Dynamics of Continuous, Discrete and Impulsive Systems
Series **B:** *Applications & Algorithms* **14 (S8) (2007)** 111-124

A FEEDBACK CONTROL SCHEME OF FLOW-INDUCED VIBRATION FROM A HIGH-FREQUENCY PERTURBATION APPROACH

W. Wu, J. Yuan, L. Cheng*

Department of Mechanical Engineering,
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
*Corresponding author: mmlcheng@polyu.edu.hk

Abstract. This research work presents a feedback control scheme to suppress Flow-Induced Vibration (FIV). The design rationale is based on the study of a simple and phenomenological model, which is usually used in the literature to describe the behavior of FIV. It is predicted that high-frequency perturbation can be used to increase the damping of the wake model, which may consequently suppress wake and then structural vibration. Experimental results have shown the validation of the idea. As a result, in order to control FIV effectively, a multi-high-frequency perturbation controller is proposed by using an active resonator and a hard limiter from a closed-loop control view point.
Keywords. flow-induced vibration, closed-loop control, phenomenological model

1 Introduction

Due to its significant relevance to engineering applications, Flow-Induced Vibration (FIV) has aroused lots of public attention and become an important research topic for many decades. For example, it is involved in the design of high-rising buildings in civil engineering, the design of aircrafts and space shuttles in aerospace engineering, and the design of heat-exchanger tubes in thermodynamic engineering. A great number of research results on the fundamental characteristics of FIV have been reported, which can be found from a series of comprehensive reviews [18, 3, 6, 22]. Furthermore, regarding the control technique to suppress FIV, active control methods are usually adopted in the literature on account of its effective applicability. Acoustic excitation [17, 12, 15] and oscillating cylinder [4, 21, 10] are two typical methods for active flow control. Recently, a novel perturbation technique using embedded piezoelectric actuators for elastically mounted cylinder is introduced by [7], which is able to decouple the interaction between flow and structure.

For a conventional controller design, a dynamic model is needed in order to find a stable and effective solution. In fluid dynamics, the most common approach is Navier-Stokes (N-S) equations with a moving structure as the boundary condition. There are some analytical works on the control problems with regard to this approach [2, 8, 16, 1]. However, to obtain the full solution for the N-S equations, it is still a painstaking and compensating computational task, which is not suitable for real-time control purpose. Another popular approach is to search for a simple but representative model for FIV phenomenon [18]. A phenomenological model based on the van der pol oscillator idea [5] is adopted. The model was firstly introduced by [11] to represent the wake oscillator. Many researchers have improved this approach in different ways [20, 13, 19, 14, 9]. Unfortunately, due to the difficulty of identifying all unknown properties of FIV, all available models are designed with the qualitative approach. Therefore, it is really a challenge to employ available models for practical real-time control purpose.

This research work presents a controller design idea from the study of the above phenomenological model in the literature. We concentrate on the high-frequency perturbation effects on the characteristics of FIV, such as wake and structural velocities. The controller is developed by using the control technique in [7]. The organization of this work can be divided into two stages. For the first stage, section 2 introduces the phenomenological model and presents our design conjecture for FIV. Then, suitable experiment is conducted for the validation of the conjecture. For the second stage, after verifying the design idea, in order to give a more effective control method, section 3 gives the composition of proposed controller, called multi-high-frequency perturbation method, by using an active resonator and a hard limiter. Throughout the paper, the main control purpose is to suppress wake vortex and structure vibration in the *lock-in* regime, in which case the vortex shedding frequency coincides with the structure natural frequency and vibration amplitude is usually amplified.

2 Phenomenological Model

In this section, a typical model to represent FIV is introduced briefly. We look for the key characteristics in the model and make the initial prediction on the direction of controller design. After that, suitable experiment is conducted to verify the prediction. It should be noticed that the controller only depends on the qualitative information of the model without the knowledge of the exact model parameters since the model is a phenomenological one. For this reason, only experimental validation is adopted here rather than numerical simulations.

