Implementation of an Active Noise Control Loop to an Aerofoil in a Turbulent Air Stream

Prasertsak Tiawongsombat[1], Thomas Carolus[1], Claus-Peter Fritzen[2], Wolfgang Richter[2]

Universität Siegen, Fachbereich Maschinenbau, 57068 Siegen, Deutschland
[1] Institut für Fluid- und Thermodynamik, Email: ptiawongsombat@hotmail.com
[2] Institut für Mechanik und Regelungstechnik - Mechatronik

Abstract

Acoustic noise from axial turbo machinery originates from unsteady forces on the blades. To minimize the noise, these unsteady forces have to be decreased. In the frame work of a larger project the concept of an active blade movement has been studied in order to compensate for the noise mechanism "ingested turbulence". A first feasibility study was carried out with a single *NACA 0012* aerofoil. To simulate the unsteadiness of the incoming air the aerofoil was placed in a very low turbulence air stream but moved by a shaker in transversal direction. The resulting unsteady aerodynamic pressures on the aerofoil surface were measured and used as feedback signals to a controller which subsequently drove a second (voice coil) actuator to move the aerofoil in a way that the measured pressure signal fluctuations were minimized. As a result the unsteady aerodynamic pressures on the aerofoil surface could be reduced considerably. Unexpected harmonics were probably created from the control signal whose frequencies accidentally happened to be at the eigenfrequencies of the system.

Introduction

The idea of this work is focused on a new active regulation for the noise reduction of axial turbo machinery. Although in some applications the reduction of noise can be done employing secondary measures (e.g. mufflers), the problems upon spacing, high costs and pressure loss are not desirable. Thus a procedure for noise reduction is being developed by taking an advantage in the sense of *Active Noise Control* working directly at the acoustic source (e.g. fan blades) so that the plant characteristic is not affected. The first feasibility study was carried out with a single *NACA 0012* aerofoil. To simulate the unsteadiness of an incoming air the aerofoil was placed in an air stream of a very low turbulence wind tunnel and moved by a shaker in transversal direction to simulate the incoming turbulence [1]. The resulting unsteady aerodynamic pressures on the aerofoil surface were measured employing *Kulite* miniature pressure transducers. These pressure signals were used as feedback signals to a controller which subsequently drove a second (voice coil) actuator to move the aerofoil in a way that the measured pressure signal fluctuations were minimized. Fig. 1 shows the principal experimental layout.

Controller implementation

Identification and modeling. In a first step the dynamics of the system (aerofoil, support, actuators, pressure sensor, etc.) are identified in order to determine a *mathematical model* which represents the *dynamics* of the system, cp. [2], [3]. Various possible models with different orders and structures have to be evaluated comparing characteristics employing e.g *Bode* plots, *cross validation*, etc.

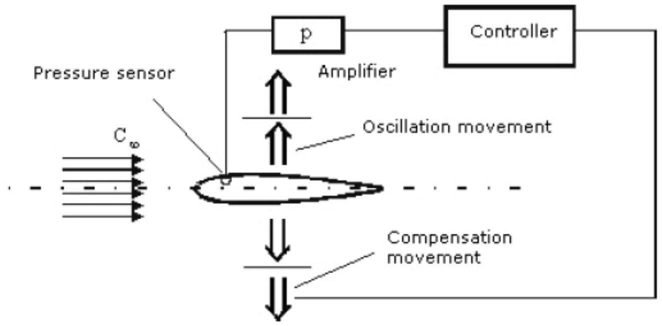

Fig. 1: Active Noise Control principle with simulated turbulent air stream

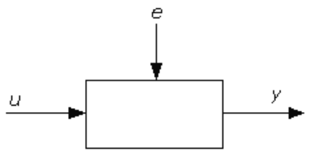

Fig. 2: Input Signal *u*, Output Signals *y* and Disturbance *e*

The root locus method. The root locuses are actually the locations of all possible closed-loop poles. From the root locus one can select a gain such that a closed-loop system can perform in a wanted way.

LQG estimation. LQG control is a modern state-space technique for designing optimal dynamic regulators. It takes into account both process disturbances and measurement noise. The optimal control solution is provided by the *Kalman filter* and the control is the *Linear Quadratic Regulator* (LQR), but of the best state estimate. Thus the LQG solution is often called "state estimation" as shown in Fig. 3.

Anti-windup. Referring to [4], it states that very basic nonlinearities of simple control loops are *saturations* on the control variable *u(t)*. They are due to the working range of the actuator which is always bounded by physical reasons to a low and high limit.

$$u = \mathrm{SAT}(u_{lin}) = \begin{cases} u_{low} \text{ if } u_{lin} < u_{low} \\ u_{lin} \text{ if } u_{low} \le u_{lin} \le u_{high} \\ u_{high} \text{ if } u_{lin} > u_{high} \end{cases} \tag{1}$$

The input constraint situation, where input refers to the plant, (i.e. the system to be controlled) is depicted in Fig. 4.

Trains of impulses, *chirp signals*, *sawtooth signals* and *sine waves* were employed in dSPACE & MATLAB/Simulink as identification signals. The obtained models were validated and analysed. The chosen models then were transformed into a continuous-time model in state-space representation. Two approaches, *classical control PI* and *LQG controller,* have been implemented in the control.

