Synchronization for the Flow Control of a High Lift System

Robert Bruce Alstrom[1], Goodarz Ahmadi[2], Erik Bollt[3], Pier Marzocca[4]

Clarkson University, Potsdam, New York 13699-5725

EXTENDED ABSTRACT

Synchronization can be defined as in-time correlated behaviour between processes. The design of a double-array of directed synthetic jet actuators (DSJAs) for an actuated NACA 0015 wing section with flap is used. We believe that the mechanism of synchronization is the key to why periodic excitation of an aerodynamic flow is effective. The *control objective is to reattach a separated flow*; as such it is necessary to design a control law that exploits the nonlinear behaviour in the flow. Further, the application of nonlinear signal analysis will illustrate the mechanism of synchronization in the flow when it is under open and closed loop control.

A NUMERICAL DEMONSTRATION OF SYNCHRONIZATION

There are many different types of synchronization such as complete synchronization, lag synchronization, generalized synchronization, phase and imperfect synchronization. With respect to active flow control, phase synchronization or frequency locking is of interest. Self-sustained oscillators that are external driven by a periodic forcing function exhibit frequency locking. Similarly, a *fluid system* is a weakly coupled nonlinear system that when forced by a periodic or unsteady excitation results in a re-organization of the flow structures present in the fluid system hence the relevance of synchronization to active flow control. A typical boundary layer attached to a lifting surface possesses frequency scales or instabilities/frequency receptivity that can be exploited to affect the manipulation of the boundary layer. Experimental work has shown aerodynamic fluid flow to be sensitive to the magnitude of the forcing amplitude and the input frequency. The best way to understand the concept of synchronization is to perform a simple numerical experiment. To facilitate this we will now introduce the well known Rossler oscillator. The Rossler oscillator is the simplest chaotic system with continuous time, because it has a single second order nonlinear term, *zx* in its equations. The Rossler oscillator also exhibits strong phase coherence. The Rossler oscillator equations are given as follows:

$$\dot{x} = -\Omega y - z + F(t)$$

$$\dot{y} = \Omega x + ay + F(t) \qquad [1]$$

$$\dot{z} = b + z(x - c) + F(t)$$

where $\Omega = 1, a = b = 0.2 \; and \; c = 5.7$. These parameters yield a Rossler oscillator in a chaotic regime. In the physics literature there are two main methods for inducing synchronization; they are external forcing via a coupling with another nonlinear dynamical system and open loop

[1] Graduate Student, Department of Mechanical and Aeronautical Engineering, AIAA Senior Member
[2] Professor, Department of Mechanical and Aeronautical Engineering
[3] Professor, Department of Mathematics and Computer Science
[4] Associate Professor, Department of Mechanical and Aeronautical Engineering, AIAA Senior Member

periodic forcing. Since we are interested in the effects of closed loop excitation of fluid systems, we will use a simple method given by Pyragas. Pyragas presents work on time continuous self controllers [3]. The results show that for a relatively small feedback gain, stabilization of an unstable periodic orbit can be achieved. Pyragas makes reference to a 'periodic external force of special form'. The special form that Pyragas discusses is of the form:

$$F(t) = k[y_i(t) - y(t)] \qquad [2]$$

The term $y_i(t)$ is the desired periodic orbit and the constant k is known in the dynamical systems literature as a coupling constant and in the control systems community it is a proportional gain. The second term $y(t)$, is a state from the system that is feedback. The specific control law for this numerical experiment will be of the form given in Equation 2.2 and can be written as follows:

$$F(t) = k[\sin(2\pi f_F\, t) - y] \qquad [3]$$

The resulting closed loop equation is given as follows:

$$\dot{x} = f(\mu)\mu + B + gu \qquad [4]$$

where

$$f(x) = \begin{bmatrix} 0 & -(\Omega + k) & -1 \\ \Omega & a + k & 0 \\ z & -k & x - c \end{bmatrix}$$