Let us consider a typical 1-dof elastically mounted rigid cylinder with diameter D and length l. The cylinder is restricted to oscillate transversely to the uniform and stationary flow with free stream velocity U as shown in Figure 1.

2.1 Nonlinear damping term

The phenomenological model is a double oscillator model to describe FIV, which consists of a structure oscillator $y(t)$ for cylinder transverse motion

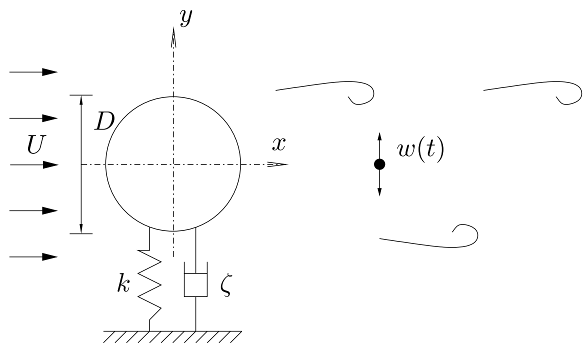


Figure 1: Model of cylinder vibration and wake oscillator for FIV

and a wake oscillator $w(t)$ for vortex shedding. The equation of structure oscillator can be written as

$$m_0(\ddot{y} + 2\zeta\omega_0\dot{y} + \omega_0^2 y) = \frac{1}{2}\rho U^2 C_L D l \tag{1}$$

where m_0 is the sum of cylinder mass and added fluid mass, ζ is the damping ratio, ω_0 is the undamped natural frequency of cylinder, ρ is the fluid mass density and C_L is the nondimensional lift coefficient of the fluid flow around the cylinder. For the wake oscillator, all available phenomenological models use a van der pol equation with a nonlinear damping term to describe the self-sustainable fluid oscillation. There are different modeling approaches in the literature. Here, we adopt the simplest form from [14]. The model is written as

$$m_f\left[\ddot{w} - 2\zeta_f\omega_s\left(1 - \frac{w^2 + \dot{w}^2/\omega_s^2}{w_0^2}\right)\dot{w} + \omega_s^2 w\right] = -\frac{1}{2}\rho U^2 F_C D l \tag{2}$$

where F_C is the force term imposed by cylinder, m_f is the equivalent mass of wake oscillator, which is proportional to the fluid mass density ρ and the structure characteristic volume $D^2 l$, ζ_f is the damping ratio, ω_s is the vortex shedding frequency expressed in terms of $2\pi StU/D$ with St as the Strouhal number. In the vibration interval $(0, w_0)$, the damping term is negative to excite wake oscillation, and outside $(0, w_0)$ it is positive. The reason for choosing this damping model will be discussed in the next section, which is related to the controller design.

The coupling format of these two oscillators is also an intensively discussed topic. For equation (1) and (2), C_L and F_C are usually regarded as coupling candidates in the literature. The substantial research is based on how to choose the combinations of $\{w, \dot{w}, \ddot{w}\}$ or $\{y, \dot{y}, \ddot{y}\}$ to represent C_L and F_C respectively [11, 14, 9]. While in this paper, we concentrate on controller design for FIV by using only qualitative information in the model. Therefore, the coupling effects are left open in this study.

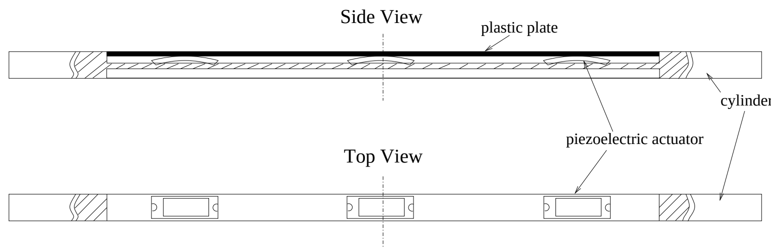


Figure 2: The layout of control technique [7]

