In future aircraft well-established jet engines could be substituted by contra rotating open rotor (CROR) propulsion systems. Due to their fuel efficiency they are able to reduce costs and CO$_2$ emissions significantly. But up to now the high noise emission of CROR engines in certain frequency bands impede dissemination on the market. This conflict can be solved by the implementation of modern noise reduction techniques like Active Structural Acoustic Control (ASAC) in aircraft. In this paper an approach for the reduction of noise transmission through a section of a fuselage is presented. The experimental aircraft Dornier 728 of the DLR is equipped with an ASAC system. The system is mounted on a side panel including two windows and covers an area of $1000 \times 1500$ mm$^2$. Sensors on the inner fuselage measure the normal acceleration in specified points of the structure. A narrow-band robust controller calculates the desired actuator signals to reduce the sound transmission at the specific CROR bands in the bandwidth from 1 to 500 Hz. Since the Dornier 728 aircraft has no CROR engines, their acoustic excitations have to be synthesized. A 112-channel loudspeaker array is placed close to the fuselage. The loudspeakers are driven with synthesized signals and produce a complex CROR sound pressure field on the outer side of the fuselage. The synthesized excitation gives the opportunity to test the ASAC system with realistic loads. Beside a detailed description of the ASAC realization and the algorithms, the results of the experiments and the effectiveness of the control concept are shown.

1. Introduction

Contra rotating open rotor (CROR) propulsion systems are a promising concept to reach a resource efficient transport demanded by the European Commission in the Horizon 2020 framework program. Due to their fuel efficiency they are actually discussed as an alternative to common jet engines. The disadvantage of CROR engines is the radiation of annoying multi-harmonic noise which leads to high sound pressure levels in the cabin. Already in the 1980s when CROR engines first became popular, their noise was predicted by simulations and compared to measurements \cite{1}. Even today, noise emission characteristics for different CROR setups are investigated in wind tunnel experiments \cite{2}.

The impact of the CROR engines on the sound pressure level in the cabin can be reduced by the installation of an Active Structural Acoustic Control (ASAC) system on the fuselage. Within the scope of the project Enhanced Cabin Comfort Computations (ECCO) of the German Aerospace Center (DLR) an ASAC system is experimentally tested at DLR’s Dornier 728 aircraft. The objective of the presented work is to reduce noise transmission through the fuselage structure into the cabin.
by use of a narrow-band $H_\infty$ controller. Preliminary studies were carried out in DLR’s acoustic transmission loss test facility (ATB) [3]. Based on the gained experience the Dornier 728 experiments were planned and conducted.

First, the experimental setup is described, followed by a short review of the sound field synthesis for the loudspeaker array. Afterwards, the feedback control system and its synthesis are described in detail. Finally, experimental results are shown and discussed.

2. Experimental Setup

The Dornier 728 aircraft is a regional jet with 70 seats and an operating range of up to 4,700 km. Before the first flight of the 728 had been made, the entire program ended due to the insolvency of Fairchild Dornier in 2002. Three prototypes were built for testing purposes. The nearly completed first prototype was bought by the DLR in an auction to use it as an experimental aircraft for cabin research. It is now grounded at the DLR facility in Göttingen, Germany.

The ASAC system is mounted at the inner side of the fuselage covering two frame widths. The fuselage has a diameter of 3,470 mm and has four stringers and two windows in the area of the active system (see Fig. 1). The distance between the frames is 500 mm. The active system consists of twelve Visaton® EX60 S actuators (Dim.: $58 \times 58 \times 21 \text{ mm}^3$) and twelve single axis accelerometer of type PCB® 352A24 (Dim.: $7.1 \times 9.9 \times 4.8 \text{ mm}^3$). The actuators are placed according to the peaks in the map of Fig. 3 and to the constraint of an at most equal distribution. The map is created by a summation of the velocity amplitudes of the measured operating deflection shapes (ODS) at the first seven CROR frequencies. The sensors are positioned nearby the actuators to gain minimal phases in the controlled plant.

