Method for isolating the tonal components of counter-rotating turbomachinery phased array microphone data for beamforming

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ABSTRACT

Counter-rotating turbomachinery systems can be used in numerous applications where fuel efficiency and load reduction are crucial, such as the engines of drones or aircrafts. These unducted rotors are associated with a large magnitude of noise emission. Beamforming combined with microphone array measurements provides an appropriate method for noise source localization. The tonal components generally dominate narrow frequency bands, but in some cases their levels are of the same order of magnitude or lower as the broadband components. Using pre-processing methods on the recorded noise signal, the broadband component can be generated. With the use of cross spectral matrix operations, the broadband components can be subtracted from the original signal, extracting the tonal components of the noise of the investigated turbomachinery. This was not possible earlier using conventional single microphone pre-processing methods, due to the counter-rotation of the rotors and slight variations in forward and aft rotor rpm values throughout the sample. On the beamforming maps of the tonal signal resulting from the cross spectral matrix based pre-processing method, many of the formerly hidden tonal noise sources are now visible, which helps in unambiguously separating apart and identifying the tonal and broadband noise sources which have similar amplitudes.

1. INTRODUCTION

Counter-Rotating Open Rotors (CROR) are highly efficient aircraft and drone engines, but prior to their widespread application, some technical problems must first be solved [1]. One of these problems is the reduction of their noise emission levels [1-7]. Therefore, the noise generation mechanisms of CROR have to be investigated, understood, and eliminated. In this paper, a novel method for the better investigation of

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the tonal noise sources of CROR configurations is proposed. It should not be forgotten that the method described in this article is valid for all turbomachinery applications beside CROR.

Turbomachinery noise often consists of tonal as well as broadband components. The frequency of the tonal components can be calculated based on rotational speeds and basic geometric information, such as number of blades. Therefore, typical components of tonal noise can often be identified in a spectrum with the help of basic calculations. The broadband components, on the other hand, are present for a wide frequency range. One means of localizing noise sources and hence identifying the noise generation mechanisms of turbomachinery is the use of beamforming techniques [2,8]. In the case of CROR, tonal components appear very densely spaced throughout the entire spectrum. In the frequency bins, which do not contain a harmonic of the rotational frequency, the most dominant noise source is a broadband noise source. The presence of the broadband noise sources makes it hard to isolate the tonal components and investigate them, especially the shaft order tones, which can be characterized as having small amplitudes. Examining the tonal noise of a CROR would therefore be easier after the removal of the broadband component, resulting in only the tonal noise sources being localized on the beamforming maps.

Generally, the for single rotor turbomachinery uses the average of one revolution long segments, which is equal to the tonal component of the signal. If this average is subtracted from the original segments of the recorded signal, it results in the broadband component [5]. Unfortunately, this averaging method is not appropriate for double rotor configurations, due to the jitter and deviations in rotor speeds along with random phase shifts in measured data [4]. Therefore, the average cannot be subtracted during the investigation of the noise of a CROR. Sree and Stephens have developed a signal processing technique, which can effectively isolate the broadband portions of the signal of a recorded audio file for the noise of counter-rotating turbomachinery configurations [4,5]. The technique carries out operations on segments of the recorded signal, which are one revolution in length, but only took neighbouring bins into account. In [4], they generated the broadband noise component by carrying out a subtraction between neighbouring segments. The tonal component generated by the rotation is almost the same, while the broadband component is statistically equivalent in the neighbouring segments. Therefore, the applied subtraction removes the tonal component from the signal [4], and results in a broadband signal which is statistically equivalent to the broadband component of the original signal. This statistically equivalent broadband noise time series can then be further investigated. The recorded signal of the microphones will be referred as Original signal; the generated broadband signal will be referred as Broadband signal throughout the text.