2.2 High-frequency perturbation effect

After the brief introduction of the phenomenological model, we try to design the controller based on an experimental study. Consider the control technique developed in [7] as shown in Figure 2. A local perturbation effect p is imposed on the flow around the cylinder by the excitation of a movable plastic plate driven by embedded piezoelectric actuators. Suppose p causes a sinusoidal vibration component at frequency ω_p to the wake oscillation signal $w(t) = A_p sin(\omega_p t)$. Obviously, it should also affect the FIV model given by (1) and (2). Due to the fact that coupling mechanism is still not clear, we only consider the perturbation effect on the damping term in the wake oscillator. Due to the perturbation, the damping term becomes

$$2\zeta_f \omega_s \left(\frac{A_p^2 \omega_s^2 sin^2 \omega_p t + A_p^2 \omega_p^2 cos^2 \omega_p t}{w_0^2 \omega_s^2} - 1 \right) \tag{3}$$

with values between $2\zeta_f \omega_s \frac{A_p^2 \omega_s^2 - w_0^2 \omega_s^2}{w_0^2 \omega_s^2}$ and $2\zeta_f \omega_s \frac{A_p^2 \omega_p^2 - w_0^2 \omega_s^2}{w_0^2 \omega_s^2}$. One key point is that if perturbation frequency ω_p is much higher than vortex shedding frequency ω_s, the maximum damping value of wake oscillator will be larger. This helps us make the following conjecture.

Conjecture 2.1 *Assume that the flow-induced vibration can be described by a phenomenological model given by equation (1) and (2). If a control scheme helps to increase the frequency of wake oscillation in the local flow around structure, then this scheme will help to suppress vortex shedding in the wake.*

To avoid using ambiguous findings in formulating a suitable numerical simulation for the verification of this conjecture, we prefer to conduct an experiment for the validation. The systematic block diagram is shown in Figure 4 for an active controller based on the perturbation technique in Figure 2. An open-loop control is implemented by using sinusoidal signals with a fixed amplitude but different frequencies. The results are monitored by a laser vibrometer for structure vibration and a hotwire for wake vortex shedding, which are shown in Figure 3. The flow condition is set at the FIV lock-in regime, where $\omega_s \approx \omega_0$. Define the dimensionless frequency as St_f, the

