Active Resonance Control at the Audi aero-acoustic wind tunnel (AAWT)

Fabian Evert[1], Hans Miehling[2]
[1] *Müller-BBM GmbH, D-82152 Planegg, Germany, Email: fevert@muellerbbm.de*
[2] *AUDI AG, D-85045 Ingolstadt, Germany, Email: hans.miehling@audi.de*

Introduction

A well-known problem associated with open-jet wind tunnels is the occurrence of low frequency pressure and velocity fluctuations. This so-called 'wind tunnel buffeting' negatively affects the flow parameters and thus the quality of both aerodynamic and aero-acoustic measurements.

The observed disturbances mainly originate from a periodic vortex shedding at the nozzle, which supports resonant modes of the tunnel duct. In principle, the destruction of large-scale vortices by passive means leads to a disturbance attenuation. However, due to the additional higher frequency noise generated by such devices, these methods are inapplicable to aero-acoustic wind tunnels.

Therefore an active control scheme for the suppression of wind tunnel buffeting has been developed and implemented at the Audi aero-acoustic wind tunnel facility. This control system, termed Active Resonance Control (ARC) utilizes a global control of the acoustic resonances of the tunnel duct in order to attenuate the observed buffeting. Both operational experiences with the actual ARC system and Enhancements of the Control Scheme (EARC) will be presented.

Effect of the Wind Tunnel Buffeting on Measurements

It is well known that the wind tunnel buffeting negatively affects both aerodynamic and aero-acoustic measurements. As an example, the sound pressure level spectrum measured inside a car with an open sunroof at a wind speed of 60 km/h is shown in Fig. 1 and 2 (split for easier observation of the main effects). A strong disturbance due to the wind tunnel buffeting can be observed at 2.4 Hz, based on the excitation of the second acoustic resonance of the tunnel duct (Fig.1).

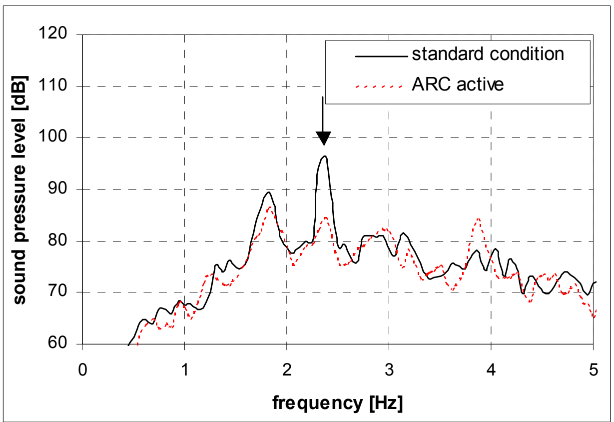

Figure 1: Wind Tunnel Buffeting at 2.4 Hz with and without ARC; U=60 km/h.

At the same time a resonant mode of the car interior cavity is excited by the shear-layer instability forming at the sunroof opening. Beneath the resonant frequency of the cavity, which is about 20Hz, modulation sidebands (at 20 ±2.4 Hz) originating from the wind tunnel buffeting can be seen in Fig.2. If the buffeting at 2.4Hz is suppressed by the ARC-system, also the sidebands disappear (Fig.1 and 2).

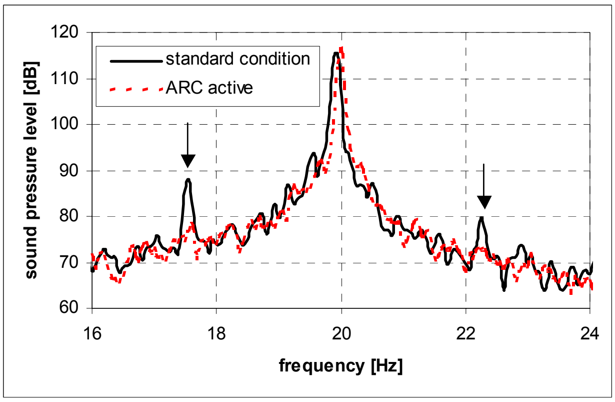

Figure 2: Cavity resonance of a car with open sunroof at 20 Hz and additional sidebands caused by wind tunnel buffeting, with and without ARC system; U=60 km/h.

Especially for broadband noise generated by the flow over a car, the observed modulations cannot be removed from the measurement data by means of filtering and strongly affect the measurements and the psychoacoustic judgment.

Principle of the ARC System

In order to facilitate high quality aero acoustic measurements the Audi AAWT is equipped with an active system for the suppression of low frequency disturbances. A simplified sketch of the setup is shown in Fig. 3.

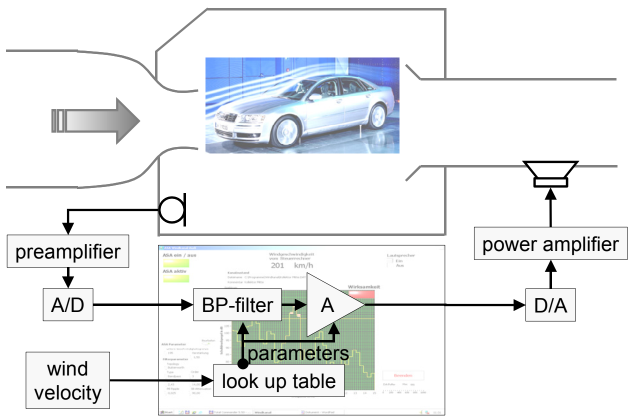

Figure 3: ARC system in the Audi AAWT

The disturbance signal is picked up with a microphone located at the test section wall. After preamplification and

A/D-conversion the signal is filtered by means of a digital band pass filter. The resulting signal is multiplied with an adjustable amplification factor and fed to a loudspeaker array, after D/A-conversion and power amplification. The loudspeaker array is located in a chamber, which is directly coupled to the tunnel duct.

