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Investigation of the broadband noise sources of counter-rotating open rotors using beamforming

Thesis booklet

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1. INTRODUCTION

The Counter-Rotating Open Rotor (CROR) is an aircraft propulsion engine with favorable characteristics. As a result of the two rotors rotating in opposite directions, it has a much higher efficiency than the turbofan engines commonly used today. Counter-rotating turbomachinery can be used as a substitute for single-rotor turbomachinery, thus increasing efficiency and reducing fuel consumption.

The widespread use of counter-rotating turbomachinery is significantly hampered by some drawbacks, including their high noise emission. The interaction of the two rotors with each other and other non-rotating parts of the support structure results in significant noise emission. It can be concluded that the noise generated by counter-rotating turbomachinery, including the CROR, must be reduced before they can be widely used. For that, knowledge regarding the characteristic noise-generating mechanisms is essential. Microphone array measurement techniques and beamforming technology provide a means for determining the strength and locations of the generated noise sources, thus facilitating acoustic studies.

The generated noise sources can be divided into tonal noise sources associated with the narrow frequency band and broadband noise sources. Tonal noise sources are typically present in the generated noise with high amplitudes, while broadband noise sources are present in a wide frequency range with lower amplitudes. Due to the wide frequency range of occurrence and the successful reduction of tonal noise generation, the broadband component significantly contributes to the noise generated by CROR. Hence, an essential element in reducing CROR noise is the reduction of broadband noise, which requires an understanding of the noise-generation mechanisms. Due to the lower amplitude, it is not practical to investigate broadband noise generation in the presence of a tonal component. However, it is preferable to investigate it separately, which requires an appropriate signal processing technique.

2. LITERATURE REVIEW AND AIMS

The use of microphone array measurement techniques and beamforming is a helpful tool to investigate noise generation; however, it has not been widely used for counter-rotating turbomachinery. Kennedy et al. [1] investigated the noise of a CROR engine attached to a fuselage using beamforming, where they could identify the engine as a noise source. However, the noise generation properties of the CROR were not investigated in detail. Horváth et al. [2] point out the difficulties of investigating the tonal noise sources of a CROR by beamforming, and then in a continuation of their research [3], they conducted a more detailed investigation of the location of tonal noise sources generated by CROR. In [3], broadband noise sources were also investigated, and some typical locations of broadband noise sources were mentioned. Beamforming offers the possibility to investigate noise sources by their location, which the professional community has not yet sufficiently exploited. The main objective of this research is to apply beamforming to investigate the broadband noise of CROR.

Removing the higher amplitude tonal components from the time signal is recommended for the practical analysis of broadband noise sources. Many of the signal processing methods used to separate the tonal and broadband noise components for conventional single-rotor rotating machinery cannot be applied to the generated noise of CROR. Some methods in the literature can be used for counter-rotating turbomachinery. The method developed by Sree [5] applied the averaging operation used in conventional single-rotor turbomachinery. By averaging the time signal per revolution, the repetitive tonal component can be gernerated, while the random broadband component is filtered out. The efficiency of the method depends significantly on the number of averaged time signal sections. In the case of coaxial propfan, only the adjacent rotations can be averaged, making the method less efficient. In his research, he investigated the noise generation of a CROR using a single microphone. Stephens and Vold [4] used Vold-Kalman filtering. The method can generate a time signal for each individual tonal component, which can be summed to obtain the tonal time signal. Subtracting the tonal time signal from the total time signal results in the broadband time signal. The disadvantage of this method is that it requires a rpm signal for efficient operation. By modifying Sree's filtering algorithm, Sree and Stephens created a signal processing method [6] capable of filtering out the rotational tonal noise components of the CROR by directly generating a time signal equivalent to the broadband component. When investigating turbomachinery noise generation, the generated noise may include a rotational tonal component, a non-rotational tonal component, and a broadband component. The method of Sree and Stephens [6] is only suitable for filtering out the rotational tonal component. Sometimes, in addition to the rotational tonal component, another non-rotational tonal component may be present, which may be due to the tonal noise of the setup or the equipment used in the measurement, to the tonal signal component compromising the recorded time signal during signal processing. The data series processed in the present research also contains a non-rotational tonal component, which, like the rotational, limits the analysis of the broadband component, so it is advantageous to filter it out of the time signal. Hence, this research aims to create and apply a signal processing method suitable for removing both the rotational And non-rotational tonal components. The method will benefit from requiring as few input parameters as possible (e.g., no rpm signal required) and from directly generating the broadband component. In addition, it is necessary to use a method whose result can be processed by beamforming, which allows the location of broadband noise sources to be investigated.