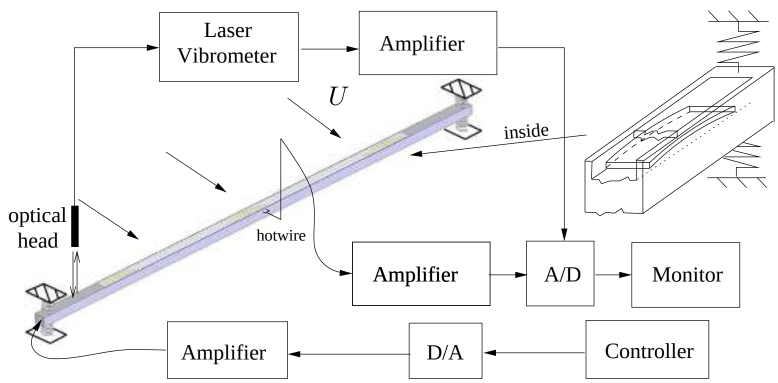


Figure 3: Open-loop control experiment setup

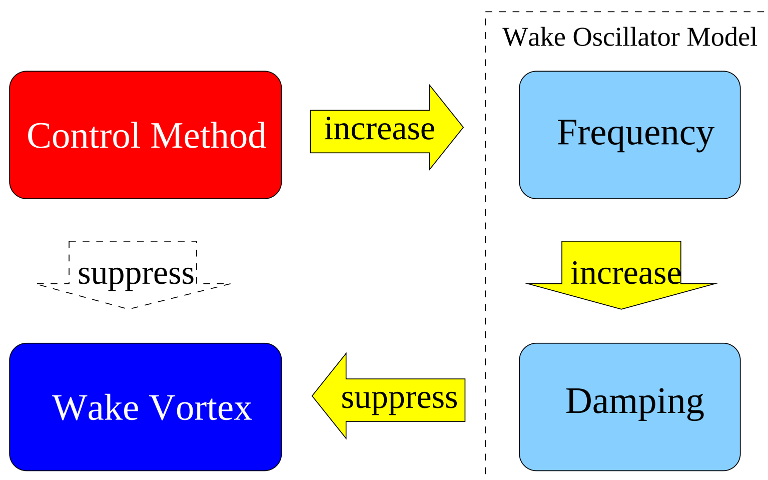


Figure 4: Systematic block diagram of Conjecture 2.1

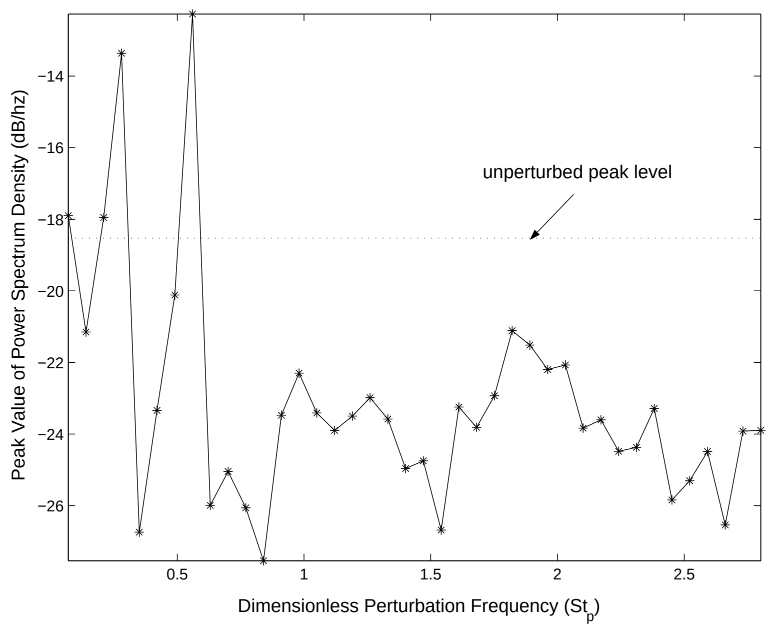


Figure 5: Peak value of power spectrum density of wake velocity ($St_p \in [0.07, 2.8]$)

dimensionless shedding frequency as $St_s \approx 0.13$, and the dimensionless perturbation frequency as $St_p = f_p D/U$. In the experiment, power spectrum densities (PSD) of wake velocity signals are obtained under different perturbation frequencies $St_p \in [0.07, 2.80]$. These signals are plotted in Figure 5. It is found that for $St_p \geq 0.7$, the peak level of PSD drops significantly and the overall peak level in this St_p region is much lower than that in the region of $St_p < 0.7$. Besides the peak level, the rms reduction value of signals between controlled and non-controlled cases is also plotted as in Figure 6 to assess the overall control effect. As for wake velocity reduction, the rms reduction level for $St_p \geq 0.7$ is higher than the rms reduction level for smaller St_p. The experimental results matches the description of Conjecture 2.1.

This phenomenon also agrees with other findings in flow control using acoustic excitation. It is found as in [12, 15] that effective perturbation frequency range for acoustic excitation is related to shear-layer instability frequency that is of higher order than vortex shedding frequency and dependent on Reynolds number [17]. When St_p is in the order of 1, as mentioned in [12], another 'lock-in' phenomenon occurs. The instability waves are amplified, and momentum transport and flow mixing are enhanced, which affects wake characteristics significantly when compared to no perturbation condition. In our investigation, the phenomenological model also agrees with this point. In addition, considering the frequency effect of perturbation p on structure

