

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

Investigation of Counter-Rotating Open Rotors Using Phased Array Beamforming Technology

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Introduction

During the course of my research, I have investigated Counter-Rotating Open Rotor (CROR) propulsion systems using phased array microphone beamforming methods. As a result of the increased fuel prices of the 1970s and 1980s, CROR were investigated as a possible means by which to reduce the fuel burn of aircrafts while maintaining similar cruise speeds to that of turbofan aircrafts. There are many questions and concerns with regard to the implementation of CROR technology, which were only partially resolved during these tests. 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. The interest in a radically new engine technology diminished as fuel prices fell and therefore the research and development programs of the 1980s were ended.

A renewed interest has been triggered by rising fuel prices, as well as the increasingly stringent limitations regarding aircraft greenhouse-gas emissions and noise, which have led designers of modern aircraft engines back to the further investigation of CROR propulsion systems. It is believed that state-of-the-art testing and simulation technology will help in resolving the remaining questions and challenges. With regard to noise levels, state-of-the-art beamforming technology has made the localization and investigation of noise sources of complex aeroacoustic phenomena a realizable task. The deciphering of the beamforming maps of rotating noise sources on the other hand poses a great challenge, requiring the development of new beamforming measurement and post-processing techniques.

This dissertation consists of three sections. In the first section, it is explained how the interaction patterns of circumferential spinning modes of rotating coherent noise sources interact with phased arrays, often giving misleading results, as the apparent sources do not show where the actual noise sources are located, but rather point to the Mach radius. These important results help explain the beamforming maps of CROR and are valid for rotating coherent noise sources in general.

The second section of the dissertation examines the tonal noise sources of a CROR with the help of beamforming maps. A novel approach to evaluating the results is used for identifying noise generation mechanisms which are significant contributors to the radiating sound field of uninstalled CROR, grouping them into families accordingly.

The third section introduces a novel approach for investigating the broadband noise sources of an uninstalled CROR with the help of beamforming maps. In addition, an explanation is given regarding the origin of particular tonal noise sources which do not line up with their Mach radii.

The application of phased array microphone beamforming methods to turbomachinery research is made much more effective with the help of the methods presented in the dissertation. The results presented herein will aid in the further development of the state of the art of CROR technology.

Results

The application of beamforming analysis to counter-rotating open rotors was examined in this dissertation. It was shown that conventional beamforming techniques place the apparent sources of noise for certain tones off the blade (outboard of the tip or inboard of the root). These misleading results were explained by appealing to the concept of Mach radius and further elucidated by examining the predicted spiraling wavefronts emanating from the CROR, tracing the normal to the wavefronts at the location of the phased array back to the apparent source region. Together, these theoretical devices provide a robust explanation of the nature of the beamforming maps. It was further shown that the apparent source location corresponding to a rotating coherent noise source will always be at the Mach radius regardless of whether the Mach radius is smaller or larger than the blade tip radius. For real blades, it was shown that beamforming may place the dominant noise source of a tone at a location other than the Mach radius due to variations in the blade geometry, due to sources which are not accounted for in the simulations, or due to the tonal components being buried in the broadband. These results support the findings, giving evidence that only rotating coherent noise sources will be localized to the Mach radius, and incoherent noise sources and rotating incoherent noise sources of CROR will be localized to their true locations.

A series of planar phased array microphone measurements conducted on the F31/A31 Historical Baseline Blade Set in the Low Speed Wind Tunnel of NASA Glenn Research Center were presented. These CROR beamforming results provide a means for validating research tools, as well as offering the research community a data set for the investigation of CROR. The design takeoff nominal and approach conditions were investigated using a novel approach in analyzing the tonal noise sources. Though the results do not provide noise source distributions along the blades, they are significant, identifying the noise sources which are truly responsible for the investigated BPF or interaction tones, separating them from all other noise sources. The axial and radial positioning of the noise sources was investigated, giving insight into the effects of the potential-flow field and viscous wake loading of the rotors on the noise signature of CROR and organizing the interaction tones accordingly. The state of the art of CROR noise reduction has therefore

been advanced by a means of localizing noise sources to a given rotor and sorting them according to noise source mechanism. The results were then organized into groups, setting out families of interaction tones which dominate the sound field of CROR at design takeoff nominal and approach conditions from the rest of the interaction tones. This advances the state of the art of CROR noise reduction by limiting the tonal noise sources to a few families, which need to be taken into consideration when designing CROR of low noise. The dominant noise source families of the uninstalled F31/A31 CROR at design takeoff nominal and approach conditions are $XBPF_F+XBPF_A$, $1BPF_F+YBPF_A$, $2BPF_F+YBPF_A$, and $XBPF_F+2BPF_A$. Subscripts F and A refer to the forward and aft rotors, respectively. X and Y are positive whole numbers. For other designs, a shift of the dominant noise source families within the presented tables (e.g. $(X + 1)BPF_F + XBPF_A$ instead of $XBPF_F+XBPF_A$), as well as some slight variations regarding the significance of given families of interaction tones is expected.

The broadband noise sources of the design takeoff nominal and approach conditions were also investigated using a novel approach in analyzing the beamforming results, localizing broadband noise sources of CROR to given sections of the forward and aft rotors. The method advances the state of the art of CROR measurement technique by providing a means by which CROR broadband noise sources can easily be localized, identified, and sorted according to noise generation mechanism. The results were analyzed, setting out broadband noise sources which dominate the noise signature of the F31/A31 Historical Baseline Blade Set at design takeoff nominal and approach conditions from other possible broadband noise sources. The results also give an answer as to why certain shaft order peaks in the PSD spectra do not align with their Mach radii in the beamforming maps. The localization of the noise sources of the given shaft orders advances the state of the art of beamforming for turbomachinery by presenting how beamforming can be used to identify the true noise sources in a case where the turbomachinery noise sources are incoherent or rotating incoherent. Without such a beamforming method, the true source of the noise would be unknown and would misleadingly be associated with either the broadband or the rotating coherent tonal noise sources of CROR.

