PROJECT NKFI K 119943

"Aeroacoustic and aerodynamic investigation of counter-rotating open rotors, utilizing beamforming methods"

FINAL TECHNICAL REPORT

In this Technical Report, only the publications elaborated within the framework of the project and listed in approximate chronological order at the end of the Report are referenced. These publications cite the recent international technical literature representing the state of the art in the project topic, thus supporting the novelty content and the technical merit of the project results.

1. PROJECT TARGETS, PRACTICAL RELEVANCE

The increased fuel prices of the 1970s and 1980s, resulted in engine developers testing alternative solutions, such as Counter-Rotating Open Rotor (CROR) propulsion systems as a possible means by which to reduce the fuel burn of aircrafts while maintaining similar cruise speeds to that achieved using turbofan engines. Many questions and concerns with regard to the implementation of CROR technology were addressed, but not all were fully resolved at that time. One of these concerns was the challenge of reducing the noise of CROR engines in order to meet noise regulations, while maintaining their advantageous propulsive efficiency. A renewed interest in the technology has led to many engine developers and research institutions revisiting the topic and furthering the work carried out in the past. Recent investigations have answered many questions that remained and have brought the technology one step closer to appearing on commercial aircrafts. In 2019, the Open Rotor demonstrator, which is a part of the Clean Sky Program, was awarded Aviation Week's Annual Laureate Award in the category of Propulsion. The reward recognizes major achievements in aerospace and defense, and hence the state-of-the-art research and development effort of the approximately 50 partners participating in the project. I mention this, as it shows that ***many hurdles have been overcome by the community in the further development of CROR technology, and it can be expected that efforts will continue with the goal of putting the technology on the market***.

Beamforming can play a key role in further understanding and hence eliminating the noise sources of CROR. Prior to the research of the team carrying out this project, no planar phased array microphone measurement data was presented in the literature. The first publications by the team showed that beamforming results of planar phased array microphone measurements of a CROR are difficult to comprehend, as they can be misleading in nature. On the other hand, having vast experience and knowledge regarding phased array microphone beamforming measurements of turbomachinery test cases, and combining what has been learned from phased array microphone measurements with what has been learned from other turbomachinery measurement and simulation methodologies, as well as theoretical investigations, has led to a great deal of useful information being extracted from the beamforming results.

This research teams experience and knowledge regarding turbomachinery aerodynamics and aeroacoustics, especially with regard to uninstalled CROR, has been essential in accurately interpreting the beamforming results of CROR with a pylon. ***The results presented herein have filled a void in the literature regarding the effect of a pylon on the noise signature of a CROR, have provided novel methods for evaluating the broadband, tonal, as well as shaft order noise sources of CROR, and have provided design guidelines for CROR of reduced noise.***

The following project targets were established prior to beginning the project, and reached during the course of the funding:

- ***To investigate the aerodynamic and aeroacoustic effects of a pylon on CROR operation and the resulting noise signature.***
- ***To further develop beamforming approaches to be applied on CROR data in order to take into account the effect of a pylon on CROR noise signature with regard to both tonal as well as broadband noise.***
- ***To categorize CROR and pylon noise sources according to noise generation mechanism, location, character, and significance, with regard to broadband and tonal noise sources of CROR with a pylon.***
- ***To provide a better understanding as to the connection between the aerodynamics and aeroacoustics of CROR with a pylon, making it possible to determine the noise generation mechanisms and to make suggestions as to their reduction or even elimination.***
- ***To provide aerodynamic and aeroacoustic design guidelines for CROR.***

2. PROJECT ACTIVITIES

2.1. Investigated the aerodynamic and aeroacoustic effects of a pylon on CROR operation and the resulting noise signature.