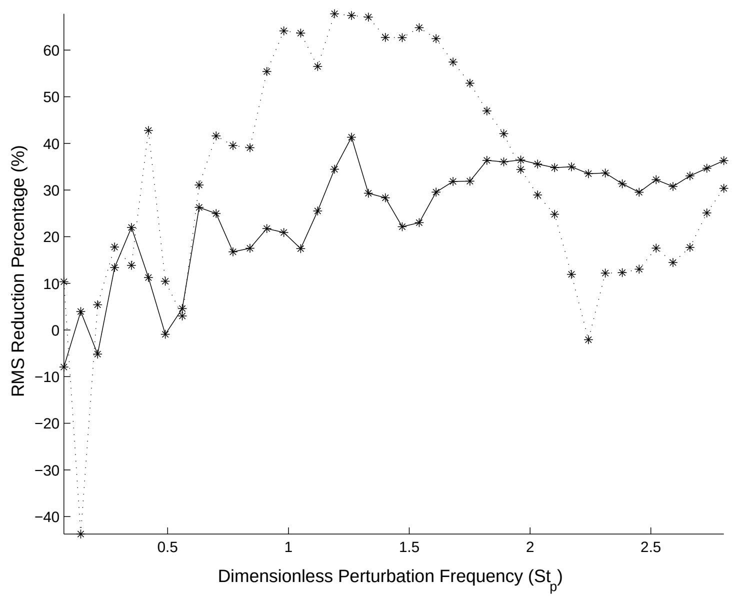


Figure 6: RMS reduction values (percentage): structure velocity and wake velocity ('- -' structure velocity, '—' wake velocity)

vibration, higher frequency results in more energy imposed on the structure in the same time interval. Therefore, the control of FIV must be balanced between counteracting flow energy on structure by increasing damping and imposing perturbation energy on structure by increasing frequency. Indeed, in Figure 6, there is an optimal frequency region $St_p \in [0.5, 2]$, where both wake and structure velocity have considerable reduction. This finding of high frequency perturbation effect gives one possible control design direction for controlling FIV based on the phenomenological model.

3 Controller Design

After studying the high-frequency perturbation effect on the phenomenological model, we now apply the finding to the controller design. One merit of high frequency control is that since St_p is far away from the lock-in regime, the perturbation phase can be neglected. It is also known that closed-loop control method provides more satisfactory performance than suppressing FIV with open-loop [23]. In this section, we introduce a closed-loop control method by using the structural vibration velocity as the feedback signal as shown in Figure 7. There can also be other control approaches for the model-independent problem, such as variable structure method and active resonator method. However, in this research work, we aim at introducing

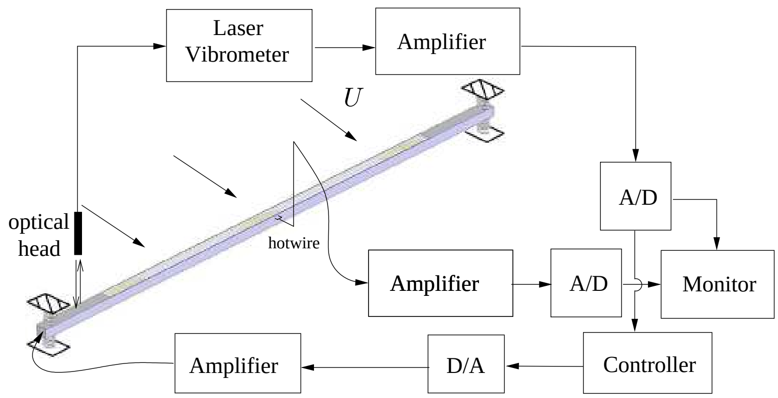


Figure 7: Closed-loop control experiment setup

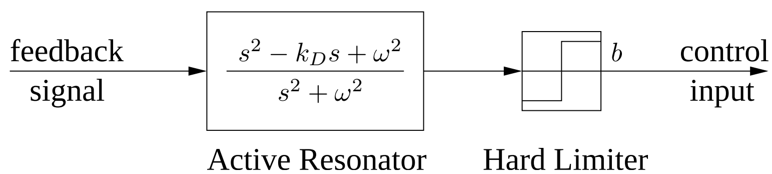


Figure 8: Promoted control method: multi-high-frequency perturbation

the new design approach by using a phenomenological model rather than comparing the results among different methods. Here, we only present the design procedure for our proposed controller.