Due to the difficulties in investigating the broadband noise generation of CROR, there is a paucity of literature on identifying and investigating broadband noise-generation mechanisms based on measurement results. Broadband noise sources have often been investigated based on simulation or mathematical models of conventional single-rotating turbomachinery noise characteristics. Blandeau [7], in his dissertation on broadband noise sources of CROR, only mentions possible noise-generation mechanisms because they are limited in their verification and identification by measurement results. Stephens, Vold, and Sree, in their publications [4,5,6] on separating the tonal and broadband noise components of CROR, generate the broadband spectrum but do not link it to noise generation mechanisms or identify different broadband noise sources. In his paper [3], Horváth points out some typical broadband noise source locations, which he links to noise-generating mechanisms. Examining tonal and broadband noise sources together imposes a limitation on investigating broadband noise sources, so his findings can be extended. The primary aim of the investigation methods established and applied in the present research is to extend the literature on broadband noise sources of CROR, identify broadband noise-generating mechanisms based on measurement results, and group and classify the different broadband noise sources. The research considered two cases, one with an installed pylon and one without a pylon. The pylon is a streamlined attachment element that significantly affects the noise generation of CROR. The most significant effect is observed for tonal noise sources, but it also affects broadband noise generation. A detailed impact assessment is lacking in the literature, so the impact of the pylon on broadband noise generation has not been identified. My research aims to supplement this impact assessment and define the pylon's effect on the broadband noise propagation of CROR.

3. RESULTS

Sree and Stephens's method of filtering out the rotational tonal component of CROR [6] was further developed to filter out an additional non-rotational tonal component, creating double filtering. As with the rotational tonal component, the presence of a non-rotational component is not desirable when investigating broadband noise sources. I have determined the filtering parameters for the non-rotational component so that it can be effectively filtered out of the time signal. In Sree and Stephens's method, the filtered signal's length is reduced to half the length of the original signal, which limits the signal processability. Double filtering minimizes the signal loss in the process, making the resulting double-filtered time signal suitable for further signal processing.

I. Thesis:

The double filtering method shown in Figure T1.1 is an improvement of the method developed by Sree and Stephens [T1.1] for filtering the rotational tonal signal component of a counter-rotating open rotor to remove the rotational tonal component and a non-rotational tonal component.

