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Innovative In-Flight Aircraft Noise Measurements

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EXECUTIVE SUMMARY

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Innovative In-Flight Aircraft Noise Measurements

Problem area

Novel engine technology can deliver a step change in the reduction of fuel consumption and noise. The development of innovative propulsion concepts and their integration in aircraft is therefore a key contributor to achieve the carbon-neutral growth and specific community noise reduction targets for aviation. Full scale flying demonstrators of the new propulsion concepts enable accurate acoustic measurements in cabin (at one side of the engine) and on-ground (below the aircraft). Following a need expressed by Airbus, NLR aims to provide an innovative acoustic in-flight measurement method that provides accurate measurements in all directions and at various distances from the flying demonstrator and in various operational conditions. A special focus is on the assessment of noise generation of Open Rotor engines (including CROR – Contra Rotating Open Rotors- engines) in all directions and in cruise.

Description of work

The innovative acoustic in-flight measurement method is based on acoustic measurement from the nose boom of a chase aircraft, which is flying close to the flying demonstrator. The challenge is to be able to measure the noise of the flying demonstrator while not being disturbed by the "background noise", i.e. the noise of the chase aircraft itself, by the boundary layer noise of the air passing over microphones or by reflections on other chase aircraft parts before reaching the microphones. Putting the acoustic sensors on a nose boom of a tail-engined chase aircraft provides the maximum distance between the acoustic sensors and the chase aircraft engines and minimises reflections.
The feasibility of the chase aircraft acoustic in-flight measurement method has been investigated in an experimental test campaign in which NLR's Cessna Citation research aircraft is measuring the noise of a propeller aircraft. Two types of acoustic sensors have been tested and measurements have been taken from several directions and at several distances in different flight conditions.

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Results and conclusions

It has been demonstrated that aircraft noise of an FTD can be measured in-flight with a chase airplane. In the flight test the noise of the propeller aircraft was detected during various flight procedures, such as constant aircraft to aircraft distance and fly-by routines. Both static runs and dynamic flight patterns generate valuable noise data. Flight procedures and manoeuvres developed turned out adequate and suited for safe flight test operations. Data processing algorithms and procedures applied were successfully.
The background noise for the single top pressure sensors which was installed behind a grid was 78-85dB. The SNR of the measurements have been shown to increase significantly (over 11dB) by evaluating the cross spectra of the sensors. The sound pressure levels of future Open Rotor engines for transport aircraft will be typically larger and therefore louder than this small FTD aircraft. Furthermore the full microphone array installation of the measurement set-up will enable more advanced cross-correlation techniques and background noise suppression. Therefore this test demonstrates that the technique is well suitable for in-flight assessment of noise generation of Open Rotor engines.

Applicability

The work at hand describes and demonstrates a method to determine aircraft noise in-situ at real flight conditions, without the burden of making assumptions, as is the case in all theoretical and wind tunnel measurements. Using the in-flight measurements, aircraft noise can be measured at conditions which are hard or impossible to reach in wind tunnels. Therefore, it can be used to validate theoretical acoustic models and acoustic wind tunnel measurements. This method also does not suffer from ground reflections and wind conditions, which are complicating factors for traditional fly-over measurements.

GENERAL NOTE
This report is based on a presentation held at the 29th SFTE-EC Symposium, Delft, The Netherlands, May 29-31, 2018

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INNOVATIVE IN-FLIGHT AIRCRAFT NOISE MEASUREMENTS

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Abstract: NLR developed and tested a new method to measure the noise of aircraft engines during a flight. NLR's Cessna Citation research aircraft has been equipped with a nose boom which catches the noise of another aircraft nearby. With this method the noise of an aircraft engine can be measured more extensively compared to flyover tests and adds to windtunnel tests.

The feasibility of the chase aircraft acoustic in-flight measurement method was demonstrated in a small experimental test campaign in which NLR's Cessna Citation II (C550) research aircraft is measuring the noise of a Cessna Supervan (C208) propeller aircraft. Two types of acoustic sensors have been tested and measurements have been taken from several directions and at several distances in different flight conditions. The operational procedures for the flight test campaign were developed and proved adequate. The noise of the propeller aircraft was measured with the microphones on the boom of the chase aircraft.

1 INTRODUCTION

The flight test described in this paper has been performed under the Clean Sky 2 program which aims at greener aircraft with less emissions, both gaseous and noise. The test flight is a first step within a broader study in which the noise emission of aircraft engines needs to be measured in-flight. For this broader study, an instrumentation package is finally to be developed as well as flight operational procedures and measurement data analysis methods.

