I would like to begin by thanking the examiners Prof. Young for taking the time and effort required read and asses this theses. As per the recommendations made by Prof: Young major revisions have been made in this revised submission.

Overall the shortcoming of the thesis pointed out by both examiners was the clarity of the presentation. Thus, most of the chapters were re-written to make the arguments more clear. Chapter 5 of the previous submission was merged with Chapter 4 of the same submission and re-written. The typographical errors have been fixed.

**Abstract**

“Mixing past and future … Language needs to be corrected throughout”

It is conceded that the writing of the previous version of this thesis was not satisfactory. The thesis has been extensively restructured and re-written. The language throughout has been improved in an effort to convey the ideas of the thesis as clearly as possible.

**Table of contents**

**Dedication**

**Nomenclature**

“Seems out of order - why are c\* and Cy not placed between c and D near the top of the nomenclature? Normal practice is to group all English, then all Greek, in their own alphabetic orders.”

The nomenclature was re-ordered in English and Greek alphabetical order.

**Chapter 1 – Preliminary Remarks**

“Vortex induced vibration (VIV) contrasted with fluid-elastic galloping. VIV is resonance when vortex shedding frequency aligns with structural natural frequency (lock-in). Does not sufficiently draw out the differences between VIV and FEG, reader would need to consult the quoted references to understand. If FEG is to be more fully explained later, this should be noted.”

It was noted in the preliminary remarks section of the thesis that FEG will be explained in the literature review section. The mechanism of FEG is fully explained in the Literature-review section. Kindly refer to page 3

“why does the fluid have to be Newtonian? ”

As a system under galloping abide the laws of Newtonian flows

“ When a bluff body moves along the transverse direction of the fluid flow, it generates a force along the transverse direction. This force, also known as the induced lift" - wouldn't this be drag, not lift? Do you mean a force normal to the transverse direction, not along it? ”

As illustrated in figure 2.1 the cross section under the influence of galloping generates a force perpendicular to the fluid flow. In order to generate this transverse force the body should be oscillating in the transverse direction of the fluid flow. For bodies under the influence of galloping this force is in the same direction as the transverse velocity. Here, the transverse direction is defined as the direction perpendicular to the direction of the flow.

“ When a bluff body moves along the transverse direction of the fluid flow, it generates a force along the transverse direction. This force, also known as the induced lift" - wouldn't this be drag, not lift? Do you mean a force normal to the transverse direction, not along it? ”

Taking the downward direction as positive means that a positive angle of attack is given by a clockwise rotation (pointing the front of the body “up”).

As illustrated in figure 2.1 the cross section under the influence of galloping generates a force perpendicular to the fluid flow. In order to generate this transverse force the body should be oscillating in the transverse direction of the fluid flow. For bodies under the influence of galloping this force is in the same direction as the transverse velocity. Therefore, for galloping to occur, pointing the front of the body up needs to produce a lift force down, which is the opposite direction to what would be expected for an airfoil – hence why airfoils are not susceptible to transverse galloping. Hence the downward direction is taken as positive.

p.7 Section 2.2.2: Jumps to a reference to Figure 2.2 with no explanation of what is being compared, why, and how the results were obtained. Needs to be made much clearer that this is a figure reproduced from Parkinson and Smith, for the purpose of showing that the quasi-steady model can achieve results close to experiments under certain conditions.

I thank the reviewer for identifying this error. The error was identified and an explanation for the results of Parkinson and Smith was added kindly refer to page 7

p.7: "...stationary Cy data (which consists of both lift and drag components)": this statement is difficult to understand, given that equation 2.1 is specifically modelling motion in the y direction only. Are lift and drag measured in directions that are normal and parallel to the free stream velocity, or to the instantaneous effective velocity experienced by the body? This needs to be made clear.

The Quasi-Steady State model assumes that the instantaneous induced lift force of the oscillating body is equal to that of the lift force generated by the same body when static at the same induced angle of attack.

