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Virtual damper–spring system for VIV experiments and hydrokinetic energy conversion

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ABSTRACT

A device/system V_{CK} is built to replace the physical damper/springs of the VIVACE Converter with virtual elements. VIVACE harnesses hydrokinetic energy of currents by converting mechanical energy of cylinders in Vortex Induced Vibrations (VIV) into electricity. V_{CK} enables conducting high number of model tests rapidly as damping/springs are set by software rather than hardware. V_{CK} consists of a cylinder, a belt–pulley transmission, a motor/generator, and a controller. The controller provides a damper–spring force feedback using displacement/velocity measurements, thus introducing no artificial force–displacement phase lag, which biases energy conversion. Damping is nonlinear, particularly away from the system natural frequency, and affects modeling near the VIV synchronization ends. System identification (SI) in air reveals nonlinear viscous damping, static and dynamic friction. Hysteresis, occurring in the zero velocity limit, is modeled by a nonlinear dynamic damping model Linear Autoregression with Nonlinear Static model (LARNOS). SI performed in air is verified using monochromatic excitation in air and VIV tests in water using physical damper and springs. A resistor bank added to the device provides an integrated V_{CK}/Power Take-Off (PTO) system. VIV testing is performed in the Low Turbulence Free Surface Water Channel of the University of Michigan at $40{,}000 < Re < 120{,}000$ and damping $0 < \zeta < 0.16$.

1. Introduction

The phenomenon of Vortex-Induced Vibration (VIV) was first observed by Leonardo daVinci in 1504 and the underlying vortex shedding mechanism was described by Lord Rayleigh in 1878. Nevertheless, till recently, no attempt was made to enhance this potentially catastrophic phenomenon to harness energy. In 2005, Bernitsas and Raghavan invented (Bernitsas et al., 2006/2008, 2006/2009; Bernitsas and Raghavan, 2009) and in 2009 patented (Bernitsas and Raghavan, 2007, 2009) the VIVACE Converter, which utilizes VIV, galloping and other forms of Flow Undiced Motions (FIM) to generate power from ocean/river currents. The VIVACE Converter is scalable from compact devices generating a few Watts to underwater farms generating hundreds of MW. The requirements for high performance in the marine environment include: (i) operating in the high-lift regimes TrSL3 and TrBL0 ($20{,}000 < Re < 300{,}000$) (Zdravkovich, 1990) where VIV response is maximum, (ii) maintaining high VIV response at high damping needed for energy harnessing. The first VIVACE Converter models used physical springs and dampers, and a generator to convert hydrokinetic energy to mechanical and subsequently electrical energy. Due to hardware limitations, harnessed power of the early VIVACE Converter was optimized only in limited ranges of spring stiffness and damping ratio. This limitation is overcome in this paper by building a virtual damper/spring (V_{CK}) system using a motor-controller feedback system. Such system enables conducting high number of model tests quickly as damping and springs are set by software rather than hardware.

The first VIV testing device named Virtual Cable Testing Apparatus (VCTA) was built and upgraded by Hover et al. (1997, 1998). VCTA combines force-feedback control with real-time numerical simulation of a structure model (Hover et al., 1997, 1998). Even though VCTA is the first VIV testing device which enables to replace physical mass, damper and spring with virtual ones, it causes an additional phase lag of 12° (Hover et al., 1997) or 5° (Hover et al., 1998), respectively, to the cylinder displacement with respect to the actual oscillating cylinder in VIV with real springs. This phase lag is due to filtering of noisy measured fluid force signal, which is fundamentally inevitable for the cylinder position control in the non-yielding water environment. The induced artificial phase lag would bias energy conversion (Bernitsas et al., 2006/2008) since work is the product of force by displacement. The V_{CK} system designed and built in this paper

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provides damper–spring forces based on displacement and velocity feedback, thus introducing no additional phase lag.