Tokaji and Horváth [9,10] applied Sree's method to microphone array data and combined it with beamforming techniques. The beamforming maps of the Broadband signals show the broadband noise sources of the original broadband component of the noise of the CROR. As a result of the combination of Sree's method and beamforming, the broadband noise source localizations can be investigated. The resulting Broadband signal can also be useful in the investigation of the tonal noise sources of turbomachinery. In [2,11] the broadband and tonal noise sources of a CROR were investigated. The authors developed a sorting process, which determines what type of noise source the dominant noise source is in every frequency bin. The sorting method is highly subjective, as it depends on decisions made by the researcher. For some categories of tonal noise sources (rotating and stationary coherent noise sources), it is easy to define the noise generation mechanism, while for other cases (rotating incoherent noise sources and broadband noise sources), it is hard to differentiate between multiple possible noise generation

mechanisms. The beamforming maps of the tonal component can help to perform the sorting process. Fenyvesi et al. [12, 13] presented a method for objectively investigating CROR noise source maps. They presented a post processing method of beamforming maps, which uses Proper Orthogonal Decomposition (POD) in order to evaluate the beamforming results. In these investigations, the various categories of noise sources are defined by their power in the beamforming maps of the whole frequency range. This method can be developed by using beamforming maps created from only the tonal portion of the signal, which removes the broadband noise sources from the modes of POD. Moreover, the connectivity of the noise sources of the sorting method [2,11] and the POD post-processing [12, 13] results can be defined.

One way to generate the beamforming maps of the tonal component is to remove the effect of the broadband noise sources of the investigated CROR from the beamforming map of the Original signal, using the generated Broadband signal. Beamforming gives the opportunity to subtract the Cross Spectral Matrices (CSM) of two signals from each other. Originally it is used to remove the background noise from microphone array data. For this operation, the noise of an investigated noise source has to be measured, as well as the background noise of the measurement setup without the investigated noise source. Subtracting the CSM of the background noise from the CSM of the case with the noise source results in a CSM, which contains only the noise of the investigated noise source. Replacing the recorded background noise with the the Broadband signal, the CSM subtraction can be performed and the CSM of the tonal component can be generated. The tonal component of the recorded signal will be referred to as Tonal throughout the text.

In this paper two CSM subtraction methods are compared. One is implemented into the Beamform Interactive plugin of Optinav Inc, and it will be referred to as Beamform Intervactive throughout the text. [14]. This method is not published, and the mathematical algorithm is unknown, but it can be easily and efficiently used for removing background noise. The other CSM subtraction method is based on eigenvalue decomposition. Bahr and Horne [15] applied an advanced method for background removal of wind tunnel measurements. The method removes the eigenvalues of the background noise from the eigenvalues of the case with the investigated noise source. The method efficiently removes the effect of the background noise as compared to other signal to noise ratio improving operations. Using these methods, it is possible to remove the broadband noise component from the CSM of the Original noise of the CROR, and hence the tonal noise sources can be investigated more efficiently.

2. Generating the broadband signal

Sree and Stephens developed a signal pre-processing method [4,5], which subtracts the tonal components, which are generated by the rotation of the rotors. The method based on the subtraction of neighbouring segments (x and y) of the recorded signal of a microphone. According to Ref. [4], the recorded signal must be split into one revolution long segments. One segment consists of tonal ($\bar{x}$ and $\bar{y}$) and broadband (x' and y') components. The tonal component is repeated in every segment of the recorded signal, therefore $\bar{x} = \bar{y}$, (see Equation 1 and 2). The broadband component differs in every segment, but it is statistically equivalent, which means that its RMS value is constant, (see Equation 3). With the subtraction of two neighbouring segments the tonal component can be removed from the signal (see Equation 4). Whereas the subtraction of the broadband components ($x' - y'$) generates a new broadband component, which has an RMS value equivalent to that of the original signal multiplied by 2 (see Equation 5). Therefore, in order to generate a new broadband component having a similar RMS value

as the original broadband component, it must be divided by $\sqrt{2}$ (see Equation 6). z' is a new signal, which is statistically equivalent to the broadband component of the original signal.

