Flow-induced vibrations can lead to structural failure. It is mainly because of this reason it has been studied for the past century. Aeroelastic galloping or, to be more general fluid-elastic galloping, is one of the most common type of flow-induced vibrations in nature.

The classical incident of structural failure as a result of galloping was the collapse of the Tacoma Narrows bridge in November 7th 1940. Vibrations occurred due to galloping is another common phenomenon.

However, recently, the focus of study has been diverted to investigating the possibility of harvesting useful energy from galloping vibrations, where the investigation carried out by Barrero-Gil being one of the pioneering work in this filed.

Our research focus on looking at the energy transfer from the fluid to body at a fundamental level, which will lay the ground work to develop energy harvesting systems using fluid-elastic galloping.

Before elaborating further on our work, I would like to give a brief introduction on the mechanism of galloping and the Quasi-steady state hypothesis. Galloping, is described as a “velocity dependent damping controlled” phenomenon which occurs on a transversely oscillating body, immersed in a fluid flowing normal to the motion of the body. The vibration sustains from the forcing which occurs from the induced velocity crated as a result of the flow and the motion of the body.

In order to sustain galloping, this induced force also known as a negative damping should be in phase with the motion of the body. This can be explained using a square cross section as an example.

As you can see here, we have the free stream velocity U, the transgress velocity of the body y_dot U_i, which is the included velocity and theta which is the induced angle. As you can see U_i is the resultant of U and y_dot.

At a given point in time, the oscillating body creates an instantaneous induced velocity and an induced angle. What quasi-steady state hypothesis does is that it assumes that the transverse forcing in the moving body at a given instantaneous incident angle theta, is the same as the mean force on a static body at the same incident angle which can be seen here. Now, we can use static force data as inputs to predict response of the system. Parkinson and Smith produced an oscillator model based on this theory.

The instantaneous value of Cy was determined by an interpolating polynomial based on the lift force data for flow over a stationary body at various θ. As you can see in this equation there is a typical forced vibration system where the forcing is determined by a 7th order interpolation polynomial.

Power is expressed the product of force and velocity. In these two equation it is expressed in two different ways. One is the dissipated power due to the damping and the other is the work done on the body by the fluid. Both these quantities are the same when averaged since the net effect of mass and spring is zero because they are conservative forces.

As our study is on power transfer we were more focused on analysing the mean power and velocity amplitude data. What could be seen from literature was that the data was represented using classical vortex-induced vibration or (VIV) parameters, such as reduced velocity and the damping ratio. However, as I mentioned earlier “ galloping is a velocity dependent damping controlled phenomenon.”; and VIV is frequency dependent. Therefore the parameters associated with VIV are frequency based.

So, we formulated new non-dimensionalised parameters to obtain a better collapse for velocity and power, based on the natural time-scales of the system. First we linearised the quasi-steady state equation dropping all the higher order terms. Then the eigenvalues were obtained as you can see here, and after non dimensionlizing the quasi-steady state model we can say that it the response is a function of pi_1 and pi_2. Pi_1 is the combined mass-stiffness parameter and Pi_2 is the combined mass-damping parameter note that this is different form mass-damping in VIV which is m*zeta.

The data was obtained using QSS model and Direct numerical simulations for low Reynolds numbers. Some experiments were carried out at high Reynolds numbers.

Here the QSS data is presented in both classical VIV and our new parameters. You can see that Pi_2 produces a better collapse compared to U* for mean power and velocity amplitude.

The direct numerical simulations showed some interesting results. For power, the DNS results had a good agreement with the QSS model even at low Reynolds numbers for high Pi_1 values. We could also see that the mean power is a function of pi_1 and pi_2.

The flow-filed shows a clear wavelength of the wake as Pi_1 is increased. Qualitatively, this can be interpreted that at high Π1, the vortex shedding is simply superimposed over the path of motion of the cylinder. There is a decrease in amplitude at low Π1. This may be because of the higher levels of non-linear interaction between the vortex shedding and galloping.

From the DNS results, the error and the relative strength was turned out to be inverse functions of Pi_1. And we found relationships for both error and shedding strength. And we can see the influence of the vortex shedding at low Pi_1.

This leads to the question what is the frequency of the system?

In order to investigate this, the eigenvalues of the linearised system was re-written in terms of pi_1 and pi_2. While the term under the square root remains complex, the imaginary component could be used to define the frequency. Looking closely at the equation you could see that for a given value of pi_2 there will be a critical value of pi_1 below the square root becomes positive and no linear frequency is predicted.

The data shown here does not go to that extent as we could not obtain a clear galloping signal in DNS simulations. This is because as pi_1 is decreased significantly, galloping signal becomes weak and therefore vortex shedding over powers it. However, the discrepancy of between the frequency obtained by the linearised equation and the QSS model is minimum compared to the DNS data. But, we can say that it predicts the frequency well at high Pi_1. Note that here, f_input is the natural frequency of the system which is (1/2π)sqrt(k/m).

The frequency data in Pi_1 and Pi_2 space shows that the frequency response deviates from the natural frequency at low Pi_1 for both QSS and DNS data. However, the region where the system responds to the natural frequency is quite small in DNS data compared to QSS data. This can be mainly because of the non-linear interactions with the vortex shedding.

This non-linear interaction is well highlighted in the experiments done using light bodies. We could see a series of steps in the data. These steps are caused by nonlinear synchronisation between the galloping oscillation and an odd-integer multiple of the vortex shedding also known as phase locking.

In conclusion

Qss model could be used as a design tool to develop energy extraction devices.
Galloping response is a function of pi_1 and pi_2
The linearised equerry provides a reasonably good prediction of the frequency for the majority of pi_1.
The non-linear interaction between galloping and vortex shedding leaders to phase locking in experiments.