ADAPTIVE AND ROBUST CONTROL FOR THE REDUCTION OF TONAL NOISE COMPONENTS OF AXIAL TURBOMACHINERY WITH FLOW CONTROL

Maiko Garwon[1], Jan Schulz[2], Bram Satriadarma[1], Rudibert King[1], Michael Möser[3], Wolfgang Neise[4]

[1] **Institut für Anlagentechnik, Prozesstechnik und Technische Akustik**, Technische Universität Berlin
Hardenbergstr. 36a, 10623 Berlin, Germany

[2] **Sonderforschungsbereich 557 „Beeinflussung komplexer turbulenter Scherströmungen"**, Technische Universität Berlin
Müller-Breslau-Str. 8, 10623 Berlin, Germany

[3] **Institut für Anlagentechnik, Prozesstechnik und Technische Akustik**, Technische Universität Berlin
Einsteinufer 25, 10587 Berlin, Germany

[4] **Deutsches Zentrum für Luft- und Raumfahrt e.V**., Institut für Antriebstechnik, Abteilung Turbulenzforschung Berlin
Müller-Breslau-Str. 8, 10623 Berlin, Germany

1. INTRODUCTION

This paper presents results of the application of feedback control algorithms for the active reduction of tonal noise components of an axial fan using flow induced secondary sources instead of loudspeakers to generate the secondary sound field. Investigations have shown that blowing air into the blade tip region through nozzles in the casing wall is a practical and promising way to reduce the radiated sound [1], [2].

2. CONTROL ALGORITHM

For the noise reduction by flow induced secondary sources typical feed-forward algorithms or adaptive filters do not work, due to the problem that the generated aeroacoustic secondary field can not be regarded independently of the primary sound field. The reason for this are the simultaneous generation mechanisms of the sound fields of both the rotor-stator and the rotor-distortion-interaction. Hence, other means of closed-loop strategies have to be used for this application.

Here, an extremum-seeking controller (principle shown in Figure 1) is used to find the optimal mass flux $M_{noz}(t)$, which is equivalent to the amplitude of the secondary sound field. In consequence the plant input $u(t) = M_{noz}(t)$ minimises the overall sound pressure level, denoted here by $y(t) = SPL$, as well as the dominant azimuthal mode of the order $m = 2$ due to the set-up of the flow distortions. The phase of the secondary sound field is controlled by geometrical parameters (axial and circumferential position of the distortions).

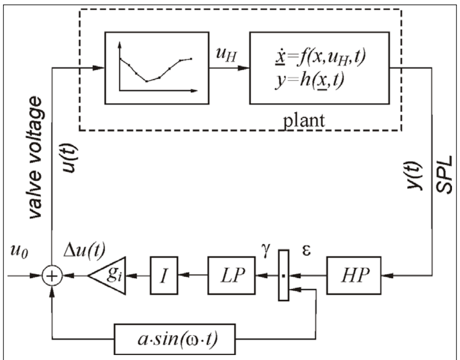

Figure 1: Scheme of the extremum-seeking feedback controller.

The control concept consists of two filters, a low-pass filter (LP) and a high-pass filter (HP), an integrator (I) and a signal generator, which supplies the controller with a sine signal.

In general the concept works as follows: The present value of the input $u(t)$ is a sum of an initial value, the controller output and an overlaying sine signal:

$$u(t) = u_0 + \Delta u(t) + a \sin(\omega t) \qquad (1)$$

Assume that the plant has a static characteristic with a maximum and the process dynamics can be neglected. At activation the controller output $\Delta u(t)$ is zero. The actuation is started with an initial value u_0, which is, for example, below the optimal one (compare Figure 2, top). Due to the harmonic perturbation $a \cdot \sin(\omega t)$ the plant input increases at first, followed by a decrease. The plant output reacts on this perturbation in phase. In this way, an increase of the input leads to an increase of the output. In contrast, a decrease of the input reduces the output, as can be seen in Figure 2 middle, where the harmonic perturbation (thick blue line) and the plant output are drawn. The high-pass filter is necessary to remove the offset of the plant output. The product of the filtered output and the harmonic perturbation leads to a non zero-mean signal as long as the maximum is not obtained. Then this signal is passed through a low-pass filter to extract the mean value. Due to the integration, $\Delta u(t)$ is changed until the actual input $u(t)$ converges towards the optimal value. The choice of the gain g_i, the cut-off frequencies of the filters as well as amplitude and frequency of the sine signal determine the speed of convergence. For more details on extremum-seeking feedback refer to [3].