Novel engine technology can deliver a step change in the reduction of fuel consumption and noise. The development of innovative propulsion concepts and their integration in aircraft is therefore a key contributor to achieve the carbon-neutral growth and specific community noise reduction targets for aviation. Full-scale flying demonstrators of the new propulsion concepts enable accurate acoustic measurements in the cabin (at one side of the engine) and on-ground (below the aircraft). Following a need expressed by Airbus, NLR aims to provide an innovative acoustic in-flight measurement method that provides accurate measurements in all directions and at various distances from the flying demonstrator and in various operational conditions. A special focus is on the assessment of noise generation of Open Rotor engines (including CROR – Contra Rotating Open Rotors- engines) in all directions and in cruise.

The innovative acoustic in-flight measurement method is based on acoustic measurement by the nose boom of a chase aircraft, which is flying close to the flying demonstrator. The noise of the flying demonstrator should not be disturbed by the noise of the chase aircraft itself, by the boundary layer noise of the air passing over microphones or by reflections on other chase aircraft parts before reaching the microphones. This noise generated by the chase aircraft is called the "background noise" in this paper. Putting the acoustic sensors on a nose boom of a tail-engined chase aircraft provides the maximum distance between the acoustic sensors and the chase aircraft engines and minimises reflections. Combined with advanced acoustic measurement techniques and post-processing of the acoustic data this provides an accurate and widely applicable in-flight acoustic measurement method.

The in-flight acoustic measurement method poses an alternative to wind tunnel measurements and simulation methods. In wind tunnel experiments, most acoustic measurements are performed at scaled models and the wind conditions and aerodynamic parameters have to be estimated and simulated, which is not necessary for the in-flight acoustic measurements. Using this method to perform the acoustic experiments, aircraft noise can be measured at conditions which are hard or impossible to reach in wind tunnels. Therefore the method can be used to validate theoretical acoustic models and acoustic wind tunnel measurements.

The in-flight method also does not suffer from ground reflections and the effect of wind conditions can be diminished by flying in the wind direction. Furthermore, the noise can be measured in all directions and at all altitudes. These are factors which complicate traditional fly-over measurements which aim to measure isolated aircraft noise.

In chapter 2 the objectives of the development and of the development risk reduction flight test reported in this paper are presented. The aircraft and the instrumentation for the flight test are described in chapter 3. Considerations with respect to the flight strategy are given in chapter 4 and acoustic results are presented in chapter 5. Conclusions are in chapter 6.

2 OBJECTIVES OF THE STUDY AND THE FLIGHT TEST

One of the overall objectives of the Clean Sky 2 project Propmat is to develop a measurement method for in-flight assessment of the noise emission of aircraft engines, including the instrumentation, the flight operation methods and the analysis methods. Special focus is on the assessment of noise generation of Open Rotor engines (including CROR engines) in all directions in cruise conditions, but the method will be applicable for all aircraft engines at all flight conditions.

The in-flight assessment will be performed by a noise measuring aircraft, hereinafter referred to as the chase aircraft. This aircraft will chase the aircraft with the engine under investigation, hereinafter referred to as the Flight Test Demonstrator (FTD). The proposed instrumentation, the flight operational methods and the analysis methods will incorporate the following innovative aspects:

- Development of safe and accurate flight procedures for generating the measurement data.
- Installation of miniature flush-mounted microphones in a nose boom of the chase aircraft.
- Data processing techniques to reduce background noise.

The integration of pressure sensors in the nose boom will enable improved noise measurements as reflections will be minimized and a linear array of microphones will enable localization of the noise sources. Furthermore, the influence of chase aircraft noise on the boom-mounted sensors will be very small compared with installations on the airframe.

A dedicated nose boom will be developed for the chase aircraft. The microphones are installed in the boom of the Cessna Citation and on the fuselage of the aircraft to form an array of sensors enabling phase correlation analysis of noise and the associated directivity and background noise reduction. The physical location of the microphones is spread to achieve the potential for directivity in the measurements. An indication of suited locations for the microphones is shown in Figure 1.

Figure 1: Indication of the positions of microphones in the boom and on the Cessna Citation for creating an array of microphones for in-flight acoustic measurements

Before applying the instrumentation on the Open Rotor engine installed on the FTD, the instrumentation and the flight procedures is validated. The flight campaign described here with a propeller aircraft is part of this validation.