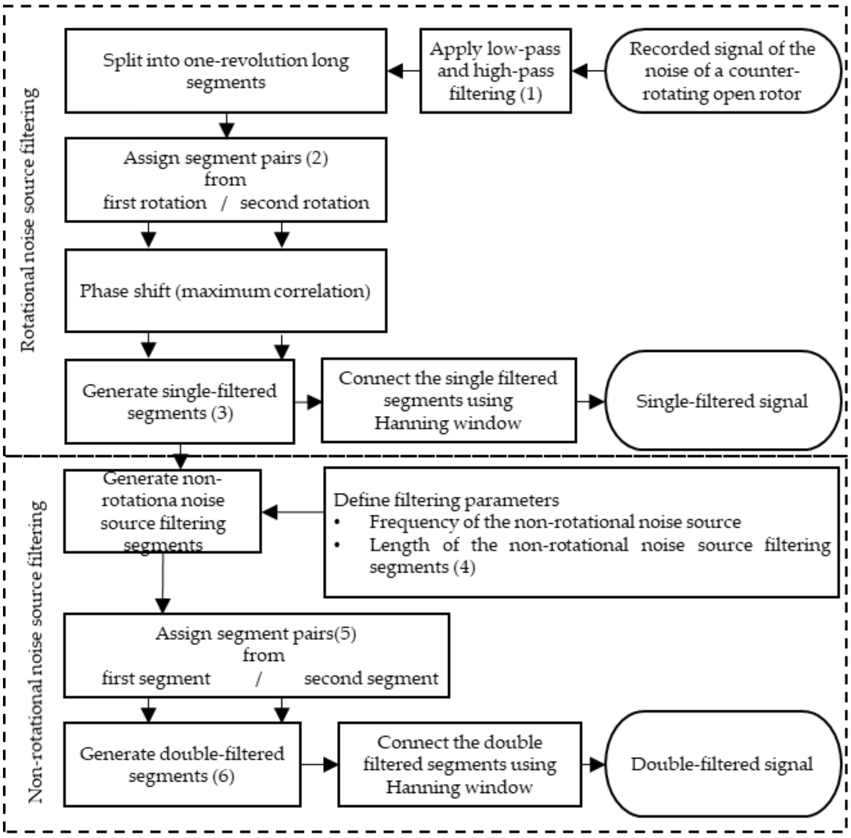

Figure T1.1. Double filtering flowchart, numbering the steps with further explanation

Explanation of some steps of double filtering:

Rotational noise source filtering:

1. **Use a high and low pass filter according to the typical frequency range of the signal component to be tested.**
2. **Assign segment pairs**
    - **starting from the first rotation by selecting neighboring pairs of X and Y segments,**
    - **starting from the second rotation by selecting neighboring pairs of X and Y segments,**

    where X is the first one-revolution-long segment of a pair of segments, and Y is the second one-revolution-long segment of a pair of segments.
3. **Generation of a single-filtered segment:**

$$\mathbf{Z} = \frac{\mathbf{X-Y}}{\sqrt{2}} \qquad \textbf{(T1.1)}$$

where Z is a one-revolution-long single-filtered segment

Non-rotational noise source filtering:

(4) The non-rotational tonal filtering segment length is $k \cdot t$, where k is the number of non-rotational noise source periods in the non-rotational filtering segment, and t (s) is the non-rotational noise source period time. k is an integer in the range $1 \leq k \leq \left\lfloor \frac{T/t}{2} \right\rfloor$, where T (s) is a rotation time and $\lfloor \blacksquare \rfloor$ is the integer part. The value of k within the specified range is the value for which the tonal component to be filtered out disappears from the time signal. The expected value of k can be calculated using equation (T1.2).

$$k_{expected} = \left\lfloor \frac{T/t}{4} \right\rfloor \tag{T1.2}$$

(5) Assign segment pairs

- **starting from the first non-rotational filtering segment by selecting neighboring pairs of x and y segments**
- **starting from the second non-rotational filtering segment by selecting neighboring pairs of x and y segments**

where x is the first and y is the second segment of a pair of segments of length k·t.

(6) Generation of a double-filtered segment:

$$\mathbf{z} = \frac{\mathbf{x-y}}{\sqrt{2}} \tag{T1.3}$$

where z is the double-filtered segment of length $k \cdot t$.

[T1.1] Sree D. and Stephens D. B., "Improved separation of tone and broadband noise components from open rotor acoustic data." Aerospace, Vol. 3, No. 3, 2016. https://doi.org/10.3390/aerospace3030029

Publications related to the thesis: [P1,P2,P3,P4,P5,P6,P7,P8]

Double filtering is applied to microphone array data to generate beamforming maps showing the location of broadband noise sources. The information on the location of noise sources allows the separate analysis of each noise-generating mechanism. Using beamforming to investigate the noise generation of CROR is less common, mainly for investigating broadband noise sources. The double filtering is designed so that the resulting double-filtered signal is suitable for processing by beamforming, thus allowing the location of broadband noise sources to be investigated. During filtering, the time signal is repeatedly divided into shorter sections, which are subtracted from each other to produce the double-filtered signal. Due to these operations, the origin of the noise sources appearing in the double-filtered beamforming maps is uncertain. By analyzing the beamforming operations and the double filtering steps, I have shown that the double-filtered beamforming maps are identical to the beamforming maps obtained for the original broadband component. Hence, the location of the broadband noise sources of CROR can be investigated on double-filtered beamforming maps without the presence of tonal noise sources.