The 112-channel loudspeaker array generates realistic acoustic loads at the outer side of the fuselage (see Fig. 2) to simulate a CROR engine. The array is 1,120 mm wide and has a height of 1,960 mm. Therefore, it is able to excite the entire structure in the active area. The array is curved so that all loudspeaker membranes nearly have the same distance to the fuselage of app. 150 mm. The loudspeakers of the array have a horizontal and vertical spacing of 140 mm. Each loudspeaker is driven by different excitation signal using a PC-based playback system. The frequency response of the loudspeakers is flat in the bandwidth of 80-8,000 Hz.
3. Sound Field Synthesis

Realistic experiments with ASAC systems need to have an excitation that reconstructs the real noise source as precisely as possible. To simulate the sound pressure field that emanates from a CROR engine the 14 × 8 loudspeaker array was built. Driving each loudspeaker by a particular signal, complex sound pressure fields can be synthesized on the fuselage. The algorithm used here calculates loudspeaker signals to synthesize the target sound pressure spectra in several microphone positions on the fuselage. These target spectra were derived from numerical CROR engine simulations, coupled with a Ffowcs-Williams and Hawkings (FW-H) solver to propagate the calculated sound pressure field towards virtual surface microphone positions on the test fuselage [4]. Requirement for such synthesis is the knowledge of the transfer paths from all loudspeakers to all surface microphones. In experiments these paths were measured and the loudspeaker signals were synthesized by the algorithm afterwards. The fundamental CROR frequencies are \( f_1 \) and \( f_2 \). All following CROR frequencies are harmonics so-called rotor-to-rotor tones generated by linear combinations of the fundamentals. The first five CROR frequencies in Table [1] are chosen for the control experiments because they are located in the frequency range below 500 Hz. In this domain active systems usually show better performance than passive ones, due to the large acoustic wave lengths.

4. Control

The dynamics of the controlled plant from actuator inputs \( u \in \mathbb{R}^{n_u} \) to sensor outputs \( y \in \mathbb{R}^{n_y} \) are described with the discrete linear time-invariant (LTI) state-space model \( G \). With experimental time data from a multi-reference measurement the matrices \( A, B, C, D \) of the state-space model are identified by subspace identification routines [5]. Typically, a number of \( n_x = 270 \) states is sufficient for a detailed modeling of the vibration behavior in the bandwidth from 1 to 500 Hz. The sampling frequency is set to 1,200 Hz.
In this paper the active system has to reduce the rotor noise transmission through the fuselage of the Dornier 728. The acoustic excitation concentrates on the five frequencies in the considered bandwidth (see Table 1). The disturbance is very determined and coherent to the revolutions of the engines. Although this scenario is a typical application for feedforward control with adaptive filters, a feedback approach introducing narrow-band $\mathcal{H}_\infty$ control is presented here.

In $\mathcal{H}_\infty$ control the controller synthesis is based on a linear fractional transformation (LFT) framework (see Fig. 4). The generalized plant $P$ is connected to the controller $R$ by the error output $e$ and the actuator input $u$. The disturbance $w$ enters the plant while the performance $z$ is the output. The generalized plant includes the controlled plant $G$ and additional filters to specify the design goals. The controller $R$ is synthesized such that the $\mathcal{H}_\infty$ norm of the transfer function from disturbance inputs to performance outputs is less than or equal to the desired upper bound $\gamma$:

$$||T_{zw}||_\infty \leq \gamma.$$  \hspace{1cm} (1)

Since multi-harmonic disturbances are a typical domain for feedforward adaptive control [6, 7], the narrow-band $\mathcal{H}_\infty$ control presented here is an interesting alternative in terms of computational efficiency and the negligible reference signal. Due to the multi-harmonic characteristic of the disturbance, its reduction has to be very concentrated in the CROR frequencies. Here, the advantage of the LFT framework, the fact that performance and measurement outputs must not be the same signals, can be utilized. The sensor outputs $y$ of the plant $G$ are filtered with a diagonal state-space system $F$ where each diagonal term $F_{nn}$ is a series connection of five discrete elliptical bandpass filters. The passband center frequencies are the five CROR frequencies of Table 1 while the passband width is only 2 Hz. The filters of fourth order realize 1 dB passband peak-to-peak ripple and a minimum stopband attenuation of 25 dB. Fig. 5 shows the singular value plot of a diagonal term $F_{nn}$. The closed control loop with plant $G$ and filter $F$ is given in Fig. 6. All external disturbances are modeled as disturbances $d$ of the actuator signals.