Even though the body is moving transversely (in the y direction), The frame of reference changes as the lift force of the corresponding static condition is considered. Hence, Cy consists of both lift and drag data. An illustration of the forces in the static frame of reference is given below:

Macintosh HD:Users:kassa:research-3:research:thesis:chapter-literature-revirw:fnp:f_y-illustration.eps

p.7: How is the Cy data (which is to be interpolated) obtained? Equation 2.3 just creates a form of interpolating function, but does not define the data itself (i.e. how are coefficients a1 to a7 determined)? Use of the term "interpolating" is probably not appropriate here, this appears to be a 7th order polynomial curve fit to the data, which will not pass through every data point exactly (which the term "interpolating" implies).

The Cy data is obtained through simulations or experiments of the static body at incrementing angle of attack.

The term interpolation polynomial was changed to “Curve fit ” kindly refer to page

p.9: "vortex shedding will be correlated well": correlated with what? Do you mean well developed?

It is an established fact that the vortex shedding is correlated along the span at the laminar region. This was not clearly written the in initial submission and was corrected. Kindly refer to page 9 of the amended thesis.

“p.9: What is hysteresis in a galloping context? What is its significance, i.e. why should the reader be interested in whether or not hysteresis occurs? This sort of background must be explained in a thesis, not left as assumed knowledge as may be done in a journal article.”

Two outputs can be produced for the same input in the hysteresis region. Thus This fact is quite vital for energy harvesting as two values of energy levels can be present for the same reduced velocity. The reviewer is correct the lack of information of this section was identified and an explanation was added in the amended thesis please refer to page 10

p.11 Section 2.2.3 "Galloping is governed by the the shear layers created at the leading edge due to flow separation on the top and bottom corners of the bluff body." (note two "the" in the text): this sort of explanation of the phenomenon should be up front in Chapter 1, not buried down in the literature survey. How is this different from VIV, which is also governed by the shear layers leading the formation and shedding of an alternating vortex wake?

VIV and galloping are both governed by the shear layers. However, VIV sustains through an alternating shedding of the shear layers where galloping is sustained through the difference of proximity of the mean shear layers to the body occurred when the body is in motion.

“ this sort of explanation of the phenomenon should be up front in Chapter 1” Justin I need some help answering this if I change the order of the thesis the flow will mess up.

“p.11 Figure 2.4: is this based on your own results (if so how were they obtained), or is it extracted from the literature (in which case it should be referenced)? If these are your own results, then they are out of place as you have not yet described your methodology, they belong somewhere other than in the literature survey.”

The illustrations which now has been to contours of shear strain rate magnitude, was used for illustration purposes to show the wall jets created in the leading edge of the body, to present the reader a better understanding on how the shear layer behave.

The author was compelled to do so as similar illustrations could not be found in the literature.

p.12 Section 2.2.4 "It is clear that the cyclic motion of the shear layer harmonize with the mechanical system.": Under what conditions is this statement true? For all flows, body shapes, Reynolds numbers, structural parameters? Just the ones shown in Figures 2.3 and 2.4? This needs to be explained.

Galloping is occur when the transverse forcing Fy is in phase (in the same direction) with the motion of the body. The transverse force is generated through the proximity of the shear layers to the body. The proximity of the shear layers alternates the in harmony with the motion of the body. Thus for any system under galloping the cyclic motion of the shear layer has to be in harmony with the mechanical system of the body.

The statement is changed to “It is clear that the cyclic motion of the shear layer will harmonize with the mechanical system of a body under the influence of galloping.”

Figure 2.5: reproduced from Paidoussis (2010), but with different terminology to that used here - CFy instead of Cy, alpha instead of theta (presumably), should be explained in the caption.

The reviewer is correct. This shortcoming was identified and an explanation is added in the caption of the figure in the amended thesis (figure 2.6, page 8)

Section 2.2.6: The findings of the two main references cited here (Barrero-Gil, Vicente-Ludlam) are not discussed in sufficient detail.

An explanation is added to mitigate this shortcoming in section 2.17 in the amended thesis kindly refer to page

p.16: "equation 3.1" possible misprint, should be "equation 2.1"? If so, I cannot see how this equation could be used to draw conclusions about delayed shear layer reattachment. If not, it is not appropriate to use an equation that has not yet been seen by the reader as justification for an objective of the thesis, it must have been discussed in the introduction or literature survey.