If the parameters of the filter (type, order and cutoff frequency) are optimally chosen, the system exhibits strong disturbance suppression by up to 20 dB. Prior to normal wind tunnel operation, the parameters are manually adjusted for each critical wind velocity and stored in a look up table. Under operational conditions the algorithm picks the correct parameters in dependency of the actual wind velocity.

Assuming disturbance suppression by means of out of phase superposition (global control of tunnel resonances), the phase-shift of the control loop and the amplification factor are the main control variables. Therefore only a slight shift of the disturbance frequency might lead to a sub optimal control result, depending on the phase-gradient and amplitude characteristics of the band pass filter at the frequency it was optimized for. This is exactly the drawback of the actual system, which was experienced in operation. Due to variations of the buffeting (frequency, amplitude) for different test setups (car type, collector position) several different parameter setups of the control system have to be used.

Enhanced Active Resonance Control

Based on the above-mentioned findings a novel control system was designed, which gives direct access to the main control variables (phase shift, amplification A). A simplified sketch is shown in Fig.4.

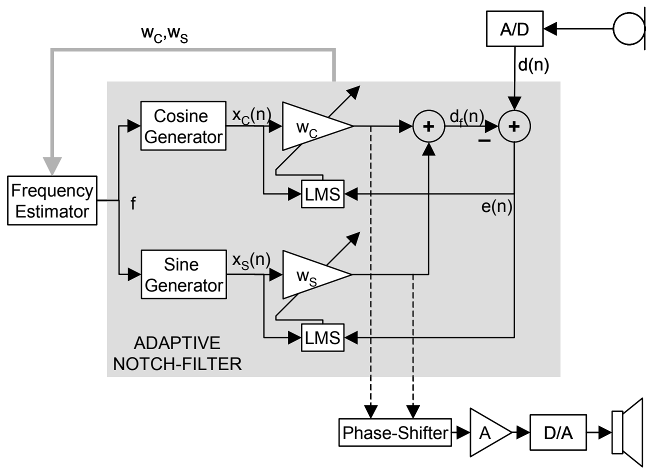

Figure 4: Algorithmic structure of the novel system concept

The disturbance signal (microphone) is filtered by means of an adaptive notch filter. The main disturbance frequency is tracked by a frequency estimator, which is directly based on the phase information given by the time invariant filter weights w_C and w_S. After convergence of the adaptive filter, the output signal $d_f(n)$ equals the disturbance signal at the main peak frequency. Since the notch filter not only gives the signal itself, but also the weighting factors w_C and w_S for the orthogonal components, an adjustable phase shift can easily be calculated (Phase-Shifter). After phase shifting the signal is multiplied with the amplification factor A and then fed to the loudspeakers.

As expected for the global control of the duct resonances by means of out of phase superposition, it has been shown experimentally, that the residual sound pressure level as a function of the control parameters (phase shift and amplification) exhibits a simple, bowl-shaped surface with a global optimum. Therefore many algorithms could be used for an automatic optimization of the control parameters.

Moreover a direct calculation of the optimal phase-shift is feasible, based on the transfer path between output and input of the control system. For the example shown in Fig.5 the phase-shift was directly calculated based on the transfer function (measured prior to the experiment without flow) and the amplification factor was automatically adjusted.

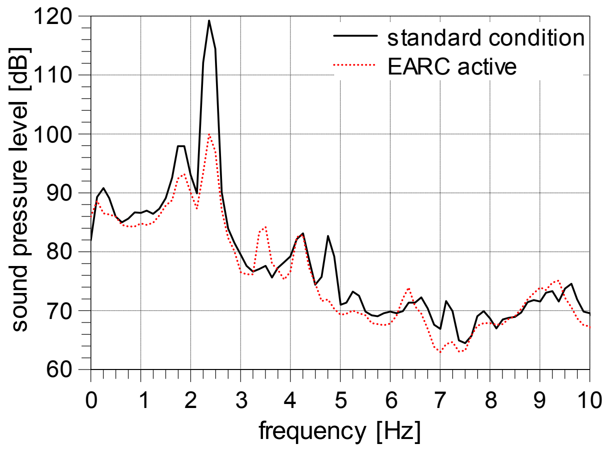

Figure 5: SPL in the test section with and without the EARC system; U=100 km/h.

A strong disturbance reduction can be observed. Due to its frequency tracking capability the novel system is more stable against variations of the disturbance frequency than the actual implementation, which is based on fixed band pass filters. A more detailed description of the system and the compensation mechanism can be found in [2].

Variations of the proposed control system with respect to the microphone position are still under investigation. A microphone position near to the loudspeaker array (tight coupled monopole) should lead to a further simplification of the system, because in this configuration the transfer function of the control loop becomes independent from the flow velocity.

References

[1] Wind Tunnel Pulsations and their Active Suppression. Wickern G., von Heesen W. and Wallmann S., SAE Paper 2000-01-0869, 2000

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