Determination of aircraft engine speed based on acoustic measurements

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ABSTRACT
In order to develop more accurate aircraft noise calculation tools, more detailed source models describing the sound emission and directivity are needed. Therefore, the correlation between the actual flight configuration and the measured sound pressure level must be known. A matter of particular interest is the individual engine power setting during take-offs which is usually unknown respectively not published by the airlines. Thus, a method had to be developed that provides the capability of its determination by external measurements.

A measure of the power setting is the engine speed respectively the rotational speed of the low-pressure shaft on which the fan is mounted. Since its rotation causes a measurable pure tone, its fundamental frequency can be detected and tracked within a sound file recorded by a measurement station on the ground. Additionally the Doppler effect and the sound propagation time must be compensated by using an accurate position and time synchronization.

This method has been evaluated by the Swiss research institute Empa for starting and landing aircrafts in the far and close range of an airport. The results contributed to the development of a new aircraft noise calculation model as part of the research project sonAIR.

Keywords: Aircraft, Frequency, Analysis

1. INTRODUCTION

The laboratory for Acoustics/Noise Control of Empa (Eidgenössische Materialprüfungs- und Forschungsanstalt) is developing a new aircraft noise calculation tool, which can be used to predict noise levels and to develop low-noise landing and take-off procedures. Its main component is a sound source model containing spectral three-dimensional directivity functions of starting and landing aircrafts (1). For this purpose the flight condition is needed, especially the actual engine power setting. Since this information is usually not published by the airlines, a method had to be developed to determine this value by acoustic measurements.

2. THEORETICAL PRINCIPLES

The power of a turbofan engine is determined from its thrust, which can hardly be measured during the flight. Therefore, the rotational speed of the low-pressure shaft, on which the fan is mounted, is commonly used as a substitute quantity. The latter is known as N1 and is given as a percentage of an engine specific reference rotational speed.

2.1 Sound generation

Apart from the pure aerodynamic noise caused by airflow around the aircraft components, the engines are the dominant sound sources of an aircraft. The main sources of the noise emitted by a turbofan engine are the fan, the compressor and the turbine. For the presented method the sound produced by the fan is of particular interest, which is mainly emitted forwards. Therefore, a determination is usually only possible during the approach of the measurement point.

Typical for the noise emitted by the fan and the compressor is a mixture of broadband noise and tonal components. The fundamental frequency of the generated sound is produced by the rotating pressure field of the rotor blades. At a fixed observation point the different pressure ratios on the

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suction and delivery side of a blade lead to alternating pressures (2) whereby the pure tone at the so-called Blade Passing Frequency (BPF) is produced:

\[ BPF = \frac{n}{60} \cdot Z \]  

(1)

where \( n \) is the rotational speed and \( Z \) the number of fan blades.

2.2 Sound propagation

Since aircrafts are relatively fast moving sound sources, the Doppler effect has to be considered to reconstruct the originally emitted frequency. For a sound source moving in three-dimensional space, the received frequency is:

\[ f_R = \frac{f_S}{1 - \frac{v_{\text{rel}}}{c}} \]  

(2)

with the sent frequency \( f_S \) and the relative velocity \( v_{\text{rel}} \) of the source in relation to the receiver (3). The latter can be determined by the scalar product of the velocity \( v \) of the source in relation to its surrounding medium and the unit vector \( e_{SR} \) pointing from the source to the receiver:

\[ v_{\text{rel}} = \vec{V} \cdot \vec{e}_{SR} \]  

(3)

Another frequency depending influence on the sound signal on its way from the aircraft to the receiver is the atmospheric absorption. It depends on the ambient temperature, the air pressure, the relative humidity and the distance. A formula for its calculation is given in the international standard ISO 9613-1 (4). The attenuation strongly increases with the distance for higher frequencies. As a consequence higher harmonics of the BPF are hardly measurable.

In order to determine the exact propagation time from the source to the receiver, the speed of sound has to be calculated by using the ambient temperature. Since the temperature sinks with increasing altitude, the speed of sound decreases, which has an influence on the propagation time and on the Doppler shift. This can be neglected at lower flight levels but should be taken into account for measurements in the far range of an airport.

2.3 Frequency analysis

In order to analyze the frequency content of a signal, it has to be transformed into the frequency domain. For that reason it is divided into short frames which are then transformed using the fast Fourier transform (FFT) algorithm.

To reduce spectral leakage, each frame is multiplied by a window function. The von Hann or so-called Hanning window function is a good tradeoff between main lobe width and side lobe attenuation (5).

By calculating a short-time FFT for every (overlapping) windowed frame and plotting its frequency components with colors corresponding to their amplitudes, a spectrogram is generated. This can be useful to get an overview of the tonal components within a signal changing over time. An example of a spectrogram of the sound signal of a starting aircraft is shown in Figure 1.

3. METHOD

The Empa carried out several measurement campaigns in the close and far range of a large Swiss airport. The measurement of the exemplary event used in this paper was done in the close range, directly below the flight path.

