the pipe behave if we change its boundaries, or if we place it on a flexible surface, or if we turn it upside down and make it jet water upwards? Païdoussis (2014) has collected the studies on this topic in the past several years in a book: hundreds of articles, tens of PhD theses and tens of lives (not lost, not wasted but dedicated to understanding the dynamics of a pipe conveying fluid). This is a very attractive problem for dynamicists. A seemingly simple system, which can be built at home, provides a myriad of complicated nonlinear dynamics. We know by now that the boundary conditions play an important role in the type of response that is observed. If instead of a cantilevered pipe we consider a pipe supported at both ends, all we observe is that the pipe buckles at a critical flow velocity. No dynamic response is observed. If we adjust the cantilevered boundary conditions, say by adding a spring or a mass to its free end, then we may observe a quasiperiodic or a period-n response, and chaos at higher flow velocities. We can generate very complicated dynamics in a pipe conveying fluid. The structural response is fascinating and very well studied. How about the fluid inside? Can we characterise its dynamics as well?

2. Overview

The paper by Xie *et al.* (2016) (referred to as XiZTriCK in the rest of this document) is the first work that shows us the flow inside a pipe conveying fluid when it oscillates. The existing literature has focused on the structure and has used a plug flow assumption. The response of the structure, even with a plug flow assumption for the fluid, is so rich that the fluid mechanics inside the pipe was left unexplored. This was also due to insufficient computational power and advance of the numerical methods. XiZTriCK provide direct numerical simulation (DNS) results of the flow inside the pipe, as the pipe oscillates. They show how the flow pattern inside the pipe changes as the structure undergoes various types of response. It is intriguing to see the fluid inside an oscillating pipe at last.

It is well known that a plain cantilevered pipe (a pipe that is hanging and nothing is attached to it) oscillates beyond a critical flow velocity. It is also well known that the amplitude of these oscillations changes with flow velocity. XiZTriCK show how the flow inside a pipe changes when the amplitude of oscillations is increased. They do this by imposing a prescribed second-mode standing-wave-type motion to the pipe, and they demonstrate how changing the magnitude of the prescribed motion makes the flow inside the pipe change from a laminar flow to a flow exhibiting signs of transition to turbulence. The two plots on the left in the figure by the title show the flow behaviour inside a pipe when it is forced to oscillate with a small or a large amplitude, respectively. The previous models of this system, based on a plug flow assumption, could not capture this change in the flow characteristics. Now we know that the flow inside the pipe varies with changing amplitude of structure oscillations. But this is based on an externally imposed motion of the pipe. How about flow-induced oscillations?

XiZTriCK also characterise the flow inside a pipe undergoing flow-induced oscillations. To make the three-dimensional flow computations possible, they have used a 'discontinuous' forcing model. In their simulation, they calculate the flow forces using a periodicity condition along the flow direction for a pipe with pinned boundary conditions. In their 'discontinuous' forcing model, they use a part of this flow force starting at one end and ending at a point before the other end of the pipe, and couple this force with the structure. This forcing model is equivalent to a cantilevered pipe with a new boundary condition for the flow at its exit (compared with the boundary conditions previously addressed in the literature), which, as expected, can result in flow-induced instabilities of the structure not previously observed. The structure's pinned-free boundary condition is also new, considering that previous cantilevered pipes had a clamped-free boundary condition for the structure. Although the boundary conditions are new, the most interesting results in the paper are the observations of the flow.

XiZTriCK show that even for the simplest pipe oscillations (planar periodic response at the pipe's second mode), the axial flow velocity changes across the cross-section and its pattern changes along the length of the pipe. They show that the flow pattern inside the pipe stays symmetric with respect to the plane of pipe oscillations, as long as the pipe undergoes planar periodic oscillations (the third plot from the left in the figure by the title). When the oscillations go out of plane, the changes in the flow velocity and vorticity along the length of the pipe and across the cross-section become even more dramatic (the last plot from the left in the figure by the title). This complicated flow pattern is accompanied by chaotic oscillations of the structure.