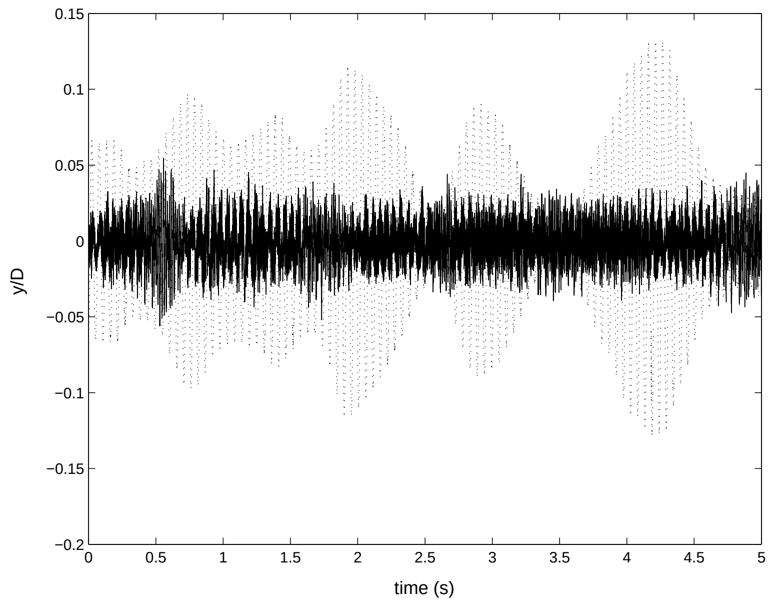
3.1 Multi-high-frequency perturbation method

Recalling the results in Figure 6, there is an optimal perturbation frequency region $St_p \in [0.5, 2]$. An active resonator with an optimal frequency St_p should be adopted. However, considering the limitations of active resonator in closed-loop feedback control for FIV, the negative damping term has to be used to provide a 'limit-cycle' behavior of the controller. This is also reasonable by analyzing the phenomenological model. In the wake oscillator, a nonlinear damping term is used to allow self-sustainable oscillation in the FIV model system. As a result, a similar measure to allow self-sustainable oscillation in the controller should be applied so that the controller can counteract FIV continuously. Furthermore, in order to prevent the controller input diverging due to negative damping, a hard limiter should also be added before feeding control input. In practice, it is possible to use a low-frequency resonator, which actually produces multi-high-frequency perturbation signals when integrated with a hard limiter. The proposed control method is shown in Figure 8.