$$x = \bar{x} + x' \tag{1}$$

$$y = \bar{x} + y' \tag{2}$$

$$\overline{x'^2} = \overline{y'^2} \tag{3}$$

$$x + (-y) = \bar{x} + x' - \bar{x} - y' = x' - y' \tag{4}$$

$$\overline{z'^2} = \overline{x'^2} + \overline{(-y)'^2} = 2\overline{x'^2} \tag{5}$$

$$z' = \frac{x-y}{\sqrt{2}} \tag{6}$$

The pre-processing method of Sree [4] consists of the following steps: First, the recorded signal of a microphone has to be filtered, below the frequency of 500 Hz and above the frequency of 20 kHz. Below 500 Hz the dominant component of the noise is generated by the wind tunnel [11], which is not investigated in this study. Above 20 kHz, the measurement results were compromised by the additional noise of the measurement equipment. The second step is splitting the recorded signal into one revolution long segments (Figure 1). The third step is performing a phase shifting on neighbouring segments. This step corrects the effect of the drifting of rotational frequencies, and therefore the segment subtraction will be performed with maximum correlation. During the phase shifting, the method does not shift the chosen segment and subtracts the overlap of the segments, but replaces the chosen segment on the original signal, therefore the subtracting operation is performed on one revolution long segments (Figure 1). As a result, the measurement data are not corrupted, and the tonal component is in the same phase. Performing the subtraction of the segments according to Equation 6, the broadband noise component (z') can be generated. One segment is used only once during the process, and therefore only one broadband segment can be generated from two neighbouring segments of the original signal. Step four is to form a new signal from the resulting broadband segments and creating the Broadband signal. The length of the Broadband signal is half of the Original signal. This signal pre-processing method can be continued and remove the remained tonal components, which are mostly generated by other noise sources, not by the CROR [10].
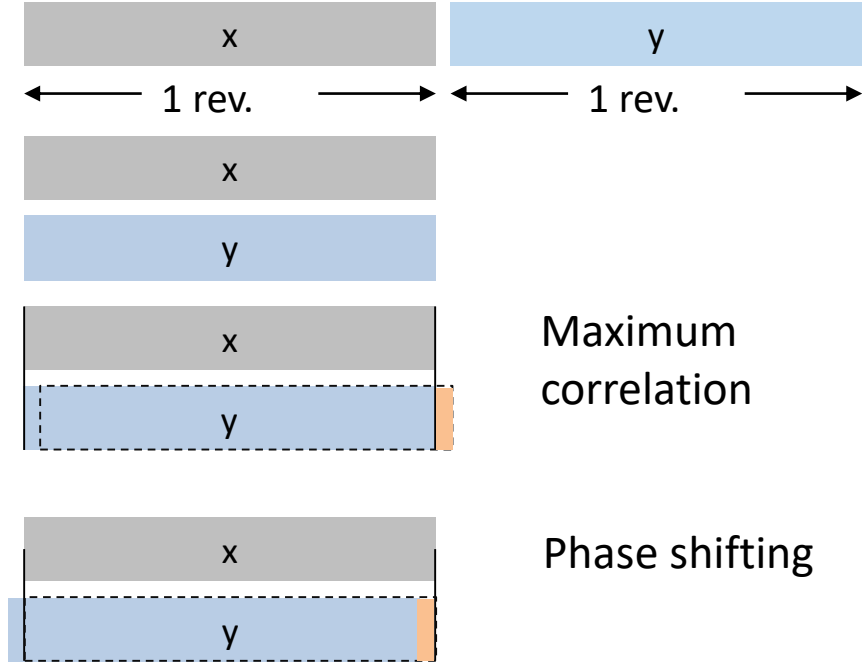
Figure 1. Step 2 and 3 of Sree's method [4]

3. Removing the broadband component

After applying the pre-processing method presented in Section 2, the Broadband signal of each microphones are available. Using a CSM subtraction method, the broadband component can be removed from the Original signals. As a result, the Tonal CSM can be generated, which helps in the investigation of tonal noise sources of turbomachinery.