Some of the trajectories of the free end of the pipe are reminiscent of the fascinating trajectories that Copeland & Moon (1992) observed in their experiments on a very long pipe conveying fluid with a large mass attached to its free end. Francis Moon is known for his contribution to nonlinear dynamics. In his search for new routes to chaos, or rather for simple systems capable of undergoing various routes to chaos, he conducted a series of experiments on a long hanging flexible pipe, by adding different masses to its free end. He observed subcritical structural instabilities, quasiperiodic and period-doubling routes to chaos, as well as some fascinating trajectories of the free end. It took more than two decades for nonlinear models to reproduce what Copeland and Moon had observed experimentally (Modarres-Sadeghi & Païdoussis 2013). The trajectories of figure 8 in XiZTriCK's results are for a different set of parameters and different boundary conditions compared with Moon's results, but XiZTriCK also observe trajectories similar to what Copeland and Moon call 'Nutating Trajectories' (figure 1). These are very complicated dynamical responses to reproduce numerically, and these numerical results give access to the flow inside the pipe as it undergoes these trajectories.

3. Future

The results of XiZTriCK have shown us the flow inside an oscillating pipe. The literature on a pipe conveying fluid is very rich already, but our information about what the flow does inside the pipe has been limited. It is anticipated that the work by XiZTriCK will be followed by several other numerical simulations of the flow inside a pipe conveying fluid to understand the flow behaviour that accompanies the rich nonlinear dynamics of the structure. Numerical simulations can be conducted in the future to show us how the flow behaviour changes when we observe period-2, period-4, quasiperiodic or chaotic oscillations in a pipe. There are even simpler cases that deserve further investigation. Future simulations could characterise the flow during simple out-of-plane periodic oscillations of the pipe, instead of the chaotic

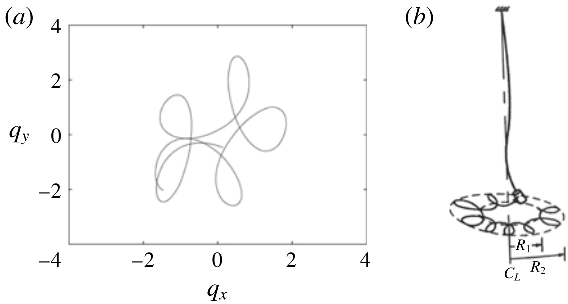

FIGURE 1. Free end trajectories observed by (*a*) XiZTriCK and (*b*) Copeland & Moon (1992).

out-of-plane oscillations that XiZTriCK observe. Will the flow remain symmetric with respect to a plane (similar to the planar oscillations) or will it yield chaotic responses, although the structure's response is a periodic one? Future simulations may also help to understand the relation between different structural responses and various types of flow instabilities inside the pipe. Moreover, they may provide a description of the flow during the transition from one type of structural response to another. They may also provide the flow behaviour inside the pipe in the Moon's problem and pinpoint how the different trajectories are related to different flow patterns. The future challenges will not be limited to the numerical methods. Can existing experimental techniques be used to quantify flow properties inside an oscillating pipe, and experimentally observe what XiZTriCK have observed? Another challenge is to extend XiZTriCK's results to other similar systems. A pipe conveying fluid is one example of axial flow problems – problems where the flow direction is parallel to the long axis of a flexible structure. Another, more practical example, with several applications is a flexible circular cylinder placed in external axial flow. Now that we have observed the flow inside a pipe, can we extend the approach to characterise the flow outside of a circular cylinder in axial flow? This has been done for the case where the flow makes an angle with the structure in vortex-induced vibrations of inclined cylinders (Bourguet & Triantafyllou 2015). But can we run DNS for flow around a cylinder in pure axial flow as it undergoes flow-induced instabilities? And can we relate all the flow-induced instabilities, flutter, quasiperiodic and chaotic oscillations that have been already observed in a flexible cylinder to different flow patterns around it? When this has been achieved, we may say that we have seen a flexible cylinder placed in axial flow, inside and out.

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