Throughout the funding period, the main goal has been to investigate, better understand, and document the noise sources of an installed CROR with a pylon as compared to an uninstalled CROR without a pylon. Ultimately, the goal has been to understand these noise sources and provide guidelines for avoiding or eliminating them. In a first approach, methods developed by the participants prior to the funding were further developed and applied in the beamforming investigations in order to investigate the tonal and broadband noise sources. This was not only done in order to study the noise sources, but also to reevaluate the advantages and disadvantages of the approaches at hand in the investigation of the effect of the pylon. Results from the investigations utilizing these methods have shown that ***a properly designed pylon, at zero angle-of-attack, and placed upstream of a CROR, can have minimal influence on the rotating broadband noise sources [4 and 21]***. It has also been shown that ***the tonal noise character of an installed CROR is significantly altered by the addition of a pylon placed upstream of the forward rotor [4 and 21]***. Tones falling in the Blade Passing Frequency (BPF) bins have shown a significant increase in Sound Pressure Level (SPL). It has been determined that this increase results from the wake of the pylon interacting with the rotor blades. A novel approach has been introduced for separating the noise of the pylon wake interacting with the rotor blades (a stationary coherent noise source) from that of the BPF (a rotating coherent noise source).

In order to identify those noise sources which are associated purely with the pylon, as compared to those which result from the interaction of the pylon and the rotors, an investigation has been carried out on the CROR test rig without blades, with and without a pylon, from both a tonal as well as broadband point of view. It has been concluded that ***a properly designed pylon at zero angle-of-attack can be characterized as having insignificant noise sources on its surface [12].***

2.2. Further developed beamforming approaches to be applied on CROR data in order to take into account the effect of a pylon on CROR noise signature with regard to both tonal as well as broadband noise.

In the investigation of the broadband noise of a given CROR test case with and without a pylon, it has been found that the broadband noise associated with the installed case differs only slightly from the uninstalled case. It has also been shown that the frequency range which can be investigated using common beamforming methods is rather limited, as the spectrum of a CROR is typically dominated by tonal components, which are much louder than the broadband noise sources. These aspects have presented a need for a method which can investigate the broadband noise sources more effectively and in greater detail. Therefore, ***a novel approach has been developed, which preprocesses the time signals collected for each microphone prior to carrying out the beamforming step. By doing so, it is possible to carry out the beamforming for only the broadband portion of the signal, removing the disturbing tonal components from the noise source maps.*** The development of this method has opened the door for many opportunities during the investigation of turbomachinery as well as other periodically repeating test cases, as the frequency bins which were formerly dominated by tonal noise sources can now by investigated in order to better understand the broadband noise sources. The method is described in detail in [10, 14, and 19].

In parallel to the development of a beamforming method for extracting and investigating the broadband noise sources, ***a novel approach has been developed for investigating those noise sources which are periodically reoccurring throughout the spectrum (in the frequency domain).*** The method couples beamforming with Common-Base Proper Orthogonal Decomposition (CPOD), taking advantage of the capabilities of CPOD analysis in identifying reoccurring phenomena, even if those are of relatively small amplitude. ***The method helps reduce the subjective nature of identifying and sorting noise sources into groups.*** It has been successfully applied in the investigation of shaft order noise sources, shedding light on the aerodynamic disturbances leading to the noise sources [7, 15, and 20]. The method has also been applied in the investigation of BPF tones [17], and is currently being applied in the investigation of interaction tones.

In an effort to remove the disturbing broadband noise sources from the noise source maps during tonal noise source investigations, cross-spectral matrix operations have been used in order to subtract the broadband signals from the phased array microphone data, making it possible to isolate the purely tonal components on noise source maps and investigate them. The investigated methods have proven to be effective in decreasing the levels or even removing the broadband components under certain conditions [16]. These methods are currently being combined with the CPOD method described above in order to further improve our capabilities in localizing tonal noise sources that have relatively small amplitudes. As seen here and in the two previously described methods, ***we have successfully developed beamforming methods for separately processing the broadband and tonal noise source components of CROR from a single set of data.***