The reviewer is correct. This equation reference was incorrect and has been fixed please refer page 46

**Chapter 1 and 2 overall comments:**

These two chapters do not adequately set the scene for the remainder of the thesis, as they do not fully explain the background to the project and galloping to a reader unfamiliar with the phenomenon. Rather it is discussed piecemeal. For example, Figure 2.5 appears to give the criterion under which galloping can be expected (dCFy/dalpha > 0) for a range of shapes, yet this criterion is not mentioned or explained in the text in Chapters 1 or 2. The objectives (Phase 1) use parameters (damping ratio, reduced velocity) that have not yet been introduced in the literature survey, so a case that their use for fluid-elastic galloping is not appropriate, cannot possibly have been made.

The author thank the reviewer for pointing the shortcomings of the two chapters. Overall as the reviewer has pointed out main shortcoming of these two chapters was the inadequacy of explanation and necessary corrections have been made.

The criterion dCFy/dalpha > 0 was explained as this explanation was lacking in the initial submission (refer page 15 and 16). An introduction to the classical governing parameters has been added (page 13 and 14). A sketch of the shear layers have been added (figure 2.4 page 12) for better illustration of a galloping system.

**Chapter 3 - Methodology and Validation**

“p.18: Re = 200 was selected for the low Re regime, based on the 3-dimensional transition in the wake of a square cross section being at Re = 160. This implies that the flow regime being studied is 3-dimensional, but on p.17 the statement is made that the low Re range was intended to be where the flow was laminar and 2-dimensional (at least that is what I assume, see previous comment). These two statements seem to be contradictory.”

The author agree with the comment from the reviewer; an clearer explanation is needed here. The following explanation was added in the amended thesis.

“Leontini et al. (2007) concluded that the oscillation of the bluff body essentially stabilizes the wake, for example the the limit of three-dimensional transition of an oscillating circular cylinder can be as high as Re = 280, compared to the transition Reynolds number of Re ≃ 190 for a stationary cylinder. As the essential flow physics such as the formation of the Karman vortex street is common for both a circular and square bluff body, it can be assumed that the wake is also stabilised for oscillating square cross sections. Thus, Re = 200 was selected as the Reynolds number for the “low” Reynolds number region as a compromise between keeping the flow strictly two-dimensional, and providing a high enough lift to generate vigorous galloping.”

p.18: Parameters such as Re, mass ratio and U\* are chosen to be the same as previous works in the literature, but what are the physical justifications for these parameter choices? Why did these previous authors choose these parameter values?

Considering previous studies (Robertson et al., 2003; Joly et al., 2012) m∗ was kept at m∗ = 20 which was a level of inertia not so high as to suppress galloping and not so low for vortex shedding to dominate and weaken galloping as observed by Joly et al. (2012). The reduced velocity U∗ was kept U∗ ≥ 40 to keep the natural frequency of the system far from the frequency of vortex shedding to ensure that the primary mode of flow-induced vibration was galloping as opposed to vortex-induced vibration (VIV).

The above explanation was added in the amended thesis kindly refer to page 23

p.21: "and the dynamic by" should be "and the dynamic viscosity by", "velocity vector filed" should be "velocity vector field" (this error is made multiple times in the following paragraphs).

The author thanks the reviewer for pointing out this error. The error has been corrected.

p.24: "The velocity of the cylinder is in advance by half a time-step of the position of the cylinder", and "However, both the cylinder positions and velocities are located at the same discrete times". I'm not sure I understand what these two sentences are saying, as they seem to be contradictory.”

The sentence has been removed as it created unnecessary confusion. (Justin need some help here)

“p.24 Eqn 3.13: What is N in this equation? It is not in the nomenclature, or in the text prior to the equation. Same question for Eqn 3.16.”

N is the non-linear convection term in the NavierStokes equations. The reviewer correct this term was not mentioned in the nomenclature or prior to the equation and the term was added in the nomenclature.

Section 3.4.2 Convection substep: the entire process described here would benefit from a graphic showing the various steps.

An illustration of the sub-steps was added to gain a clear picture of the numerical scheme in section 3.4.2 kindly refer to page 28.

p.28 onwards: "could be" probably better replaced by "may be" or "can be", which does not have the implication of speculation. This change should be made throughout the thesis.

The author thank the reviewer for brining this error to notice and it is rectified in the amended thesis.