$$B = [0 \quad 0 \quad b]^T$$

$$g = [1 \quad 1 \quad 1]^T$$

$$\mu = [x \quad y \quad z]^T$$

$$u = k\sin(2\pi f_f\, t)$$

Note the uncontrolled oscillator dynamics in Figures 2 and 3. The results show that when the frequency held constant at some multiple of the natural frequency of the system and the forcing amplitude is gradually increased, the system frequencies re-distribute themselves in order to match the input frequency (Figure 4). If the forcing amplitude is fixed and the input frequency is increased, again, all other modes are attenuated and the system frequencies re-align to match the input frequency, which is 0.34 Hz in this instance (Figure 5). When the system frequency matches the input/forcing frequency, this is called synchronization; that is when $\hat{X}\,(\tau_F) \gg \hat{X}(\omega)$ if $\tau_F \epsilon\, [\tau - \epsilon, \tau + \epsilon]$ with $\omega \neq [\tau - \epsilon, \tau + \epsilon]$, $\tau_F = 2\pi f_f$. In the context of active flow control, the reorganized flow dynamics leads to suppression of vortex shedding which reduces the amplitude of the pressure fluctuations.

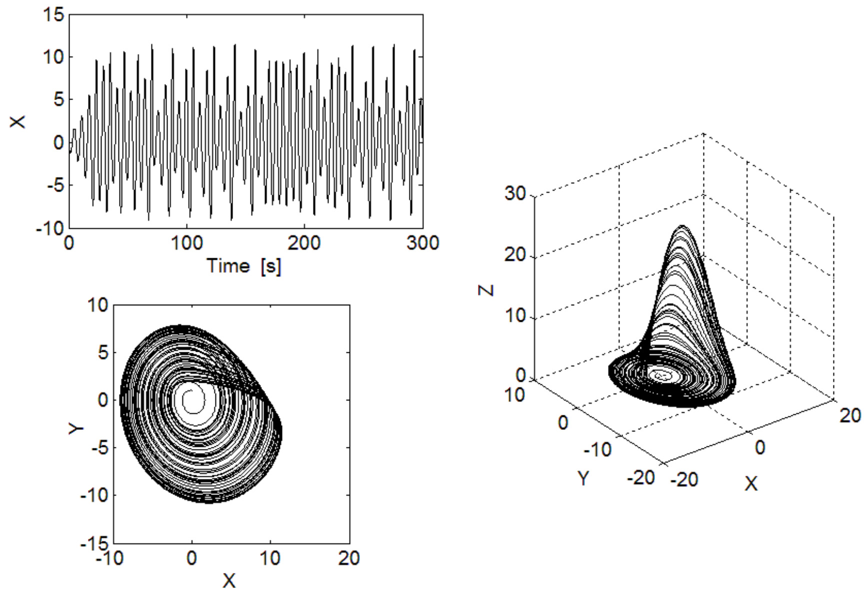

Figure 2 Open Loop dynamics of Rossler Attractor

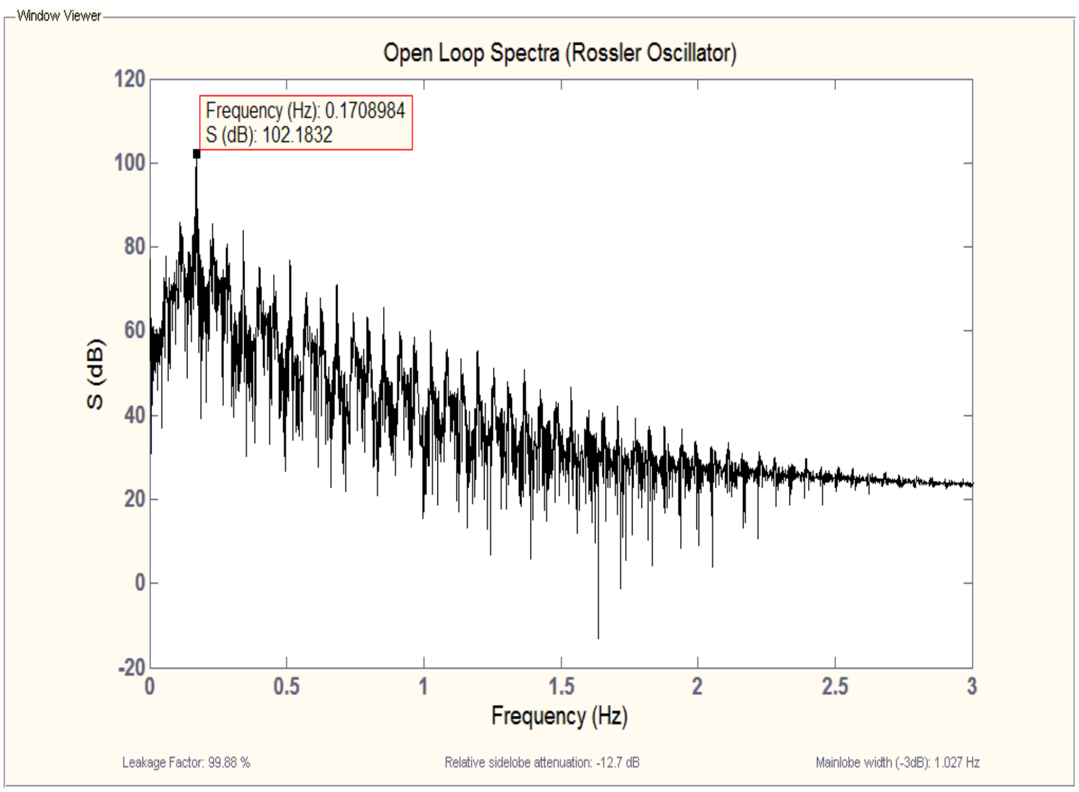

Figure 3 Open Loop Spectra for the Rossler Attractor

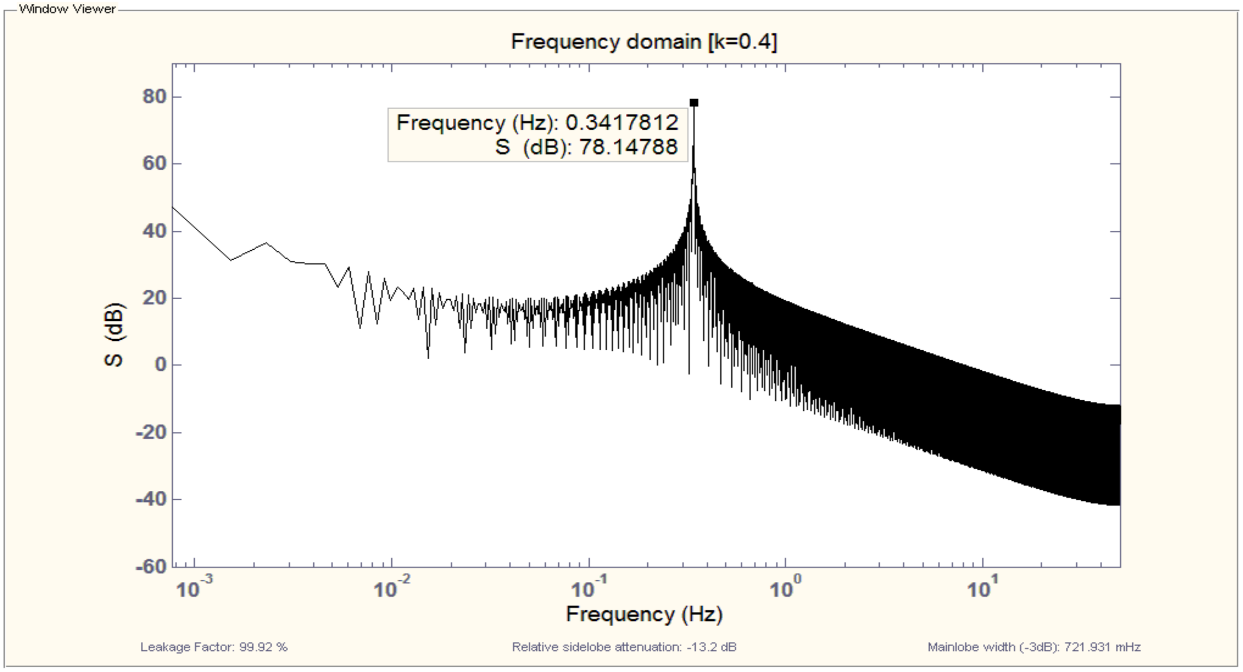

Figure 4 Spectra for increased amplitude and fixed input frequency

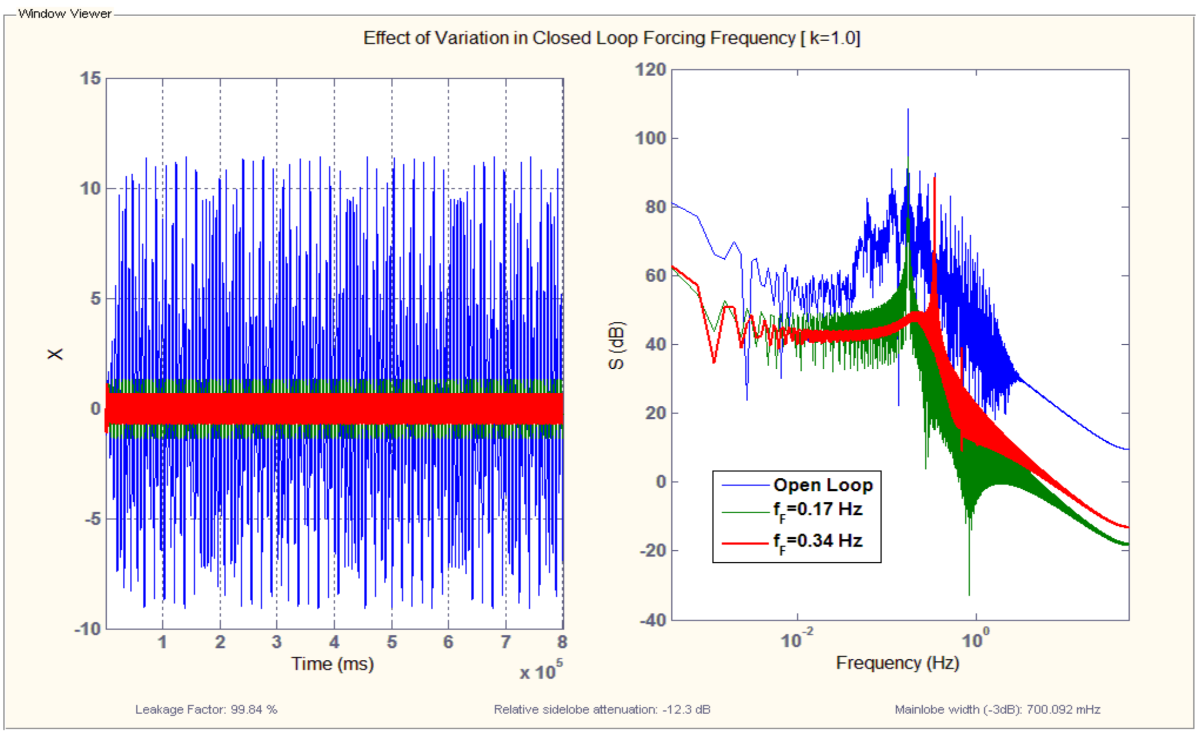

Figure 5 Spectra for increased frequency and fixed forcing amplitude

EXPERIMENTAL STUDY

A wind tunnel experiment demonstrating active flow control (both open and closed loop) of the NACA 0015 high lift system using a dSPACE 1103 ACE Kit is performed. Closed loop control of the high lift system is accomplished using extremum seeking control [4]. Because the NACA 0015 High Lift system experiences turbulence induced vibration due to flow separation, the investigation includes analyzing the effect of active flow control strategies, using synthetic jet actuators, in altering the structural dynamic response of the wing. Pressure, Force balance and accelerometer data is used to investigate the flow physics (Figure 7 and Figure 8) and the nonlinear relationship between the aerodynamics and structural dynamic responses of the airfoil. As indicated previous, the mechanism synchronization will be examined via nonlinear signal processing techniques. The experimental configuration is given in the schematic below (Figure 6). Figures 7 and 8 show the spectra for pressure and lift at 5 m/s, at 12 degrees angle of attack. These spectra, for example are used in the determination of the frequency region of receptivity and to correlate the behavior of the flow on the surface of wing, the force balance and the accelerometer spectra by identifying similar frequency features. This information is also used to help tune the controller parameters and any filters that maybe employed in the closed loop control of the wing.