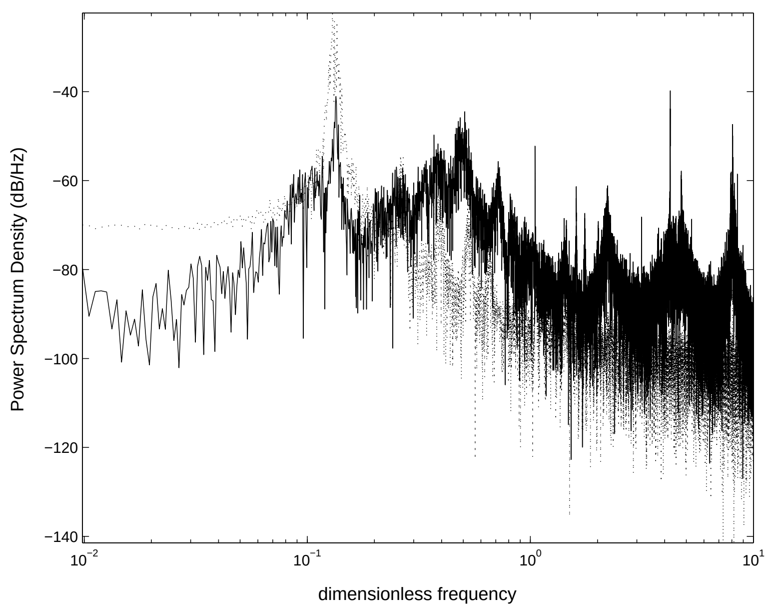
3.2 Controller performance

By now, a novel controller has been found with the aid of the phenomenological model as a design guide. Moreover, together with the pre-design study, this controller verifies Conjecture 2.1 derived from the model study. As shown in Figure 8, k_D denotes the damping term of the controller, St_ω is the normalized resonator frequency ω and b provides control output bound. There has been no systematic parameter tuning included in the present work. However, studies on the control effect of individual parameters showed an effective range for each parameter. We choose a typical parameter set $(k_D, St_\omega, b) = (3500, 0.02, 0.095)$ as an example. Each parameter is in its effective region obtained during the individual parameter analysis. However, we must notice that this simple combination may not provide the optimal control performance, since three parameters need to be considered together during an iterative tuning procedure. Nevertheless, this example has revealed most characteristics about control effectiveness of the proposed controller. Figure 9 gives experimental results of structure vibration. Clearly, in Figure 9(b), there are multi-high-frequency responses around the region $St_p \in [0.5, 2]$, which has been considered as optimal perturbation frequency region in Figure 6. Furthermore, considering Equation (3) for the wake oscillator damping term, if $\omega_p = \omega_s$, which means perturbation frequency is equal to shedding frequency, then this damping term will be $\frac{A_p^2}{w_0^2} - 1$. If perturbation amplitude A_p is moderately small, then $\frac{A_p^2}{w_0^2} < 1$ gives a negative damping term in all situations. This will increase wake oscillation, which also agrees with experimental analysis about St_p around St_s in [7].

A simple analysis of control effect on the flow field is provided. The flow field is measured using Particle Image Velocimetry (PIV). Figure 10 shows the main setup. Generally, particles in the fluid are illuminated by a sheet of laser, which is pulsed twice. The particles scatter light into a photographic lens of camera located at 90$^\diamond$ to the sheet, so that its in-focus object plane coincides with the illuminated slice of fluid. Images are formed on the video array, which are then postprocessed by the computer. Mostly, we use a kind of paraffin oil from shell, which will be vaporized and then, mixed with air flow. As for the data postprocessing of the flow wake field, the calculating method of vortex circulation detailed as in [23] is used. A comparison between controlled and uncontrolled cases is based on the instantaneous results of PIV. Contours of spanwise vorticity for controlled and uncontrolled cases are shown in Figure 11 and 12 respectively. A comparison between the two figures shows a clear reduction of the overall level, leading to a reduction of about 25% in the vortex circulation. Therefore, this method is possible to suppress both FIV and vortex shedding simultaneously.



(a) time domain response



(b) power spectrum density

Figure 9: Experimental results of structure vibration by no control and proposed control ('- -' no control, '—' proposed control)