2.1 Objectives for the flight test

The objective of the performed flight test was to reduce the risk of the development of the full instrumentation. Therefore, in the first test, only a first and basic implementation of the instrumentation was tested. Further development of the instrumentation will be guided by information about the noise levels from different origins and information about which sensors produce the highest measurement quality.
The first flight test will provide

- a measure of the noise on the chase aircraft consisting of:
    - Engine noise
    - Airframe noise
    - Boundary layer noise
- a demonstration of the measurement of engine noise of a regular propeller aircraft acting as FTD with a chase aircraft.
- a first evaluation of:

- The performance of microphones,
- The data collection system
- The flight procedures / maneuvers
- The data processing algorithms and procedures

3 AIRCRAFT AND INSTRUMENTATION

3.1 Introduction

In the flight test two aircraft were used. NLR's Cessna Citation II research aircraft has been used as the chase aircraft. It has a flexible instrumentation suite, including a nose boom. NLR has an experienced team of experts operating the aircraft consisting of qualified people like research pilots, flight test (instrumentation) engineers, R&D engineers, certifying staff, technicians and support personnel.
The FTD aircraft was a Cessna 208B Supervan 900, which was hired for this flight test from Nationaal Paracentrum Teuge and flown by an NLR test pilot and an NLR Flight Test Engineer. This aircraft qualified as it is a propeller aircraft and was available for the test.

Figure 2: NLR's Cessna Citation II research aircraft (PH-LAB)

NLR's Cessna Citation II research aircraft (PH-LAB) (see Figure 2) is used to measure the engine noise levels of the FTD. Originally designed for executive travel, the aircraft has been extensively modified by NLR to serve as a versatile airborne research platform. The Citation II is a twinjet aircraft of conventional aluminum construction. It has two Pratt & Whitney JT15D-4 turbofan engines. The basic flight crew consists of two pilots and a flight test engineer. When empty (no or little instrumentation), a maximum of seven observers can be seated in the cabin.

The aircraft "under investigation" for the flight test is a Cessna 208B Supervan 900 (see Figure 3). The engine noise level of this aircraft will be measured by the chase aircraft in-flight.

Figure 3: Cessna 208B Supervan 900

3.2 Instrumentation

The Cessna Citation II (PH-LAB) chase aircraft has been equipped with a modified nose boom (Figure 4). This nose boom contains three transducers (Figure 5) to measure the noise of the FTD, the Cessna Supervan (PH-JMP). One pressure microphone, a surface microphone, manufacturer GRAS, type 40LS, and two pressure transducers, manufacturer Endevco, type 8510B were installed. The top Endevco is indicated as Endevco-1. The surface microphone is installed 20 mm downstream the Endevco 8510B. Another Endevco 8510B pressure transducer, Endevco-2, is installed on the lower side of the boom, exactly opposite the Endevco-1. The Endevco transducers have a sensing element behind a small grid in the boom. The surface microphone was installed flush at the center, as is shown in Figure 5. The diameter of the boom at the position of the microphones is 63 mm. The length of the boom upstream of the Endevco transducers is 765 mm of which the first 105 mm is an aerodynamically shaped tip and the latter 660 mm has 63 mm diameter.

The signals of the microphones are recorded with a National Instruments data acquisition system. The standard instrumentation of the Cessna Citation provided the acquisition of GPS time and position, the basic engine data, the attitude of the aircraft (measured with a Honeywell HG 1050 IRS) and air data.

The Cessna Supervan FTD was minimally instrumented as the hired aircraft was just available for a short period and it was not necessary to instrument it for the objectives of this first flight. Basic aircraft and engine data were recorded on paper by the co-pilot and a Septentrio AsteRx_U GNSS receiver recorded time and position. A handheld video recorder recorded images, but also the sound in the cabin with the frequencies linked to the rotation of the engine.

Figure 4: Noseboom installation.

Figure 5: Two microphones integrated in the upper surface of the noseboom. On the right-hand side in the aluminium section, the surface microphone is attached with 4 screws. Left of the surface microphone the grid of the upper pressure transducer is visible as a small circle.

Figure 6: The noseboom installed on the Cessna Citation II. The acoustic sensors are installed at the downstream part of the orange part of the boom.

4 FLIGHT STRATEGY

The most straightforward way to measure the noise characteristics of the target aircraft is to position the chase aircraft at a particular position relative to the target aircraft. In this test run, both aircraft will not move with respect to each other and is therefore designated a “static” flight test run.

4.1 Static Flight Test Run

The relative position of the chase aircraft with respect to the target aircraft can easily be expressed by the distance behind the target aircraft (Δd), the distance to the side of the target aircraft (Δy) and the height below the target aircraft (Δh). These distances are illustrated in Figure 7.