As it was mentioned, Beamform Interactive CSM subtraction algorithm is not published, but it can be easily applied. The second algorithm applied herein is an eigenvalue decomposition method of Bahr and Horne [15]. It can subtract the eigenvalues of the Broadband CSM, from the CSM of the Original signal of the investigated noise source. The algorithm is published in detail in [15], and consist of the following steps. The CSM of the Original signal (G) consist of a Tonal component (G_T) and a Broadband component (G_B), see in Equation 7. G_T is the desired result of the CSM subtraction process.

$$G = G_T + G_B \tag{7}$$

G and G_B can be generated from measurement results and define G_T (see Equation 8).

$$G_T = G - G_B \tag{8}$$

G and G_B are Hermitian, positive semidefinite matrices, with real positive or equal to zero eigenvalues and a unitary matrix of eigenvectors. G_B can be expressed with Λ_B real diagonal matrix containing the eigenvalues and an X matrix of the eigenvectors (see Equation 9). X has the property $X_B^H X_B = I = X_B X_B^H$.

$$G_B = X_B \Lambda_B X_B^H \tag{9}$$

The square root of the inverse matrix of $\mathbf{\Lambda}_B$ can be constructed $\mathbf{\Lambda}_B^{-1/2}$, which is a diagonal matrix containing the square root of the eigenvalues $\lambda_{B,i}^{-1/2}$ for the positive eigenvalues and zero for $\lambda_{B,i} = 0$. Removing the $\lambda_{B,i} = 0$ terms, the identity matrix can be expressed as $\mathbf{\Lambda}_B^{-1/2}\mathbf{\Lambda}_B\mathbf{\Lambda}_B^{-1/2} = \mathbf{I}$. Equation 9 can be manipulated by removing the $\lambda_{B,i} = 0$ terms from $\mathbf{X}$, as Equation 10.

$$\mathbf{\Lambda}_B^{-1/2}\mathbf{X}_B^H\mathbf{G}_B\mathbf{X}_B\mathbf{\Lambda}_B^{-1/2} = \mathbf{I} \tag{10}$$

Defining $\mathbf{B}_B = \mathbf{X}_B\mathbf{\Lambda}_B^{-1/2}$ and applying it to Equation 8 a modified version of the CSMs can be generated (see Equation 11).

$$\widehat{\mathbf{G}_T} = \widehat{\mathbf{G}} - \mathbf{I} \tag{11}$$

where $\widehat{\mathbf{G}} = \mathbf{B}_B^H\mathbf{G}\mathbf{B}_B$ and $\widehat{\mathbf{G}_T} = \mathbf{B}_B^H\mathbf{G}_T\mathbf{B}_B$. Applying eigendecomposition on Equation 11, Equation 12 can be generated.

$$\widehat{\mathbf{X}_T}\ \widehat{\mathbf{\Lambda}_T}\ \widehat{\mathbf{X}_T}^H = \widehat{\mathbf{X}}\ \widehat{\mathbf{\Lambda}}\ \widehat{\mathbf{X}}^H - \mathbf{I} = \widehat{\mathbf{X}}\ \widehat{\mathbf{\Lambda}}\ \widehat{\mathbf{X}}^H - \widehat{\mathbf{X}}\ \mathbf{I}\ \widehat{\mathbf{X}}^H = \widehat{\mathbf{X}}(\ \widehat{\mathbf{\Lambda}} - \mathbf{I})\ \widehat{\mathbf{X}}^H \tag{12}$$

which holds true due to the nature of the identity matrix and the distributive property of matrix multiplication [15]. From Equation 12, it can be seen the eigenvectors of $\widehat{\mathbf{G}}$ are equal to the eigenvectors of $\widehat{\mathbf{G}_T}$, and the eigenvalues of $\widehat{\mathbf{G}_T}$ can be easily calculated from the eigenvalues of $\widehat{\mathbf{G}}$ with the subtraction of the identity matrix. Therefore, the desired eigenvalues can be calculated with Equation 13.