For the figures shown in this paper, the overflight of a starting Airbus A319-112 with two CFM International CFM56-5B engines has been chosen as an example. The fan of this engine type has 36 blades, a diameter of 1.73 m and a maximum rotational speed of 5200 rpm, which results in a maximum BPF of 3120 Hz.
3.1 Input data

The sound of each overflying aircraft was recorded with a sampling rate of 44100 Hz and a 16-bit depth. The length of each recording is 120 s with 60 s before and after passing the measurement point. In order to calculate the sound propagation time and compensate the Doppler shift, the exact position of the aircraft during the overflight of the measurement point must be known. Since radar data provides not the accuracy needed in the close range of an airport, an optical system called SciTrackS has been used to track the position of starting and landing aircrafts with a time resolution of 200 ms. Additionally the following information was provided:

- the engine type to convert the BPF into the engine speed,
- the ambient temperature to calculate the speed of sound,
- the exact time of the shortest distance between the overflying aircraft and the measuring point to synchronize the track and the audio signal.

3.2 Pre-processing

For further processing the audio recordings are reduced to 22050 samples per second (downsampling) as the resulting frequency range up to 11025 Hz is sufficient for the intended analysis. Thereby the data can be halved and the frequency resolution is doubled with constant computing speed. The resulting loss of time resolution can be compensated by using overlapping frames.

Apart from that, the DC offset of the input signal is removed and the amplitude is normalized to its maximum to achieve a stable input.

In order to calculate the short-time spectra, the input signal is divided into short frames of $N = 4096$ samples, which results in a time resolution of 185.6 ms. The latter can be reduced to 46.4 ms by using a 75 % overlap. With the reduced sampling rate the frequency resolution is 5.38 Hz (6).

The frequency range for every overflight is different due to the used engine and velocity dependent Doppler shift. Hence specially designed filters for every event are needed. To compensate the attenuation of higher frequencies, a fourth-order high-pass filter with a cut-off frequency set to the maximum expected BPF is used. Therefore, a typical $N1$ value for the observed part of the starting or
landing procedure is estimated. With the calculated relative velocity the upper and lower frequency limit of a twelfth-order low- and high-pass filter can been be determined. The filters designed for the exemplary overflight are displayed in Figure 2 and the spectrogram of the filtered signal is shown in Figure 3.

![Filter](image)

Figure 2 – Equalization, low-pass and high-pass filter with specific cutoff frequencies for a starting aircraft

### 3.3 Determination

In every calculated short-time spectrum the frequency and level of the absolute maximum is detected. For reasons of noise reduction only peaks above a certain threshold are accepted and otherwise declined. By using the median value of four overlapping frames, the data is smoothed and reduced to the time resolution of the track data. By determining the absolute difference between the frequency of the current and the last peak, only frequencies belonging to the continuous pure tone are selected.

The resulting frequencies are part of the BPF, which is distorted by the Doppler effect. By applying Eq. 2, the constant frequency originally emitted by the fan can be restored. Therefore, the relative velocity of the aircraft has to be calculated according to Eq. 3 by using its tracked position, which is displayed in Figure 4 for the exemplary overflight.

In order to determine the engine speed, the engine specific proportionality constant relating the BPF in Hz to the $N_1$ value in percent is needed. It can be determined by the ratio of two reference values contained in the Type Certificate Data Sheet (TCDS) of the engine, published for example by the EASA (European Aviation Safety Agency) or the FAA (Federal Aviation Administration). Since only the maximum rotational speed in revolutions per minute (rpm) is given, the number of blades $Z$ has to be known to calculate the corresponding BPF (see Eq. 1).

By using the previous selected, Doppler compensated frequencies and the corresponding constant, the $N_1$ values can now be calculated. A further selection is used to eliminate outliers.
Figure 3 – Spectrogram of the filtered sound signal of a starting aircraft

Figure 4 – Calculated relative velocity of a starting aircraft
3.4 Software

The developed method has been realized with GNU Octave, a free high-level interpreted language, primarily intended for numerical computations. It is compatible with Matlab and can be used for batch processing of large amounts of data. The program flow chart, and thereby an overview of the method described above, is shown in Figure 5.

![Program flow chart](image)

4. RESULTS

For this example and other events, the airline Swiss provided cockpit data so that the Empa could validate the position data of the optical tracking system as well as the determined engine speed. For reasons of data protection this information was only available to the Empa, where the comparison was done for 222 events. Since the results were good, this method could be applied to several thousands of overflights.

The comparison of the resulting $N1$ values with the cockpit data for the exemplary take-off used in this paper is shown in Figure 6 and for an exemplary landing in Figure 7. Additionally the piecewise interpolation of the calculated values has been added. The resulting mean deviation is usually less than 2 % $N1$ (for this example 0.93 % $N1$, respectively 0.36 % $N1$).
5. SUMMARY AND OUTLOOK

A method was developed to determine the engine speed of starting and landing aircrafts by acoustic measurements. Therefore, the fundamental frequency of the sound emitted by the rotating fan was identified, tracked and restored by compensating acoustic influences like the Doppler shift.

A comparison with cockpit data showed a very good correlation with a high detection rate and
accuracy. It was shown that the developed method provides reliable results as long as the pure tone produced by the aircraft engines is measurable, which is usually the case in the close range of an airport.

Now the focus lies on improving the results of events where the tonal components could hardly be tracked. These are in particular overflights of landing aircrafts at higher altitudes or aircrafts with large-diameter turbofans and a very low blade passing frequency.

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