Once the turbomachinery broadband and tonal noise sources have been identified using the methods described above, it is important to determine which of those noise sources are resulting from the same noise generation mechanisms. ***We have algorithmized the procedure of determining which noise sources are generated by the same mechanism by applying a fuzzy c-means clustering method to turbomachinery beamforming results [5].*** It can be seen here as well as in the methods described above, that the efforts of the research group ***have provided objective algorithmic methods for localizing and grouping tonal as well as broadband noise sources without influence from subjective factors (such as visual inspection of beamforming maps and optics-based resolution criteria).***

Though the research effort of the research team has shown that rotating coherent noise sources of CROR align with their Mach radii when investigated from the sideline [1], it would be even more useful to localize these noise sources to their true noise source locations. ***New beamforming methods are therefore being developed by our group, with the intent of localizing rotating coherent noise sources to their true positions rather than to the associated Mach radii.*** The foundation of two such methods has been laid in [8], with further investigations being carried out at present.

Going beyond CROR investigations, the beamforming methods developed and applied here in the investigation of unducted turbomachinery would prove useful in the investigation of ducted turbomachinery. ***In order to apply the knowledge and methods developed within the framework of this study to ducted turbomachinery, an Acoustically Transparent Duct (ATD) has been***

developed [1-2, and 6] and applied in a comparison of multiple turbomachinery configurations [11].

2.3. Categorized CROR and pylon noise sources according to noise generation mechanism, location, character, and significance, with regard to broadband and tonal noise sources of CROR with a pylon.

It can be seen in section 2.1 that the investigations regarding the influence of a pylon on the noise sources of a CROR have led to a better understanding of the noise sources. The noise sources have been categorized, with new categories being identified, as compared to what was known from the literature. These results have shown that ***the noise components falling in the BPF bins are resulting from multiple noise sources, with the one being associated with the BPF (a rotating coherent noise source) and the other with the wake of the pylon interacting with the rotor blades (stationary coherent noise source) [4 and 21].***

Investigations carried out on the test rig with the rotor blades removed have provided a better understanding of the noise sources associated with the stand-alone pylon [12]. These investigations have been further supplemented with investigations that looked at the vortex shedding of various pylon geometries [18]. ***As an outcome of our investigations, the noise sources in the category of pylon self-noise are now easily identifiable, making them easily categorizable.***

It can be seen in section 2.2 that many methods have been developed during the investigations carried out under this funding which can be used to identify and localize various categories of noise sources more easily and with less subjectivity. These methods focus on rotating incoherent noise sources (rotating broadband noise sources [4-5, 10, 14, and 19] and shaft order noise sources [4, 7, 15, and 20]), rotating coherent noise sources (BPF and interaction tone noise sources [4, 7-8, 15-17, and 20]), and stationary coherent noise sources (blade-wake interaction noise sources [4]). Our research has ***provided a methodology for categorizing noise sources into these various categories using beamforming investigations [21].***

2.4. Provided a better understanding as to the connection between the aerodynamics and aeroacoustics of CROR with a pylon, making it possible to determine the noise generation mechanisms and to make suggestions as to their reduction or even elimination.

Upon carrying out the above stated investigations, multiple novel beamforming methods have been defined and developed. In the development and application of these new methods, ***knowledge has been gathered regarding the noise sources, their extent, magnitude, and generation mechanisms.*** Some information regarding the influence of the pylon on the aerodynamic and aeroacoustic characteristics of CROR has been given in the articles which describe the methods [1, 7, 10, 14-17, and 19-20]. As the main focus of these articles has been on the investigation methods and not on the influence of the pylon on the noise sources of CROR, we are currently in the process of comparing the installed and uninstalled CROR test cases in greater detail in order to draw further conclusions regarding the influence of the pylon on the noise signature of CROR. These results will provide the final elements in the research carried out by two of the PhD students involved in the project, providing them with the application results needed for supporting the relevance of their methods. The results will be published in at least two journal articles and two PhD dissertations, adding at least two further journal publications to the list appearing at the end of this report.