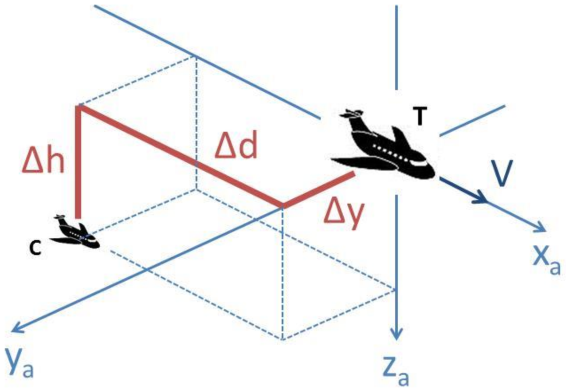

Figure 7: Decomposed relative position of chase aircraft behind target aircraft.

The static flight test run can be realised by flying in (close) formation. The advantage of the static flight test run is that a virtually unlimited number of data points can be collected for a single relative position with regard to the target aircraft.

These test runs are only possible for that part of the envelope for which the performances of the target aircraft and chase aircraft allow flying in (close) formation. Furthermore, not all chase aircraft positions with regard to the target aircraft can be safely flown. Safety issues are for instance the wake vortex of the target aircraft and the ability of the chase aircraft flight crew to keep visual contact with the target aircraft while flying in (close) formation.

4.2 Dynamic Flight Test Run

Another way to measure the noise characteristics of the target aircraft, is to have the target aircraft overtake the chase aircraft in parallel or crossing trajectories. In this test run, the relative position between both aircraft is constantly changing and is therefore designated a “dynamic” flight test run.

The advantage of the dynamic flight test run is that the target aircraft’s engine noise can be measured along different relative positions in one run. Furthermore, it allows for data collection in situations where the target aircraft outperforms the chase aircraft, i.e. when the maximum operating speed of the target aircraft does not allow flying in formation with the chase aircraft, rendering the execution of the static flight test run impossible.

4.3 Flight Test Pattern

The flight test pattern for the consecutive execution of flight test runs can best be performed (i.e. most time efficient) in a race track pattern. The race track pattern is visualised in Figure 8.

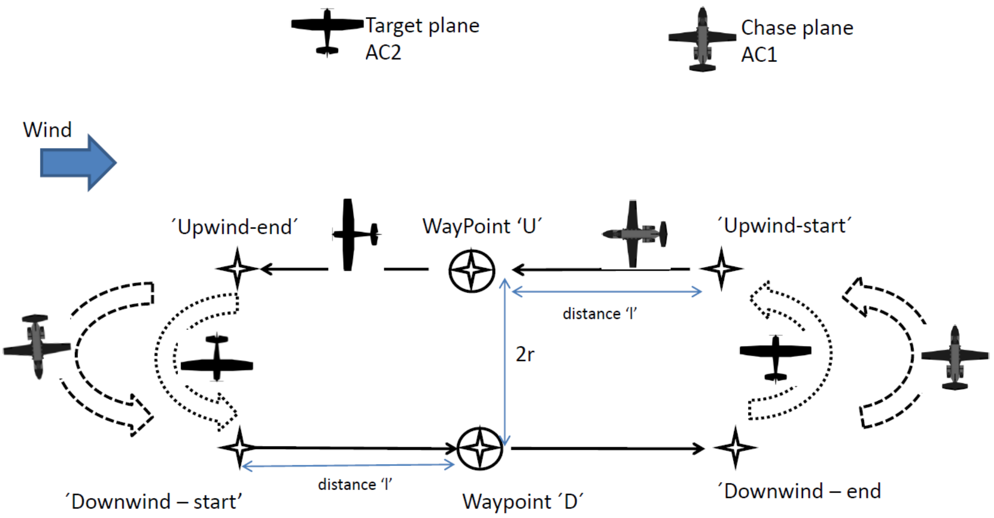

Figure 8: Flight test pattern for test runs

The chase plane (Cessna C550) overtakes the target plane (Cessna 208B) on the straight tracks of the race track pattern. At a particular time both aircraft turn into the same direction to intercept the opposite straight leg of the race track pattern, where the overtake manoeuvre is repeated. From a practical (i.e. operational) point-of-view it is most convenient to define the tracks fixed to the ground. The ground pattern needs to be chosen such that the drift angle (difference between heading and track angle) will be zero, in order to avoid an inclined angle of the nose boom microphone array with regard to the centreline of the target aircraft.

Figure 9: NLR's Cessna Citation II PH-LAB seen from the Cessna Supervan PH-JMP.

Figure 10: Cessna Supervan PH-JMP seen from the Cessna Citation II PH-LAB.