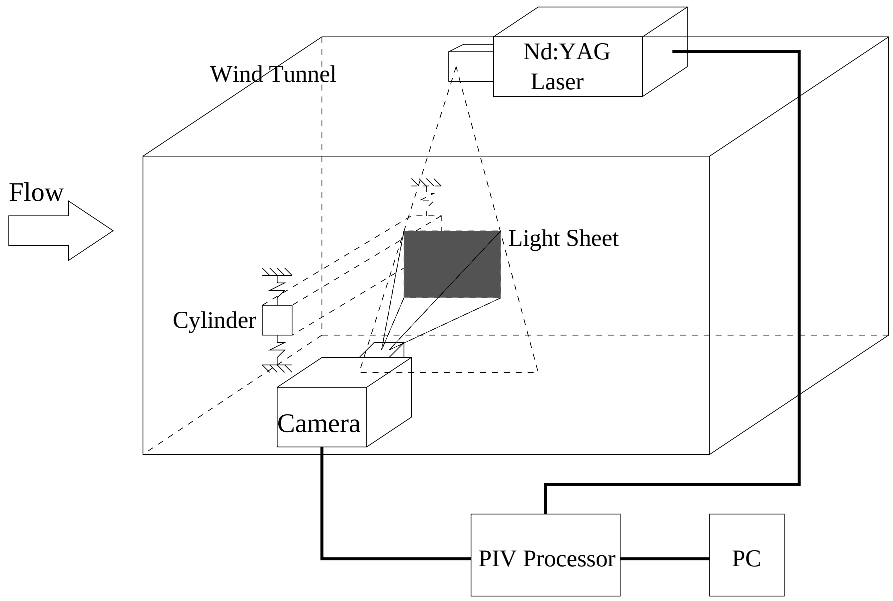


Figure 10: Experimental setup for PIV measurement

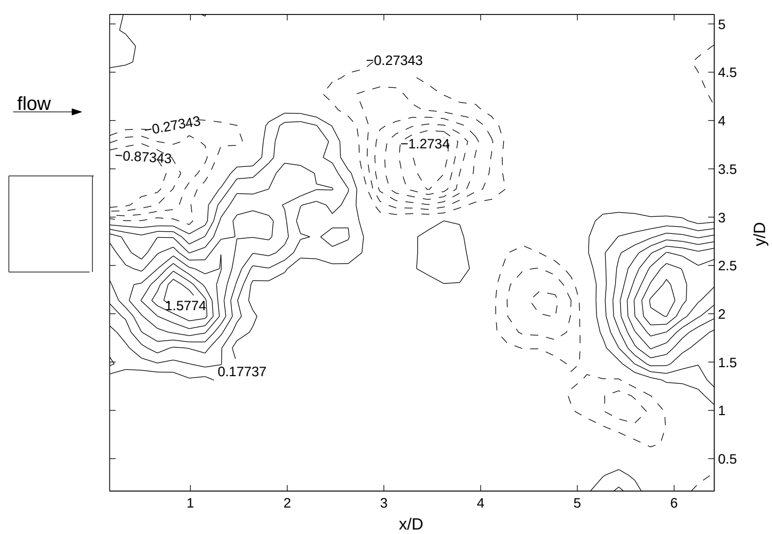


Figure 11: Contour of spanwise vorticity from PIV measurement: with multi-high-frequency perturbation method, '—' positive, '- -' negative

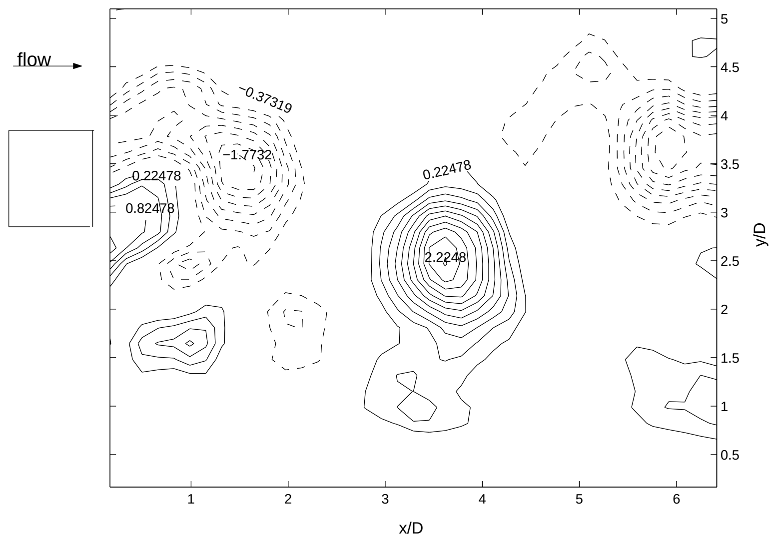


Figure 12: Contour of spanwise vorticity from PIV measurement: without control, '—' positive, '- -' negative

4 Conclusion

In this research work, a new approach for the control of Flow-Induced Vibration (FIV) is introduced. It employs the damping property of a phenomenological model of FIV in the literature to increase damping of the vortex by generating high-frequency perturbation. The experimental results validate the design idea. As a result, a multi-high-frequency perturbation method is proposed in order to suppress FIV effectively by using an active resonator and a hard limiter. This study is the first attempt to link available qualitatively developed model of FIV with its controller design and experiment has shown satisfactory control results.

5 Acknowledgments

The authors wish to acknowledge support given to them by the Research Grants Committee of The HKSAR(Grant No. PolyU 1/02C and 5294/03E). Also, W.Wu would like to acknowledge the Research Studentship awarded to him by The Hong Kong Polytechnic University.

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