The following conclusions have been drawn from the current results, with further significant results expected from applying the advanced methods developed herein, as stated above:

- ***Concluded that a properly designed pylon at zero angle-of-attack can have minimal influence on the rotating broadband noise sources of a CROR [21].***

- ***Found that the tonal noise character of an installed CROR is significantly altered by the addition of a pylon upstream of the forward rotor. Tones falling in the Blade Passing Frequency (BPF) bins show a significant increase in Sound Pressure Level (SPL). It was shown that this increase results from the wake of the pylon interacting with the rotor blades [21].***

2.5. Provided aerodynamic and aeroacoustic design guidelines for CROR.

During this study, a theoretical investigation into the noise reduction of CROR via radiation efficiency considerations has been carried out. The results have shown that ***by choosing a large and equal number of blades for the forward and aft rotors of a CROR, the noise propagating in the radial direction can be reduced [3 and 13].*** The investigations have gone on to show that ***if the blade numbers are kept equal and the relative rpm of the two rotors are varied, the noise signature can be further altered without sacrificing what has been won in noise reduction in the radial direction [9].*** This is significant since most observers are located in this direction and hence this gives a means for reducing the noise reaching observers without the use of shielding. It is interesting to note that ***though the design guidelines have been created with the aim of reducing the noise in the radial direction, no noise penalty was experienced in the axial direction [3 and 13].*** Further work is being carried out on understanding the radiation efficiency of rotating coherent noise sources and taking advantage of this characteristic in defining design guidelines for engineers developing CROR.

3. PUBLICATIONS; INVOLVEMENT OF YOUNG RESEARCHERS; EDUCATION OF TALENTED STUDENTS

In the Research Plan, the following publication activity was planned for the entire project:

- 9 international conference papers
- 5 international journal papers

The publication activity has been realized as follows:

- 1 international summer school poster [1]
- 3 international workshop presentations [2-4]
- 12 international conference papers [7-18], including: European Conference on Turbomachinery Fluid Dynamics and Thermodynamics / Conference on Modelling Fluid Flow / Berlin Beamforming Conference / International Conference of Fan Noise, Aerodynamics, Applications and Systems / AIAA/CEAS Aeroacoustics Conference / International Congress and Exhibition on Noise Control Engineering
- 3 journal papers: [5, 6, 21], including: Journal of Sound and Vibration – Q1, IF (2017): 2.618 / International Journal of Aeroacoustics – Q3, IF (2018): 0.866 / Acta Acustica united with Acustica – Q3, IF (2018): 1.037
- 2 journal papers (under review): [19-20], including: AIAA Journal – Q2, IF (2018): 1.951

- The project has contributed to the doctoral programs of 5 PhD students / PhD candidates (TÓTH Bence Mihály, BALLA Esztella Éva, FENYVESI Bence, TOKAJI Kristóf, and KOCSIS Bálint).
- In developing young talent, 7 further talented engineering students have been involved in various aspects of the project.

4. REALIZED AND ENVISIONED PRACTICAL UTILIZATION OF THE PROJECT RESULTS: AN OUTLOOK

This project has investigated CROR technology with the help of phased array microphones and beamforming methods. As seen above, many methods have been developed, noise sources have been localized, investigated, and conclusions have been drawn regarding the noise generation mechanisms of CROR. The gained knowledge has been used to suggest design guidelines for engineers working with the technology in order to help in reducing or even eliminating the noise sources of CROR, but many aspects can be further investigated.

In the near term, the newly developed beamforming methods will be used in order to ***further study the effect of a pylon on the noise of CROR in greater detail***. The results are expected to show a more detailed map of the noise sources which could not be seen in the noise source maps of commonly used beamforming methods. Conclusions will be drawn and published within a short amount of time.