Figure 11: The noseboom seen from the cockpit of the Cessna Citation II PH-LAB.

4.4 Test Matrix

The flight test was executed using a test matrix. The following acoustic measurement considerations have been used to draft the test matrix:

1. Aircraft self-noise measurement at different conditions; acceleration will provide information together with stable flight about what is boundary layer and what is engine noise.
2. Stable measurements to allow for longer signal averaging periods.
3. Stable flights at the aircraft's speed, altitude range and different attitudes.
4. Measurement of FTD sound level in different directions (upwards and downwards of the propeller).
5. Measurement of the FTD propeller sound level variation with longitudinal line below and above the propeller.
6. Measurement of the FTD propeller sound level variation on the longitudinal line with an angle of 45 degree below the propeller.

The following flight test considerations are used to define the test matrix:

1. Separation is based on visual separation between aircraft (except for a small stable segment during the dynamic runs)
2. FTD and chase plane flying in the same direction to obtain a low relative speed; increasing safety level at mentioned separation distances.
3. FTD aircraft flying at a constant altitude to minimize vertical separation errors.
4. FTD aircraft flying at FL 80 to enable the use of an unpressurized FTD aircraft.
5. During static measurements 500 feet vertical separation is applied (standard VFR).

6. The static measurements are executed slightly behind FTD plane to measure maximum noise level and to enable visual separation.
7. During dynamic measurement the vertical separation margin has been reduced to 300 feet providing more close-by measurement, while maintaining an acceptable level of flight test safety.
8. During the static flight test part, relatively low flight test speeds (160 KIAS) due to FTD airplane speed limitations.
9. During the dynamic measurements the chase plane is overtaking the FTD plane because of performance reasons.
10. The maneuvering (in altitude and speed) is executed by the chase plane because of excess in performance (SUPERVAN is restricted to 175 kts).
11. No wake vortex separation used.

4.5 Test Hazards

One of the most important hazards identified was a collision between the two aircraft. Measures to mitigate this risk were:

- The separation between aircraft was not (unnecessary) closer than needed for the measurements.
- Visual contact was maintained during most measurements.
- When visual contact could not be maintained both aircraft were in constant linear motion, at a constant altitude and for a limited time.
- A specific communication protocol between the two aircraft was in place.
- Abort procedures to increase separation between aircraft were in place.
- At least one pilot of the chase aircraft was familiar with formation flying.

4.6 Flight execution

During the flight the FTD maintained a flight level of FL80. The chase aircraft flew at different flight levels during the test flight, as is visible in Figure 12. At the start and at the end of the flight test, the chase aircraft flew solo to investigate the background noise at different flight conditions. In Figure 13, the lateral flight paths are shown. Both aircraft flew a pattern of straight legs, up and down wind, connected by turns.

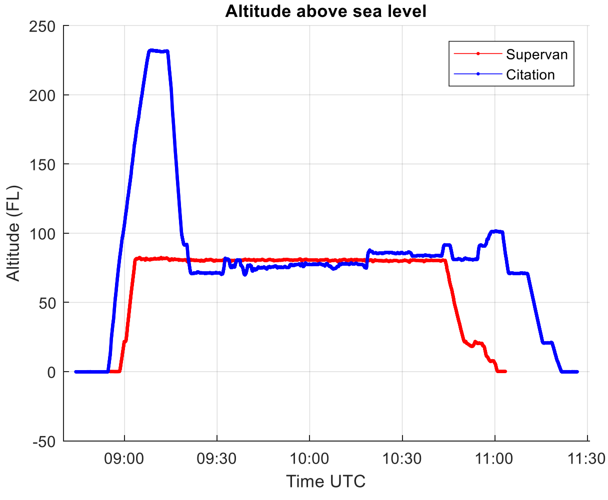

Figure 12: Altitude of aircraft during flight.

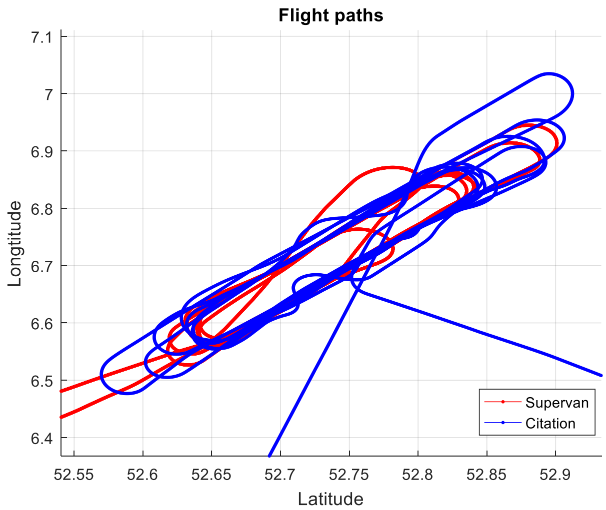

Figure 13: Flight patterns of the FTD and chase aircraft.