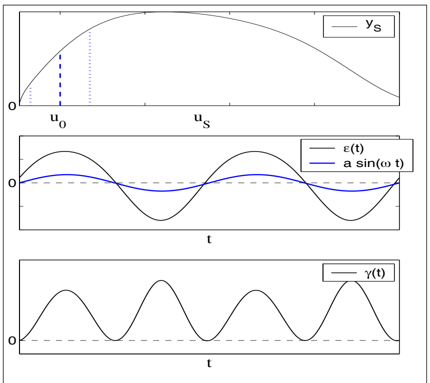

Figure 2: Principle of the extremum-seeking algorithm

3. CONTROL RESULTS

To demonstrate the performance of the proposed controller the initial mass flux was set to $M_0 = 1.2$ g/s, which is below the optimal value $M_{noz,\,opt} = 5.4$ g/s (see Figure 3, top left).

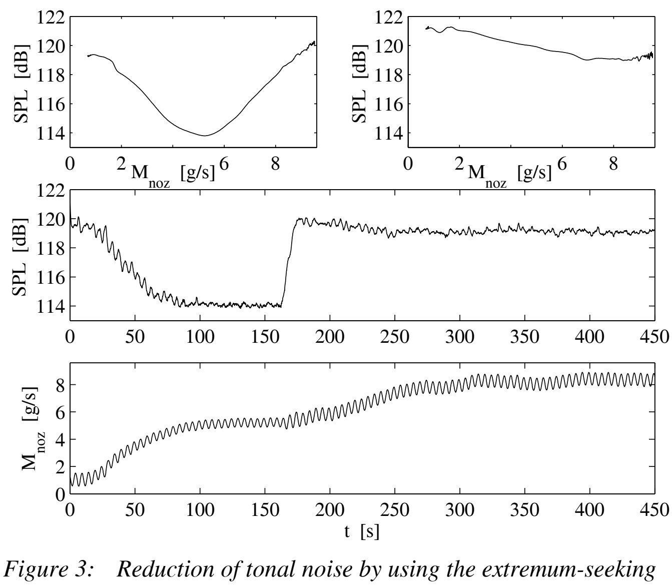

Figure 3: Reduction of tonal noise by using the extremum-seeking controller.

Activating the controller ($t = 0$ s), the mass flux increases monotonically and reaches the optimal value after a transient time resulting in a minimised sound pressure level, compare with the static input/output behaviour (Figure 3 top left). Detailed results of the acoustic measurements are given in [2].

A second feature, at least as important as finding the optimum, is the robustness of the closed-loop. To illustrate this, at $t = 165$ s the revolution of the axial fan was increased by 10%. This leads to a changed input/output behaviour of the plant, i.e. an altered process dynamics. The controller has to be able to react on the modified dynamics and to achieve the control aim, finding the optimum, even under the new conditions. As shown in Figure 3, bottom, the controller increases the mass flux further after the change of the revolution and determines a mean input of $M_{noz} = 8.4$ g/s. This value coincides with the new optimal mass flux, see static plant characteristic in Figure 3 (top right).

To improve the closed-loop performance, the sensitivity of the control algorithm was increased by using a sine amplitude (compare eq. (1)) as a linear function of the controlled sound pressure level, $a = f(SPL)$. A comparison of these particular static input/output characteristic shows, that the higher revolution number induces a higher sound pressure level and, consequently, an increased optimal mass flux, too. Furthermore, the gradient of the sound pressure level with respect to the mass flux is weaker, which is why a higher seeking radius a is necessary to get the correct information about the instantaneous gradient of the static characteristic in spite of low signal-to-noise ratios.

4. MODELLING OF THE PROCESS DYNAMICS

In a second step the non-linear process dynamics is approximated by so-called black-box models. This procedure is necessary to synthesise a model-based controller which aims to suppress disturbances corrupting the output variable. It is assumed, that the blade passage frequency can be regarded as a disturbance corrupting the plant output.

A stronger reduction of the tonal noise components is expected, when the extremum-seeking controller, which determines the mean optimal mass flux, and a model-based controller rejecting the high-frequency disturbances are combined.