II. Thesis

A double-filtered microphone array data series can be generated by performing double filtering on each time signal of a microphone array measurement data. The double-filtered data series is suitable for beamforming to generate double-filtered beamforming maps. The double-filtered beamforming maps correspond to the beamforming maps obtained for the original broadband component.

Publications related to the thesis: [P1,P2,P3,P5,P6,P8,P9]

By combining double filtering and beamforming, it is possible to investigate the broadband noise sources of CROR over the entire frequency range without the presence of tonal noise sources. By comprehensively examining the double-filtered beamforming maps of the CROR, the location of the broadband noise sources observed within the applied dynamic range can be determined and thus linked to a noise-generating mechanism on a literature basis. Previously, such a detailed broadband noise mechanism study was not possible. With the analysis method I have developed, information can be obtained not only on the strongest broadband component but also on all broadband noise sources which are present in the investigated dynamic range. Knowing the location of each noise source, an independent spectrum per noise source can be generated based on the local peak values of the beamforming level. The typical frequency range of each noise source can be determined by examining the individual spectra. In addition, the significance of the strongest broadband noise source associated with a given frequency and the significance of the weaker broadband components can be determined concerning the resulting broadband noise exposure. As a result of the test method, noise sources resulting from different broadband noise generation mechanisms of the coaxial propfan can be identified, grouped, and classified.

III. Thesis

In the double-filtered beamforming maps of the counter-rotating open rotor, broadband noise sources with different locations can be investigated independently. By examining the beamforming maps for the different frequency bands together

- **the location of broadband noise sources within the applied dynamic range can be identified,**
- **unique beamforming level spectra for each broadband noise source can be created,**
- **one can determine each broadband noise source's**
    - **characteristic frequency range,**
    - **relation to other broadband noise sources,**
    - **role in the resulting broadband noise generation.**

Publications related to the thesis: [P1,P2,P3,P9]

Using double-filtered beamforming maps and the unique spectra associated with each broadband noise source, it is possible to investigate the impact of different configurations (e.g., with and without pylon) or different operating parameters (e.g., rotational speed) on the broadband noise emissions of CROR. Using measured data, assessing the impact on the resulting broadband noise emissions has been challenging, but assessing the impact on individual noise sources has been more difficult. The test method I have developed can be used to determine the effect of a given property of the CROR on each broadband noise source appearing in the beamforming maps.

IV. Thesis

Using double-filtered beamforming maps and unique broadband noise source spectra of counter-rotating open rotors with different properties, the impact of a given property can be assessed on each broadband noise source's

- **presence,**
- **characteristic frequency range,**
- **relationship to other broadband noise sources,**
- **role in the resulting broadband noise generation.**

Publications related to the thesis: [P3,P9]

Using the developed double filtering and testing method, I investigated the broadband noise sources of a CROR, and also I showed the effect of the pylon installation on the broadband noise generation. I have determined the characteristic frequency of a noise source that appears at a given location and the frequency range in which it is found to be the dominant broadband noise source. I have identified the new broadband noise-generation mechanisms that emerge due to the installation of a pylon and the changes that occur in broadband noise sources that are present without a pylon. I have established a reference database for broadband noise generation from CROR by systematizing and grouping the identified noise sources. The database includes information on the specific location, frequency range, and dominant frequency range of broadband noise sources appearing in beamforming maps. The database provides guidance on classifying and grouping broadband noise sources of CROR. By extending the database with additional cases, a knowledge base on CROR's broadband noise generation can be created, which can serve as a reference for research on the broadband noise generation of CROR by simulation or mathematical modeling and as a valuable tool for noise reduction efforts.

V. Thesis

By testing the counter-rotating open rotors with and without pylon with the geometry, operational, assembly, and installation characteristics shown in Table T5.1, along with the measurement, signal processing, and beamforming parameters shown in Table T5.1,

the basis for the systematic reference database shown in Table T5.2 has been established, which contains the typical broadband noise sources of the counter-rotating open rotors under investigation. As a result of the installation of a pylon, a dominant blade tip noise source appears on the pressure side of the aft rotor blades, a non-dominant trailing-edge noise source appears on the suction side of the forward rotor blades, and the leading-edge noise source on the pressure side of the aft rotor blades is amplified and becomes a dominant noise source.