5 ACOUSTIC RESULTS

The measured signals are expected to be made up by the following dominating sound sources:

- Target source
  - airframe noise of the FTD
  - (Dominating) engine noise of the FTD

- Sources of background noise
  - turbulent boundary layer noise emerging from the boom
  - airframe noise of the aircraft
  - engine noise of the chase aircraft

A sound fragment of the video log in the FTD has been analyzed to show the frequency spectrum of sound perceived within the FTD. The signal shows the Blade Passing Frequency (BPF) at 106.8Hz, and the higher harmonics at 213.5Hz and 320.4Hz

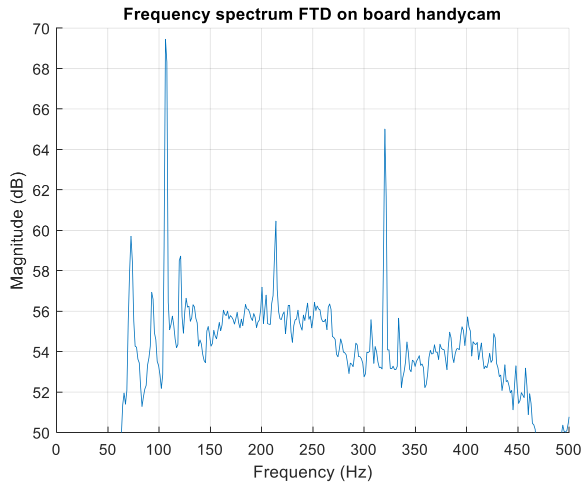

Figure 14: Frequency spectrum perceived within the FTD. The BPF at 106.8Hz and the higher harmonics are clearly visible.

The distance between the aircraft is calculated using the GPS data of both aircraft.
A number of flight sequences have been performed at a nominally constant position of the chase aircraft relative to the FTD. Several other runs have been excecuted with overtake flight procedures above and below the FTD. The latter procedures have the potential to measure the sound noise pattern along the polar angle of the FTD. From both types of procedure a few results are presented in this section.

The data was recorded with a sampling frequency of 25kHz. The datasets were analyzed using a Fourier analysis with block size of 16384 data points, i.e. 0.66s. The data was averaged over a number of time (blocks) depending on the measurement, ranging from 2 minutes to 9 seconds. A Hanning window was applied to the blocks and the 50% overlap was applied on the blocks before the Fourier modes were calculated.

It turned out that the flush installed GRAS LS40 microphone provided a higher background noise level than the slightly retracted Endevco transducers in this installation. Figure 15 shows the noise spectrum measured during a static flight. Since the distance between the aircraft was kept constant based on visual separation, the distance varied up to 100m within this experiment. The two curves shown are spectra measured when the aircraft are closest. These results show a clear peak at the FTD’s BPF 106.8 Hz.

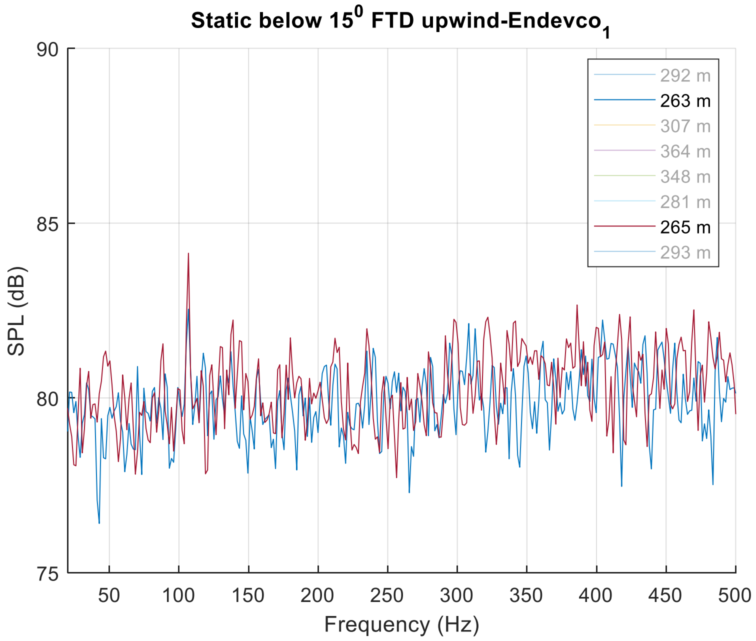

Figure 15: Measured signals clear peaks are found when the aircraft are closest. "Static below 15° FTD downwind". Averaging time 15s.