To estimate the frequency response of the process, the input variable is chosen as a sine signal with various amplitudes $\hat{M}_{noz}$ and frequencies ω

$$M_{noz}(t) = \hat{M}_{noz} \sin(\omega t) \qquad (2)$$

The amplitude of the aeroacoustic secondary field is determined by the mass flux of the injected air. The valves used to control the mass flux are characterised by a non-linear relation between the valve voltage $U_v(t)$ and the mass flux $M_{noz}(t)$, compare Figure 4 (top). Therefore, a non-linear compensation of the actuator behaviour is necessary to generate a sinusoidal input signal for the plant (Figure 4 bottom).

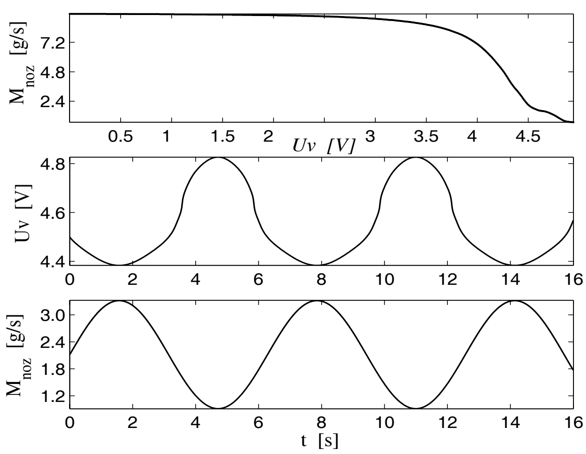

Figure 4: Static characteristics between valve voltage U_v and mass flux (top); time series of valve voltage U_v (middle) and mass flux M_{noz} (bottom).

The output variable is a short time (10 ms) RMS value of the measured microphone signal. To suppress an uncorrelated measuring noise, an averaged RMS value of eight wall-flush mounted 1/4-inch microphones, equally spaced circumferentially in the anechoic measuring duct in the far field of the fan, is used. Using this definition of the output variable the process response y(t) on the input (2) can be written as

$$y(t) = \hat{y}(\omega)\sin(\omega t + \varphi(\omega)) \qquad (3)$$

Figure 5 depicts the frequency response of the estimated 4th order black-box models obtained for different amplitudes. Here, the amplitude response, i.e. the ratio between the amplitude of the measured output (3) to the input (2), and the phase response $\varphi(\omega)$ are plotted logarithmically over the frequencies ω for various sine amplitudes. The figure shows that at low frequencies $\omega < 1$ all estimated models possess a high stationary gain of 40 dB, while the curves spread at higher frequencies. Hence, the controller has to be robust so that the closed-loop is asymptotically stable for all identified process models.

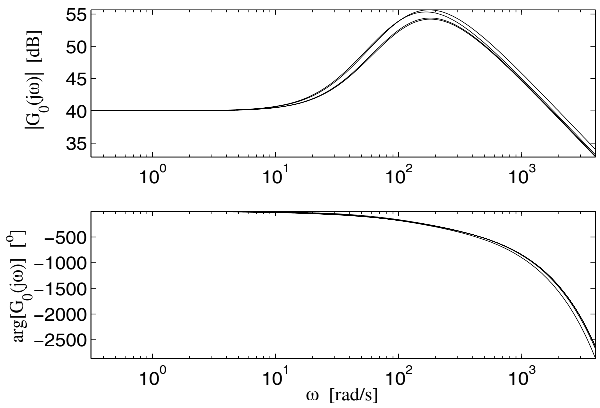

Figure 5: Frequency response (bode-plot) of the investigated process for different amplitudes M_{noz}.

Furthermore, the process is characterised by a time-delay causing a continuous phase decrease at higher frequencies (see Figure 5, bottom). It has to be noted that time-delays limit the achievable speed of the closed-loop [4].

5. SUMMARY AND OUTLOOK

It was shown, that extremum-seeking control is a suitable tool for active noise control of the tonal noise components of an axial fan using flow induced secondary sources. This control strategy was also implemented to optimise adaptive actuators in other flow control problems, refer to [5] for more details.

The future work focuses on the design of robust controllers. For example, the H_∞-synthesis is a powerful tool to design a controller in the presence of model uncertainties as shown in Figure 5. In combination with the extremum-seeking controller a better reduction of the tonal noise is expected.

6. REFERENCES

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