$$\lambda_{T,i} = \lambda_i - 1 \tag{13}$$

After defining the eigenvalues of $\widehat{\mathbf{\Lambda}_T}$, the $\widehat{\mathbf{G}_T} = \widehat{\mathbf{X}_T}\widehat{\mathbf{\Lambda}_T}\widehat{\mathbf{X}_T}^H$ matrix can be built using the eigenvectors of $\widehat{\mathbf{G}}$, due to $\widehat{\mathbf{X}_T} = \widehat{\mathbf{X}}$. Applying the inverse of the operation in Equation 10, the CSM of the tonal component can be calculated (see Eqquation 14).

$$\mathbf{G}_T = (\mathbf{B}_B^{-1})^H\ \widehat{\mathbf{G}_T}\ (\mathbf{B}_B^{-1}) \tag{14}$$

Where $\mathbf{B}_B^{-1} = \mathbf{\Lambda}_B^{1/2}\mathbf{X}_B^H$. As a result, the Tonal CSM can be calculated from the CSM of the measured Original signal and the CSM of the Broadband signal, which can be generated using the signal pre-processing method introduced in [4] and Section 2.

4. Measurement setup

In this article CROR measurement data is used for demonstrating the method for separating the tonal and broadband components of turbomachinery noise. The measurements were carried out in the NASA Glenn Research Center 9×15 ft Low-Speed Wind Tunnel, mounting the investigated rotors on the Open Rotor Propulsion Rig [3,2]. The investigated blades are those of the F31/A31 historical baseline blade set [7]. The forward blade row of the design consists of 12 blades with a diameter of 0.652 m and a blade angle of 33.5°, while the aft rotor has 10 blades with a diameter of 0.630 m and a blade angle of 35.7°. The Mach number of the flow in the wind tunnel was Ma=0.2, while the angle-of-attack of the flow with regard to the test rig was 0°. The rotational speed was set to a standard day value of 5598 rpm. The test case investigated here is that of an

uninstalled (standalone) CROR, without any installation equipment. Further details regarding the test set-up and the test matrix can be found in [2,3,7].

Acoustic measurements were carried out using the OptiNAV Array48 phased array microphone system (left side of Figure 2) [16]. The signals from the 48 microphones were simultaneously recorded, using a sampling rate of 96 kHz and then processed using Sree's method and Delay-and-sum beamforming in the frequency domain [17]. The cross-spectral matrices used during the processing of the data were made using a transform length of 4096, and 6 dB were subtracted from the results in order to account for the pressure doubling on the surface of the array. During the testing, the phased array was mounted in a cavity along the southern wall of the wind tunnel facility directly across from the test rig. In order to remove the microphones from the flow, a Kevlar® fabric was tightly stretched over the opening of the cavity, leaving a gap between the fabric and the phased array. This technique has been developed and tested by others in [18] and [19], where the ability of the technology to improve the signal-to-noise ratio was demonstrated. The signal-to-noise ratio was further improved by using a long time series (45 s) and removing the diagonal of the cross-spectral matrix. During the measurements, the microphone array was located at a distance of 1.6 m from the center plane of the test rig, the plane under investigation, which can be considered to be in the acoustic far-field according to simulations carried out by Horváth et al. [2,3]. The measurement setup is shown on the right side of Figure 2, with the Kevlar® window being located on the right hand side of the test rig in the figure.
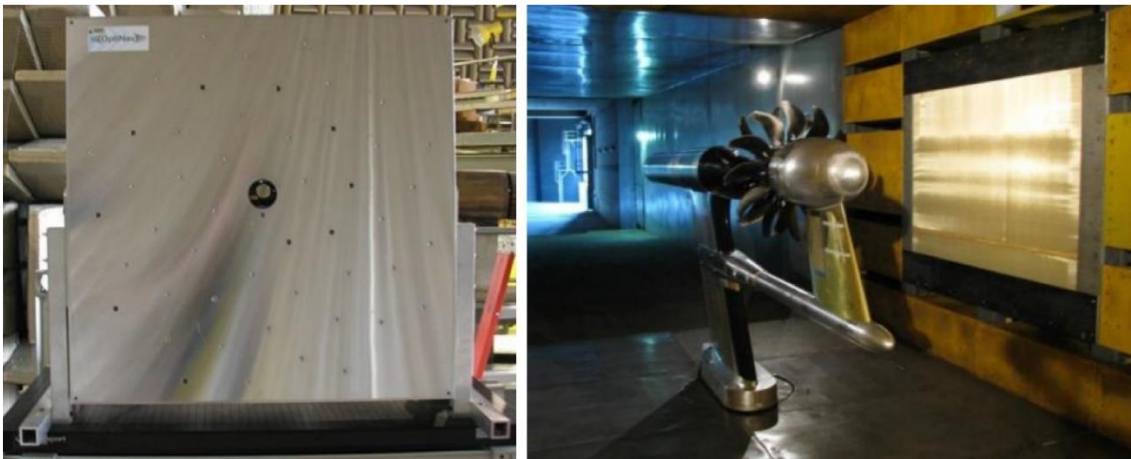