In Figure 16 an example is shown of a results from a pasing by run. In the case the chase aircraft has overtaken the FTD straight below it. Since the angle and distance to the source are changing continiously the acoustic data is averaged over different flight conditions.

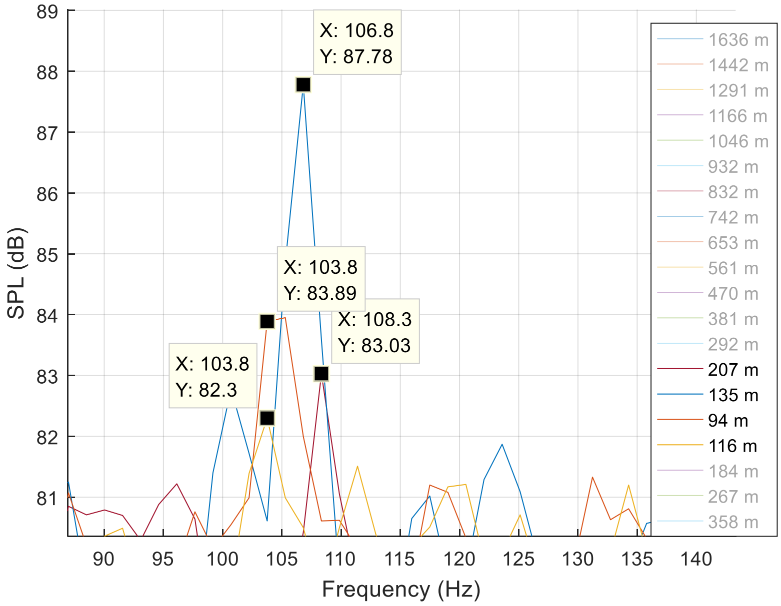

Figure 16: SPL data during overtake straight below FTD. Averaged over 8.5s

In the measurements, frequency shifts between 103.8 and 108.3 Hz have been observed. Higher frequencies are observed during the approach and lower frequencies are observed during the distancing fase. The shifts, caused by the Doppler effect, match the calculated shifts rather well, confirming that the sound is emitted by the other aircraft.

To enhance the signal to noise ratio of recordings, the microphone signals can be cross averaged. This procedure will maintain all coherent sound that arrives at the microphones, while random pressure perturbations at both sensors will average out. For this procedure to be effective, both sensors must not be at the same streamline in the flow, since they will be exposed to the same pressure perturbations in the flow. Therefore only the cross spectra of Endevcos 1 and 2 are calculated.

The individual spectra and the cross spectra from one of the static runs are plotted in Figure 17.

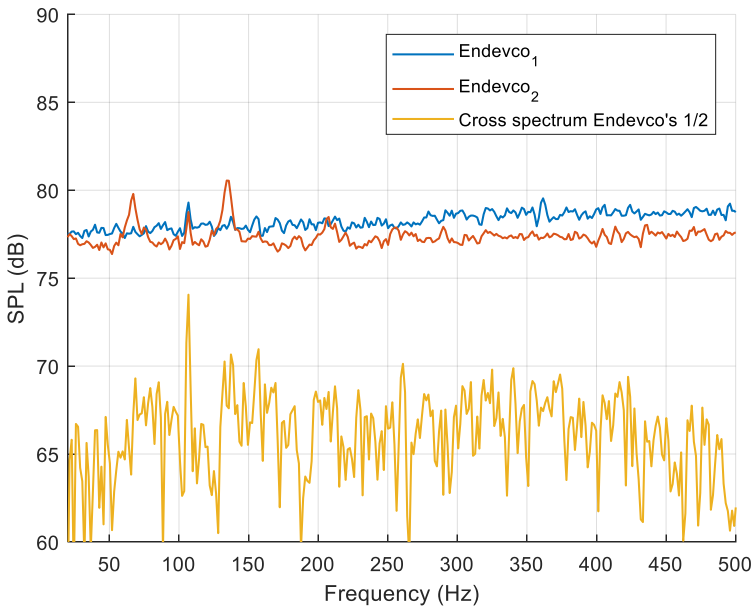

Figure 17: Individual spectra of Endevco 1/2 and the crossspectrum of both signals. Static below 15 ° FTD upwind.