In the long term, the research carried out herein will be carried on along multiple strands. The first ***will look at the influence of wind direction (angle-of-attack) on the noise of CROR*** with the methods developed herein. Preliminary results have appeared in a student competition paper (TDK) and will be submitted to a Hungarian conference in the beginning of the year. The second strand ***will look at the influence of varying the rpm of the rotors on the noise of CROR***. Preliminary results for this research have also appeared in a student competition paper (TDK). A third strand ***will carry over the knowledge gained and the methods developed in this investigation to the topic of Vertical Take-off and Landing (VTOL) aircraft, such as drones/quadcopters***. It is expected that the experience and knowledge gained in this field will be very useful in helping the development of the young and quickly developing field of VTOL technology.

5. PUBLICATIONS ELABORATED WITHIN THE FRAMEWORK OF THE PROJECT

[1] Balla, E., Benedek, T., Fenyvesi, B., Horváth, Cs., Tokaji, K., Tóth, B., and Vad, J., Turbomachinery Noise Localization and Reduction, ADOPSYS Summer School 2017, Ecully, France, July 3-5, 2017 (poster).

[2] Tokaji, K., and Horváth, Cs., Acoustically Transparent Duct. 21st Workshop of the Aeroacoustics Specialists Committee of the CEAS, Dublin, Ireland, September 13-15, 2017, (presentation).

[3] Horváth, Cs., Fenyvesi, B., Quaglia, M., Moreau, S., Kennedy, J., and Bennett, G., Counter-Rotating Open Rotor Noise Reduction via Blade Number and Radiation Efficiency Considerations. 21st Workshop of the Aeroacoustics Specialists Committee of the CEAS, Dublin, Ireland, September 13-15, 2017, (presentation).

[4] Fenyvesi, B., Tokaji, K., and Horváth, Cs., Investigation of a pylons effect on the character of counter-rotating open rotor noise using beamforming technology. 21st Workshop of the Aeroacoustics Specialists Committee of the CEAS, Dublin, Ireland, September 13-15, 2017, (presentation).

[5] Tóth, B., and Vad, J., Algorithmic Localization of Noise Sources in the Tip Region of a Low-Speed Axial Flow Fan, Journal of Sound and Vibration 393 (2017) pp. 425-441. (2017).

[6] Tokaji, K., and Horváth, Cs., Acoustically Transparent Duct, International Journal of Aeroacoustics 17:(3) pp. 238-258. (2018).

[7] Fenyvesi, B., Simon, E., Kriegseis, J., and Horváth, Cs., Investigation of turbomachinery noise sources using beamforming technology and proper orthogonal decomposition methods, In: Conference on Modelling Fluid Flow (CMFF'18): The 17th International Conference on

Fluid Flow Technologies. Budapest, Hungary, 2018.09.04-2018.09.07. Budapest: Paper CMFF18-032. 8 p. (ISBN:978-963313297-5).

[8] Horváth, Cs., and Kocsis, B., Towards a Doppler effect based beamforming method for rotating coherent noise sources, In: 7th Berlin Beamforming Conference (BeBeC). Berlin-Adlershof, Germany, 2018.03.05-2018.03.06. Paper BeBeC-2018-D27. 14 p.

[9] Horváth, Cs., Fenyvesi, B., and Kocsis, B., Drone noise reduction via radiation efficiency considerations, In: Conference on Modelling Fluid Flow (CMFF'18): The 17th International Conference on Fluid Flow Technologies. Budapest, Hungary, 2018.09.04-2018.09.07. Budapest: Paper CMFF-001. 7 p. (ISBN:978-963313297-5).

[10] Tokaji, K., and Horváth, Cs., Combining signal pre-processing methods with beamforming for broadband turbomachinery applications, In: 7th Berlin Beamforming Conference (BeBeC). Berlin-Adlershof, Germany, 2018.03.05-2018.03.06. Paper D28. 12 p.