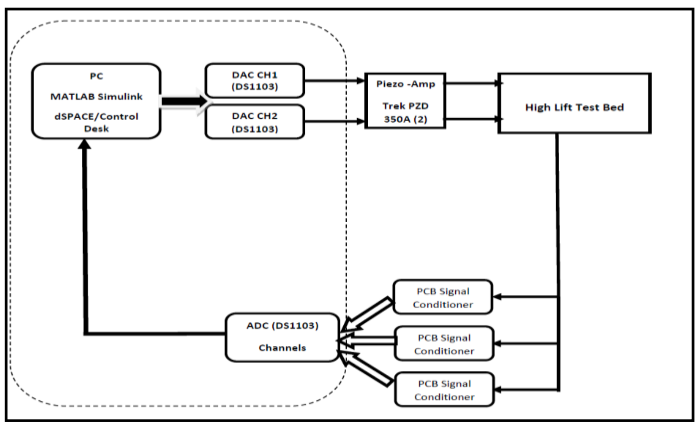

Figure 6 Wind Tunnel Experimental Configuration

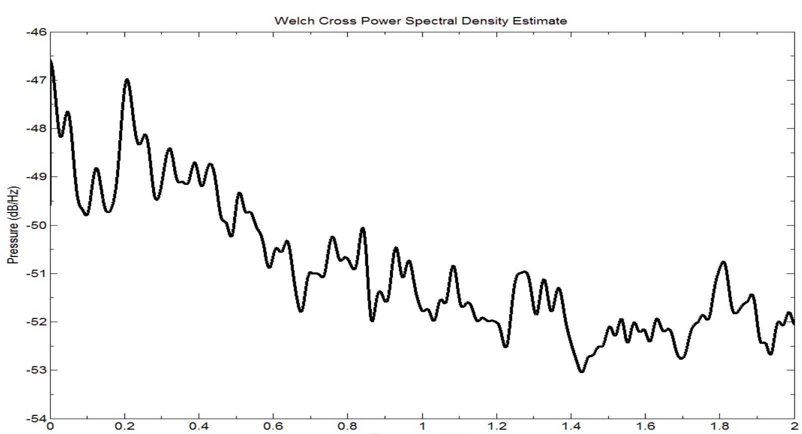

Figure 7 Pressure spectra from leading edge transducer [U= 5 m/s, α=12^{o}]

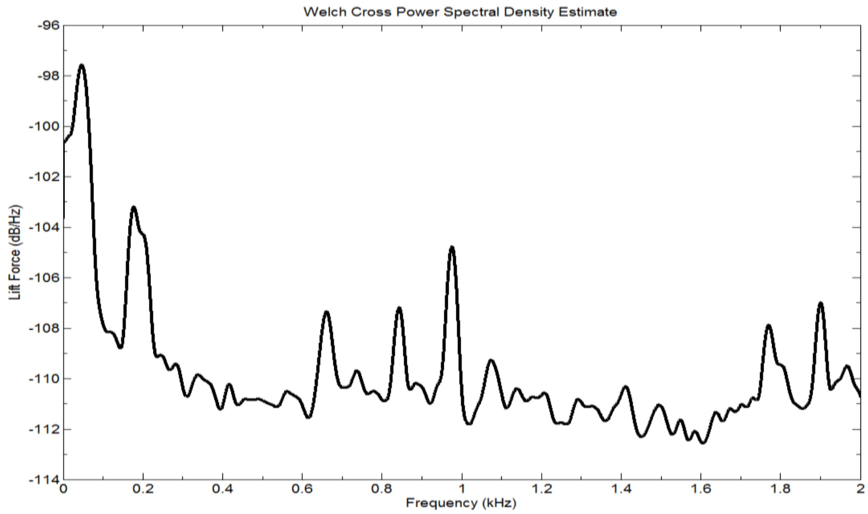

Figure 8 Lift spectra [U= 5 m/s, α=12^o]

REFERENCES

1. Pyragas, K., "Continuous control of chaos by self-controlling feedback", Physics Letters A 170 (1992), pp 421-428
2. Taira, Kunihiko, Rowley, Clarence W., "Feedback Control of High-Lift State for A Low-Aspect Ratio Wing", 48th AIAA Aerospace Sciences Meeting, 4-7 January 2010, Orland FL, AIAA-2010-357.
3. Joe, W., Taira, K., Colonius, T., MacMynowski, D., and Tadmor, G., "Closed-Loop Control of Vortex Shedding on a Two-Dimensional Flat-Plate Airfoil at a Low Reynolds Number", AIAA Paper, 2008-634, 2008.
4. Krstic, Miroslav, Wang, Hsin-Hsiung, "Stability of extremum seeking feedback for general nonlinear dynamic systems", Automatica, Vol. 36, pages 595-601, 2000