Table T5.1 Properties and test parameters of the tested counter-rotating open rotors

Setup	Uninstalled, without a pylon	Installed with a pylon
Blade type	Historical baseline F31/A31	Historical baseline F31/A31
Forward rotor blade number	12	12
Aft rotor blade number	10	10
Forward rotor diameter (m)	0.652	0.652
Aft rotor diameter (m)	0.630	0.630
Forward rotor blade angle (°)	33.5	33.5
Aft rotor blade angle (°)	35.7	35.7
Rotational speed (revolution/min)	5716	5753
Mach number (-)	0.2	0.2
The angle of attack (°)	0	0
Temperature(°C)	28.38	32.1
Microphone array	OptiNav Array48	OptiNav Array48
Distance between the array and the investigation plane (m)	1.6	1.6
Sampling frequency (Hz)	96000	96000
Length of the rotational noise source filtering segments (s)	0.01050	0.01043
Frequency of the non-rotational noise source (Hz)	3129	3149
Length of the non-rotational noise source filtering segments (s)	0.00224	0.00254
Beamforming algorithm	Frequency Domain Beamforming	Frequency Domain Beamforming
CSM diagonal operation	Delete	Delete
Fourier transformation window size (datapoint)	4096	4096
Fourier transformation overlap	50%	50%
Frequency bin width (Hz)	250	250
Dynamic range (dB)	5	5

Table T5.2 Identified broadband noise sources and their properties

Location on a blade	**Forward (F) or aft rotor (A)**	**Pressure side (P) or suction side (S) of the blades**	**Characteristic frequency (Hz)**		**Dominant noise source frequency range (Hz)**	
			Uninstalled	**Installed pylon**	**Uninstalled**	**Installed pylon**
Blade root	A	S	1500-9000	1500-9000	1500-8000	1500-7000
Blade root	A	P	1500-2500; 5000-6500	1500-2500; 5000-6500	5750-6500	1500-2250; 5750-6500
Trailing edge	F	S	-	4500-10000	-	-
Trailing edge	F	P	6500-15000	6500-15000	7500-15000	9500-15000
Leading edge	A	S	7000-15000	7000-15000	-	-
Leading edge	A	P	7000-15000	7000-15000	-	-
Blade tip	A	P	-	7000-15000	-	7000-10000

Publications related to the thesis: [P1,P3,P10]

4. PUBLICATIONS RELATED TO THE THESES

[P1] Tokaji, K., Soós Bálint, Horváth, Cs.: Beamforming method for extracting the broadband noise sources of counter-rotating open rotors, AIAA Journal, vol. 58, no 7, 2020. https://doi.org/10.2514/1.J058934

[P2] Tokaji, K., Soós Bálint, Horváth, Cs., “Extracting and understanding the less dominant broadband noise sources of counter-rotating open rotors,“ 25th AIAA/CEAS Aeroacoustics Conference (2019)

[P3] Tokaji, K., Horváth Cs., "Effect of a pylon on the broadband noise sources of counter-rotating turbomachinery." International Journal of Aeroacoustics, vol. 20, no. 8, 2021, pp. 979-1002. https://doi.org/10.1177/1475472X211055178

[P4] Tokaji K., Horváth Cs., “Method for isolating the tonal components of counter-rotating turbomachinery phased array microphone data for beamforming.” 48th International Congress and Exhibition on Noise Control Engineering, INTER-NOISE 2019, (2019)

[P5] Tokaji, K., Soós Bálint, Horváth, Cs., “Koaxiális forgógép keskenysávú zaj vizsgálatára alkalmas módszer fejlesztése.“ Tavaszi Szél 2020 Konferenciakötet, Budapest, 2020.10.16, pp. 781-793.

[P6] Tokaji, K., Soós Bálint, Horváth, Cs., “Koaxiális forgógép zajvizsgálati módszereinek továbbfejlesztése és alkalmazása mérési eredményekre.“ Tavaszi Szél Konferencia 2021 Tanulmánykötet II., pp 167-180

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