[11] Tokaji, K., Szeker, B., and Horváth, Cs., Comparison of multiple fan system assemblies using an acoustically transparent duct, In: FAN 2018 International Conference of Fan Noise, Aerodynamics, Applications and Systems. Darmstadt, Germany, 2018.04.18-2018.04.20. Paper FAN2018-33. 12 p.

[12] Tokaji, K., Fenyvesi, B., Kocsis, B., and Horváth, Cs., Investigation of the noise sources of a pylon, In: Conference on Modelling Fluid Flow (CMFF'18): The 17th International Conference on Fluid Flow Technologies. Budapest, Hungary, 2018.09.04-2018.09.07. Budapest: Paper CMFF-011. 8 p. (ISBN:978-963313297-5).

[13] Horváth, Cs., Fenyvesi, B., Kocsis, B., Quaglia, M., Moreau, S., Kennedy, J., and Bennett, G.J., Towards Counter-Rotating Open Rotor Noise Reduction via Radiation Efficiency Considerations, In: 25th AIAA/CEAS Aeroacoustics Conference. Delft, The Netherlands, 2019.05.20-2019.05.23. Paper 6.2019-2548. 16 p. (DOI: 10.2514/6.2019-2548).

[14] Tokaji, K., Soós, B., and Horváth, Cs., Extracting the Broadband Noise Sources of Counter-Rotating Open Rotors, In: 25th AIAA/CEAS Aeroacoustics Conference. Delft, The Netherlands, 2019.05.20-2019.05.23. Paper 6.2019-2572. 22p. (DOI: 10.2514/6.2019-2572).

[15] Fenyvesi, B., Horváth, Cs., and Kriegseis, J., Application of a Combined Method for the Investigation of Turbomachinery Noise Sources: Beamforming and Proper Orthogonal Decomposition, In: 25th AIAA/CEAS Aeroacoustics Conference. Delft, The Netherlands, 2019.05.20-2019.05.23. Paper 6.2019-2637. 17 p. (DOI: 10.2514/6.2019-2637).

[16] Tokaji, K., and Horváth, Cs., Method for Isolating the Tonal Components of Counter-Rotating Turbomachinery Phased Array Microphone Data for Beamforming, In: 48th International Congress and Exhibition on Noise Control Engineering. Madrid, Spain, 2019.06.16-2019.06.19. Paper 1698. 12p.

[17] Fenyvesi, B., Kriegseis, J., and Horváth, Cs., Investigation of Rotating Coherent BPF Noise Sources via the Application of Beamforming and Proper Orthogonal Decomposition, In: 48th International Congress and Exhibition on Noise Control Engineering. Madrid, Spain, 2019.06.16-2019.06.19. Paper 1572. 12 p.

[18] Balla, E., and Vad, J., A Semi-Empirical Model for Predicting the Frequency of Profile Vortex Shedding Relevant to Low-Speed Axial Fan Blade Sections, In: 13th European Conference on Turbomachinery Fluid Dynamics & Thermodynamics, ETC13. Lausanne, Switzerland, 2019.04.08-2019.04.12. Paper ETC2019-311. 12 p.

[19] Tokaji, K., and Horváth, Cs., Beamforming Method for Extracting the Broadband Noise Sources of Counter-Rotating Open Rotors, AIAA Journal (submitted), (2019).

[20] Fenyvesi, B., Horváth, Cs., and Kriegseis, J., Application of a Combined Method for the Investigation of Turbomachinery Noise Sources: Beamforming and Proper Orthogonal Decomposition, AIAA Journal (submitted), (2019).

[21] Fenyvesi, B., Tokaji, K., and Horváth, Cs., Investigation of a Pylons Effect on the Character of Counter-Rotating Open Rotor Noise Using Beamforming Technology, Acta Acustica united with Acustica, 105 (2019) pp. 56-65, (2019).