“p.31: Neumann boundary condition applied for velocity at the downstream exit, assumes flow does not spatially evolve while exiting the domain. It has been noted that this is not true for a vortex wake generated aft of a bluff body where there is significant spatial and temporal evolution, but that low Re and distant boundaries ameliorate the problem. Do you have any evidence or literature references to support this statement? While I am confident that the values used (20D upstream and laterally, 60D downstream) for domain are sufficient, I would like to see some verification in the form of a domain size variation study to back it up with evidence.”

The author agrees with the reviewer Although the physical validity of the outlet boundary condition is not quite true, this does not turn out to be a significant problem provided that the domain outflow is sufficiently far away from the body.

Leontini and Thompson (2013) was used as the numerical domain in the present study where the trailing part of the domain was increased to capture the long wave lengths associated with the low flow frequencies of galloping. This selection was done for two reasons. The first reason was that both Leontini and Thompson (2013) and the present study were carried out using the same numerical solving code. The second reason was that the cross sections used in both studies are similar. Thus, further optimisation of the domain need not be carried out as Leontini and Thompson (2013) has already shown this domain to be adequate for this class of flows.

The explanation was not provided in the initial submission and it is added in section 3.4.3 of the amended thesis kindly refer to page 38.

“p.32 Convergence: this section aims to establish the grid independence of solutions, however only p convergence has been conducted, not h-p convergence as discussed earlier in the text. How did varying the spatial refinement of the grid vary the results? What evidence do you have that you have adequately captured the details of the shear layer both spatially and temporally, given the importance of predicting the separation point and subsequent formation and evolution of vortices convecting into the wake? The time step is reduced in conjunction with increasing order p to keep the Courant number low (a numerical stability criterion), but what evidence do you have that this time step is small enough to capture the temporal flow physics? Overall the validation section seems rather cursory.”

The author apologizes for clearly mentioning this point in the initial submission. As mentioned earlier the current domain and the special and temporal parameters were obtained from Leontini and Thompson (2013). Thus, in that study it was established the domain size was adequate. However, what the author has tried for the current study is to obtain a converged value for the average velocity amplitude. This fact is quite vital as the velocity directly affects the mean power and a difference of less than 1% was achieved for both mean velocity amplitude of the body and galloping frequency using these spatial and temporal parameters.

The author agree with the reviewer more DNS simulations should be carried out however, as galloping is a low frequency phenomenon, a longer time is taken to achieve the steady oscillating state. Furthermore, as galloping is dependent on the initial excitation of the flow, the initial development of galloping takes a significant amount of time. Both of these factors result in long computation times ranging from 1 to 2 weeks or more.

These explanations have been added in the amended thesis kindly refer to pages 38-41.

**Chapter 4 - Governing Parameters of Fluid-Elastic Galloping**

Figure 4.1: Cy data here is time-averaged, given that the flow is unsteady (oscillatory) even for a stationary body. What are the implications of this?

Quasi-steady state model assumes instantaneous induced lift force of the oscillating body is equal to that of the lift force generated by the same body when static at the same induced angle of attack. Thus, stationary Cy data are used as the inputs for the QSS model. …..

p.40: "It is assumed that the stiffness plays a minor role" Explain why.

Galloping signals are low frequency signals therefore has long time periods which essentially results in a low value of the spring stiffness. Therefore, it can be assumed that stiffness is low.

p.42: Argument presented in Section 4.3.1 seems somewhat simplistic to say that PI\_1 "does not have a significant influence on the behaviour of the system". The amplitude of the oscillation A/D has not collapsed against PI\_2 in the same way the velocity and power have, in Figure 4.2, but this seems to have been glossed over in the discussion in the text.

The displacement amplitude does collapse with a scaling parameter consists of both PI\_1 and PI\_2. This scaling parameter essentially reduces to the inverse of the damping ratio. The comment by the reviewer’s was taken into account and the discussion regarding amplitude of the system has been added in 4.13 (refer page 49).

p.43: "An example case is presented in Figure 4.2", do you mean Figure 4.3?

The reviewer is correct. The error was corrected.

p.45 Figure 4.5: This figure plots Pd and Pt. Neither of these quantities have been described in the text in any manner before this figure, just in the nomenclature. How are they calculated? Both of these should be explained in the background.