The methodologies presented in this investigation will be applied in future studies, comparing the other elements of the test matrix to the design cases presented here. The novel beamforming methods also provide other researchers with a tool for evaluating their own results. The methods and the results presented in this investigation will help in advancing CROR technology to a new level, hopefully not just meeting, but going beyond the expectations of environmental regulations.

Thesis Statements

1. Turbomachinery tonal noise sources are investigated and a novel approach is presented for investigating the beamforming results of tonal noise sources of unducted turbomachinery.
 - (a) The approach applies the Mach radius concept in order to locate the noise sources which are truly responsible for the investigated BPF or interaction tones, separating them from all other noise sources in the given frequency bin.
 - (b) The approach is applied to uninstalled counter-rotating open rotors. The axial and radial positioning of the tonal noise sources is investigated, giving insight into the effects of the potential-flow field and viscous wake loading of the rotors on the sound field of counter-rotating open rotors, organizing the interaction tones accordingly. This advances the state of the art of counter-rotating open rotor measurement technique and noise reduction by a means of localizing dominant tonal noise sources to a given rotor and sorting them according to noise source mechanism.
 - (c) The tonal noise sources of uninstalled counter-rotating open rotors at design takeoff nominal and approach conditions are investigated. The results are organized into groups, setting out certain families of interaction tones from the rest of the tones which are prone to be dominant noise sources. This advances the state of the art of counter-rotating open rotor noise reduction by organizing and limiting the critical tonal noise sources to a few families that need to be dealt with. The critical noise source families of uninstalled counter-rotating open rotors at design takeoff nominal and approach conditions include the diagonal dividing the tables ($XBPF_F+XBPF_A$ or $(X + 1)BPF_F + XBPF_A$, depending on the blade count), and families of interaction tones which have loading harmonics of small harmonic index value (e.g. $1BPF_F+YBPF_A$, $2BPF_F+YBPF_A$, $XBPF_F+1BPF_A$, and $XBPF_F+2BPF_A$).

Publications related to this thesis statement: [3, 4, 5, 6, 7, 13, 14, 15]

2. Turbomachinery broadband noise sources are investigated and a novel approach for investigating the beamforming results of broadband noise sources of unducted turbomachinery is presented.
 - (a) The method is able to separate the broadband noise sources from the rotating coherent noise sources as well as other incoherent noise sources and rotating incoherent noise sources that are not broadband noise sources. This advances the state of the art of unducted turbomachinery beamforming by locating the noise sources which are truly responsible for the investigated broadband noise, separating them from all other noise sources.
 - (b) The approach is applied to uninstalled counter-rotating open rotors. Broadband noise sources are localized, identified, and sorted according to noise generation mechanism. This advances the state of the art of counter-rotating open rotor measurement technique and noise reduction by providing a means by which dominant counter-rotating open rotor broadband noise sources can easily be localized, identified, and sorted according to noise generation mechanism.

Publications related to this thesis statement: [1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]

3. Turbomachinery shaft order noise sources, otherwise known as multiple pure tone noise sources, are investigated and a novel approach to investigating the beamforming results of shaft order noise sources of unducted turbomachinery is presented.
 - (a) This advances the state of the art of unducted turbomachinery beamforming by locating the noise sources which are truly responsible for the investigated shaft orders, separating them from all other noise sources.
 - (b) The approach is applied to uninstalled counter-rotating open rotors. In a case where the noise sources are neither rotating coherent nor broadband, it is significant that the method clarifies results, localizing the shaft order noise sources to their true noise sources, which are located on the rotors, and which are associated with blade nonuniformities. The method advances the state of the art of counter-rotating open rotor measurement technique and noise reduction by associating the shaft order noise sources with their true noise sources instead of the broadband or the rotating coherent tonal noise sources.

Publications related to this thesis statement: [2, 3, 13]

4. The Mach radius literature is supplemented and further clarified.
 - (a) By examining beamforming results and the predicted spiraling wavefronts emanating from counter-rotating open rotors, it is shown that the noise sources are localized to the Mach radius due to the wave patterns emanating from the counter-rotating open rotors intercepting the observer in the same way as one emanating from a noise source located at the Mach radius would.
 - (b) It is shown that the apparent source location corresponding to a rotating coherent noise source will always be at the Mach radius, regardless of whether the Mach radius is along the blade span, on the hub, or is located beyond the blade tip.

Publications related to this thesis statement: [4, 5, 6, 7]

5. The beamforming literature regarding unducted turbomachinery is supplemented and further clarified.
 - (a) It is shown that rotating coherent noise sources will be localized to their respective Mach radii by beamforming.
 - (b) Prior to this, beamforming investigations localizing shaft order noise sources to their true noise sources have not been published in the literature. Beyond the scope of unducted turbomachinery beamforming literature, these results show that not only stationary incoherent noise sources, stationary broadband noise sources, and rotating broadband noise sources, but all stationary and rotating incoherent noise sources will be localized to their true noise sources by beamforming.

Publications related to this thesis statement: [2, 3, 4, 5, 6, 7, 13]

6. The open literature has been supplemented with a basic set of processed planar phased array microphone beamforming data for an uninstalled counter-rotating open rotor, providing the research community with a comprehensive set of data for the investigation of counter-rotating open rotor noise sources, as well as for the validation of research tools.

Publications related to this thesis statement: [2, 3, 4, 5, 6]

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