In order to design a controller for the VIVACE V_{CK} device, proper damping model selection and accurate system identification need to be performed in advance. Digital controller design and damping model identification have been studied extensively (Karnopp, 1985; Kubo et al., 1986; Ogata, 1995; Franklin et al., 1997; Xiros, 2002) providing useful information for developing the present system. Following system identification, the system inherent damping is compensated (subtracted) and pure linear viscous damping is added ensuring an accurate mechanical model for damping. Similarly, a linear spring model is introduced though any mathematical model can be introduced.

2. Modeling of the virtual damper–spring system

Fig. 1 shows a figure of the lab scale model of the V_{CK} VIVACE Converter. The V_{CK} VIVACE model consists of the components listed in Table 1. The motor generates virtual spring and damping torque using the angle and angular velocity measurements while the vortex shedding force is exerted on the cylinder. The rotational motion of the motor is converted to a linear motion by the timing-belt, which connects the two pulleys. The moving part consisting of the cylinder and its support struts, is connected to the timing-belt, and oscillates along the shafts driven by the motor. An idler is used to reduce excessive vibration of the timing-belt by providing force in the longitudinal direction of the timing-belt. Also, a coupling is used between the upper pulley and motor shaft. When excessive torque is applied, it slips to protect the motor.

Fig. 1. Lab scale model of V_{CK} VIVACE.

Table 1
Components of the V_{CK} VIVACE model.

Cylinder diameter D [in, cm]	3.5/8.99
Cylinder length L [in, cm]	36/91.44
Mass of oscillating components [kg]	8.88
Pulley radius [cm]	4.9

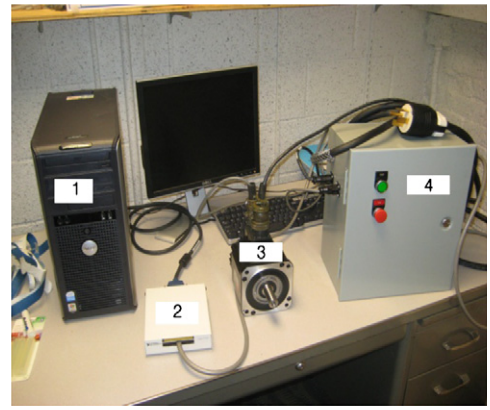

Fig. 2. Motor controller system.

Table 2
Descriptions of the motor-controller system.

Part no.	Description
1	Controller board embedded in computer (National Instruments: NI-7340)
2	Universal Motion Interface (National Instruments: UMI-7764)
3	Motor+embedded encorder (Sanyo Denki: P60B13150HXS00M)
4	Servo drive (Sanyo Denki: QS1A05AA)

Table 3
Particulars of the motor.

Rotor inertia [kg m^2]	8.28×10^{-4}
Rated torque [N m]	7.5
Max. stall torque [N m]	20

Fig. 2 shows the digital controller-motor system for the V_{CK} VIVACE model. Details of the four labeled components are listed in Table 2.

The V_{CK} VIVACE model is powered by the 200 VAC 3-phase servo-motor listed in Table 2. Particulars of the motor are presented in Table 3.

The embedded encoder inside the motor is a quadrature type optical encoder. It provides the angle and angular velocity of the motor, which are used for feedback control. In this application, one revolution of the motor corresponds to 2000 encoder counts. Communication and control are achieved by means of the NI-7340 controller connected to a Microsoft Windows based PC. The controller is programmed using LabView and loaded on the NI-7340 for closed-loop operation. In this application, NI-7340 samples data every 5 ms. The servo drive QS1A05AA is connected to the controller board through the Universal Motion Interface UMI-7764. The servo drive operates in torque-command mode and receives a command signal from the controller, amplifies the signal, and manipulates the electric current to a servo-motor in order to produce motion proportional to the command signal.

2.1. Mathematical model

A SolidWorks drawing for the physical modeling of the V_{CK} VIVACE device is shown in Fig. 3 and the description of each component is summarized in Table 4.