For the mathematical description of the design goals, the controlled plant is augmented with four weighting matrices $W$. According to Fig. 6 they are placed at the disturbance inputs and the performance outputs. The diagonal weighting matrices consist of different combinations of high- and low-pass filters which parameters are controlled by only two scalar values [8, 9]. The weighting matrices $W$, the filter $F$ and the controlled plant $G$ form the extended plant $P$ which is used for the control synthesis process. Combining $P$ and $R$ with the LFT $\mathcal{F}_l(P; R)$ according to Fig. 4 to
$T_{zw}$ gives
\[
\begin{bmatrix}
  z_p \\
  z_u
\end{bmatrix} =
\begin{bmatrix}
  W_{RS}G_F R S W_{RSr} & W_{RSu}G_F S G W_{SGd} \\
  W_{RS}R S W_{RSr} & -W_{RSu}R S G W_{SGd}
\end{bmatrix}
\begin{bmatrix}
  w_r \\
  w_d
\end{bmatrix},
\]
with the sensitivity
\[
S = \left[ E + G_R \right]^{-1}.
\]

The disturbance transfer function from external disturbance $d$ to the accelerometer signals $y$ in the closed loop is $S_G$.

### 5. Experimental Results

![Figure 6. Weighting scheme](image)

![Figure 7. Measured maximum singular value plots of plant $G$ and disturbance transfer function $S_G$](image)

The controller $R$ is synthesized and afterwards implemented on a DSPACE® rapid prototyping system. For the validation of the controller, a closed-loop system identification of $S_G$ is conducted while the CROR excitation is switched off. Fig. 7 shows two plots of maximum singular values. Here, $G$ is the open-loop and $S_G$ the closed-loop disturbance transfer function. As desired, the
controller reduces the disturbances $\delta$ by up to 19.2 dB in the five selected CROR frequencies at the sensor locations.

The vibration reduction at the positions of the twelve accelerometers is measured with the rapid prototyping system during CROR excitation with the loudspeaker array. Fig. 8 shows the summed accelerometer spectra of all sensors in open- and closed-loop case. A minimum reduction of 8.2 dB and a maximum reduction of 23.6 dB are realized. Comparing the reductions of Fig. 7 and Fig. 8 it can be seen that they are closely related even though the excitations are quite different. Thus, the assumption that the CROR disturbances can be modeled as process noise $\delta$ seems to be sufficient.

The influence of the ASAC system on the global vibration behavior is evaluated using a POLYTEC® PSV 400 scanning vibrometer (LSV). A grid of 650 scan points with a horizontal and vertical spacing of app. 40 mm is applied to the area of the active system. At each point the normal velocity is measured under CROR excitation for the open-loop and closed-loop case. The results for the five selected CROR frequencies are shown in Fig. 9(a)-9(e). They compare the operational deflection shape (ODS) of normal velocity amplitudes for each case. At the fundamental frequencies $f_1$ and $f_2$ a global vibration reduction is realized whereas the reduction at $f_3$ and $f_4$ is only nearly global. Some peaks appear in the lower region of the panel where no accelerometer is present. At $f_5$ only a small global reduction is observable. In the lower region some peaks are switching to places with no sensor.

Based on the velocity spectra measured with the LSV, the radiated sound power of the panel is estimated by the analytical radiation resistance matrix of a simple panel [11]. The scan points are treated as mid points of small elementary radiators with a side length of 40 mm. To prove that the approach with the resistance matrix of a simple panel still holds for a stiffened, slightly curved panel, an experimental validation was carried out. Under CROR excitation the panel was scanned with the LSV and a BRÜEL & KJÆR® sound intensity probe. Afterwards, the radiated sound power was calculated with data from both measurements. The two methods achieved nearly identical results. Based on this proof of concept the radiated sound power of the panel is calculated from the LSV measurement presented in Fig. 9. Table 2 summarizes the results. As expected, the highest sound power reductions are reached at the two fundamental frequencies $f_1$ and $f_2$. At $f_3$ the two peaks in the closed-loop case at Fig. 9(c) seem to be efficient radiators since the radiated sound power increases by 2.6 dB. At $f_4$ the observed reduction of 3.4 dB is sufficient and at $f_5$ it is still acceptable.

**Figure 8.** Summed accelerometer spectra under CROR excitation
6. Conclusion

This paper presented an experimental realization of an ASAC system at DLR’s Dornier 728 aircraft. The system consists of twelve exciter and twelve accelerometers installed in two frame width. A 112-channel loudspeaker array generated a realistic acoustic load of CROR noise. In the bandwidth from 1 to 500 Hz a narrow-band $\mathcal{H}_\infty$ controller successfully reduced the local vibrations up to 23.6 dB as well as the radiated sound power up to 8.5 dB at the first five CROR frequencies. The results were achieved by accelerometer and LSV measurements in the Dornier 728.

The ODS in Fig. 9(c)-9(d) show that some peaks arise in the lower part of the active panels. The controller performance could be increased by adding three accelerometer in this area to observe the local vibrations. Future experiments at the Dornier 728 will concentrate on controller enhancements and on extended control concepts.
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