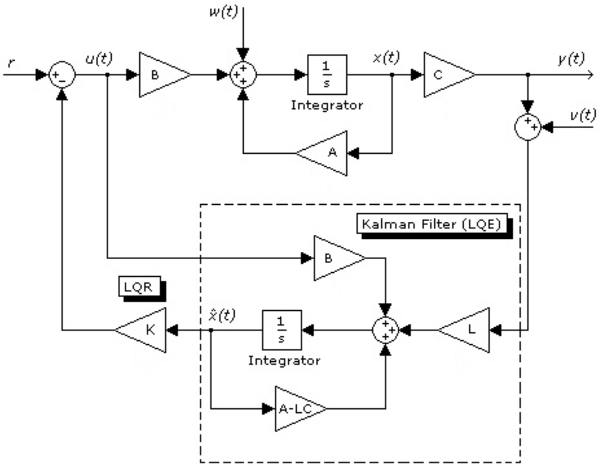

Fig. 3: Linear Quadratic Gaussian Control (LQG)

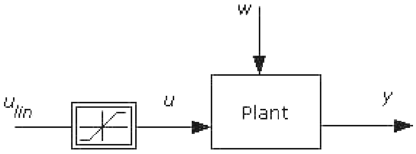

Fig. 4: Control system with "input" saturation

Test results

The LQG controller seems to be the better solution and has shown the better control capability and expected results.

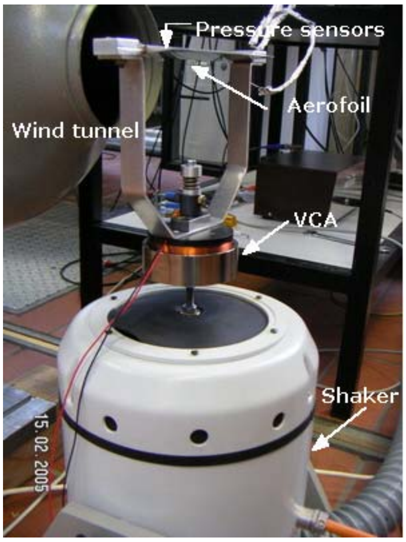

Fig. 5: Experimental setup with the second actuator (Voice control actuator, VCA) and the aerofoil mounted on the shaker

The tests were made with colored process noise in a frequency range between 50 to 100 Hz. Fig. 6 illustrates a comparison between open- and closed-loop control in the frequency domain for one of the test results, with an optimized feedback gain *K*. Fig. 7 shows a time domain test result of a fixed frequency sine wave as process noise.

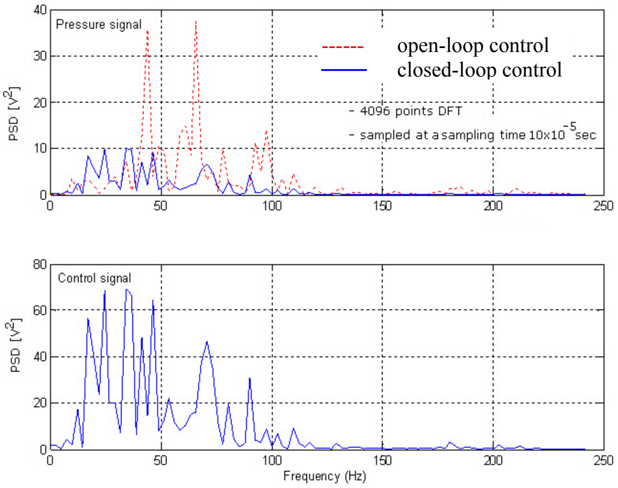

Fig. 6: Comparison of test results between open- and closed-loop outputs in frequency domain

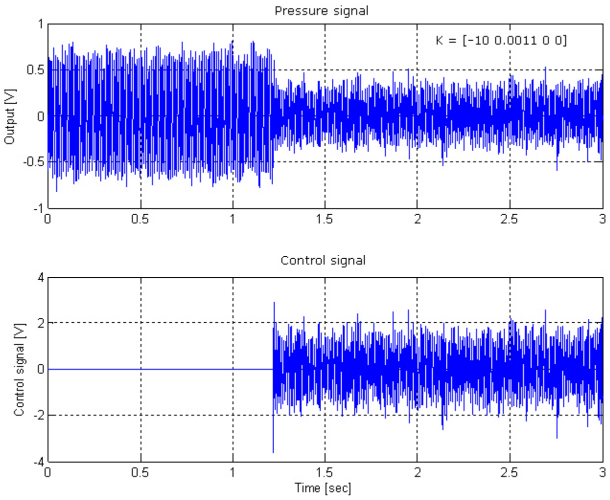

Fig. 7: Controlled output and control signal (80 Hz sine wave as a simulated turbulent process noise)

Conclusion

Although the *noise reduction* was as good as expected at the working frequencies of 50-100 Hz, the additional unexpected harmonic contents were probably created from the control signal whose frequencies accidentally happened to be at the eigenfrequencies of the system (i.e. hardware).

References

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