The background noise has dropped by more than 12dB (77dB to 65dB). Since the background noise was significant compared to the measured signal, also measured signal has dropped 5dB, which is to be expected. This is demonstrated in the table where the background SPL of the Endevcos is subtracted from the SPL of the peak of the FTD rotor noise. It shows that in all measurements the calculated FTD noise level was about 74dB. For the single sensors the background level is even larger than the FTD peak level. The Signal-to-Noise Ratio (SNR) improvement using the cross spectra is over 11 dB.

	Background level (dB)	Peak level FTD noise (dB)	Background noise subtracted from FTD noise level (dB)	SNR (dB)
Endevco 1	77.8	79.3	73.9	-3.9
Endevco 2	76.9	78.8	74.2	-2.7
Cross correlated	65.0	74.1	73.5	8.5

Table 1: Background noise level and measured FTD rotor noise level. The SNR level is increased by 11 dB using the cross spectra.

Background noise levels were measured at various flight conditions. A summary is presented in Figure 18.

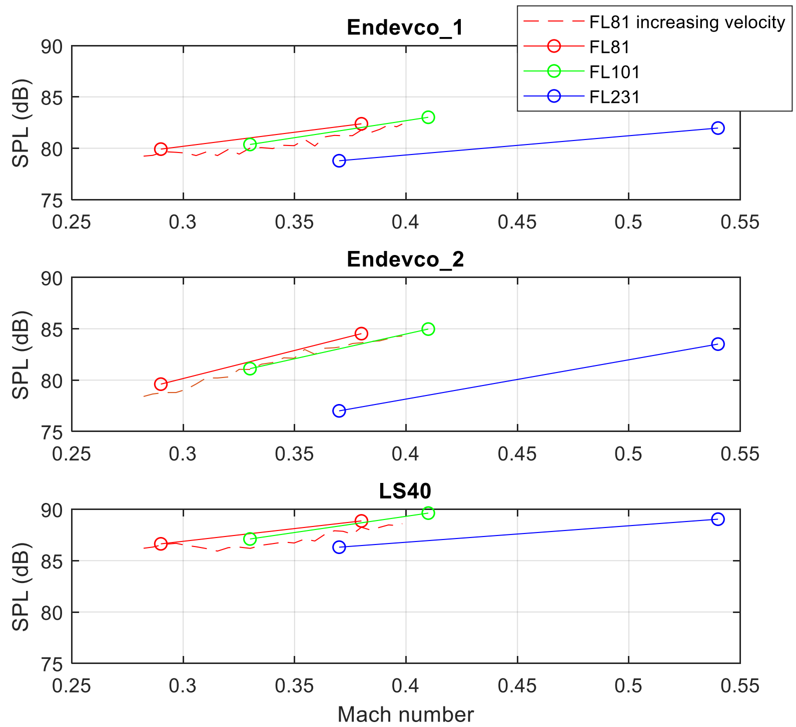

Figure 18: Influence of height on background noise.

It is found that the background noise on the sensors:

- Increases with the chase aircraft Mach number
  - The background noise on sensor below the beam changes more with changing Mach number at the test flight conditions.
- Decreases with altitude (-0.015 to -0.05)dB/FL
- (Is not influenced by up/down wind flight directions)
- Is hardly affected by the flaps settings

6 CONCLUSIONS

It has been demonstrated that aircraft noise of an FTD can be measured in-flight with a chase airplane. In the flight test the noise of the propeller aircraft was detected during various flight procedures, such as constant aircraft to aircraft distance and fly-by routines. Both static runs and dynamic flight patterns generate valuable noise data. Flight procedures and manoeuvres developed turned out adequate and suited for safe flight test operations. Data processing algorithms and procedures applied were successfully.

The background noise for the single top pressure sensors which was installed behind a grid was 78-85dB. The SNR of the measurements have been shown to increase significantly (over 11dB) by evaluating the cross spectra of the sensors.

The sound pressure levels of future Open Rotor engines for transport aircraft will be typically larger and therefore louder than this small FTD aircraft. Furthermore the full microphone array installation of the measurement set-up will enable more advanced cross-correlation techniques and background noise suppression. Therefore this test demonstrates that the technique is well suitable for in-flight assessment of noise generation of Open Rotor engines.

Project context and disclaimer

The chase aircraft acoustic in-flight measurement method is developed in the Clean Sky 2 project PropMat for Platform 1 of the Large Passenger Aircraft IADP aiming at the development of aircraft and propulsion with less emissions and less noise. This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 680954. This paper reflects only the author's views. The Clean Sky 2 Joint Undertaking is not responsible for any use that may be made of the information it contains.

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