The author thanks the reviewer for pointing out this shortcoming. The explanation regarding Pt and Pd were added kindly refer to page 51 of the amended thesis.

p.47 Figure 4.6: Caption states that "mass ratio does not have an effect on PI\_1 even at low PI\_1". Do you mean does not have an effect on the power Pm?

The reviewer is correct. The corrections has been made to figure 4.7 in the amended thesis (refer page 55).

p.51: Regarding figure 4.10 and the associated discussion, it might be worthwhile adding another figure plotting Cy and its spectrum, to draw out the difference between the occurrence of vortex shedding (shown in the Cy plots) versus the influence it has on the body (shown in the V/U plots) as the mass ratio increases. Figure 4.10 caption should explain terms fg and fs

The plots of Cy and its spectrums were added taking the reviewer’s comment (refer page 61). This figure also clearly shows how the influence of vortex shedding decreases as PI\_1 increases.

The captions were also amended explaining fg and fs (figure 4.11 page 60) which are the galloping and vortex shedding frequencies respectively.

p.51: "relative intensity of the component at the vortex shedding frequency to the component at the galloping frequency" - firstly what do you mean by "experimentally" shown? Is this based on experimental data, or on your DNS data? Secondly, use of the word "component" is confusing here - this implies a component of a force or other vector, I suggest rewording to make clearer.

The word “experimentally” was an error it has to be corrected to “explicitly”. The phrase "relative intensity of the component at the vortex shedding frequency to the component at the galloping frequency" was changed to “relative contribution of vortex shedding in the galloping system” to imply the influence of the vortex shedding in the galloping system. (page 62)

p.53 Figure 4.11: I am not completely convinced that you have plotted what the vertical axis says, i.e. the relative power of the vortex shedding, as power is force by velocity and the force has not entered into the calculations here, just the velocity (see previous comment regarding Figure 4.10). However this figure does seem to show convincingly that the behaviour of the error in Figure 4.9 is closely matched by the behaviour of the quantity plotted here, i.e. as the motion of the body shows increasing high frequency motion on top of the low frequency galloping, the error increaes.

The author agrees with the reviewer the term “relative power” is not suitable in this context. Thus, the phrase was to changed to “relative contribution of vortex shedding” which is essentially the ratio between the intensity of the vortex shedding frequency and the intensity of the galloping frequency in the power spectrum plot. (refer page 62)

p.53: "The relative strength of the vortex shedding" - again, I believe it is not the strength of the vortex shedding that you are referring to here, but rather the strength of the response of the body to that vortex shedding.

The reviewer is correct. The sentence reworded “magnitude of any vortex shedding correction term that might be added to the QSS model in an effort to decrease the discrepancy between it and the DNS simulations.” Kindly refer page 62

p.53: "Though it is unequivocal" - I think you mean "not unequivocal"?

The author is correct. The error was corrected.

p.54 Figure 4.12: are vorticity levels non-dimensionalised? If so how? This figure serves to show that vortex shedding is just as prevalent at PI\_1 = 1000 as it is at PI\_1 = 10, reinforcing the previous comments that what you have plotted in Figure 4.10 with V/U time histories is not the strength of the vortex shedding itself, but the response of the body to that shedding.

The vorticty levels are non dimensionalised using (Justin I need the parameters). The reviewer is correct. Indeed, V/U time histories is not the strength of the vortex shedding itself, but the response of the body to that shedding. This figure gives an indication of the influence of vortex shedding on a galloping system as PI\_1 is varied.

**Chapter 5 - Frequency Response of the System**

As the reviewer has pointed out this chapter was very short. Essentially the frequency study was carried out to study the influence of PI\_1 and PI\_2 on the galloping frequency. Thus, the data and the analysis of this chapter was merged with the chapter “**Governing Parameters of Fluid-Elastic Galloping”**

As the reviewer has also pointed out, the analysis of this section was not adequate. Thus, a clearer presentation of data and discussion was added.

The major objective of this section was to investigate the influence of PI\_1 and PI\_2 on the galloping frequency. Thus an expression was obtained for the frequency in terms of PI\_1 and PI\_2. The frequency data obtained using the QSS model, linear frequency and DNS simulations were compared.

Kindly refer to pages 64-73 for the results and discussion of this section.