Figure 2. The Array48 system and its installation in the wall of the Low Speed Wind Tunnel [2]

5. Results of the beamforming
5.1 Spectral results

The subtraction of the effect of the broadband component of the noise of the CROR results in a CSM, which contains more information regarding the tonal component. In Figure 3, the resulting BeamForm peak (BF peak) spectra can be seen as a function of dimensionless frequency. The BFpeak values are generated by the beamforming process from the signal of all microphones. The values are recalculated to Power Spectral Density (PSD) values to dB/Hz. The frequency is nondimensionalized by the rotational frequency of the aft rotor. In the top diagram, the spectrum of the Broadband signal can be seen. The filtering method performed well. The tonal peaks disappeared from the BFpeak PSD spectrum, due to the removing of the tonal component from the Original signal. The remaining tonal peaks belong to a tonal noise source, which is independent from the rotational frequency. It is generated by an artificial noise source

behind the rotors, which is a deer whistle, which was placed here in order to verify the spatial locations of beamforming maps. Subtraction the CSM of the Broadband signal from the Original signal, the effect of broadband noise sources can be removed. In the middle diagram of Figure 3, the result of the eigenvalue method of Bahr and Horne [15] can be seen. The graph shows that the originally tonal peaks remained unchanged, and therefore the CSM subtraction did not change the tonal component. On the other hand, the BFpeak level of the originally broadband frequency bins has been decreased. In these frequency bins, the amplitude of the spectra of the Original signal are almost equal to level of the Broadband signal. Bahr and Horne's method met the requirements of the CSM subtraction of this study, as the tonal peaks remained unchanged and the presence of the broadband component decreased. The bottom diagram of Figure 3 shows the result of Beamform Interactive method. The graph of this case looks similar to the former one, but the amplitude decrease of the broadband dominated bins is larger. The tonal peaks remained the same and the effect of the broadband component decreased. Examining the spectral results, it can be stated, that the CSM subtraction effects the investigated signal, and it partially removes the broadband component. According to the spectral results, the Beamform Interactive method is more effective than the eigenvalue method of Bahr and Horne. Beside the spectra, the beamforming maps have to be examined as well.

5.2 Beamforming results

The beamforming maps provides information about the location of the investigated noise sources. By examining the beamforming maps, the dominant noise sources of the frequency bins can be sorted into groups according to their noise generation mechanisms. The Tonal beamforming maps can support the sorting method of [11,2] and it can verify and improve the POD method of [13,12]. The spectral result showed that the effect of the broadband component can be decreased by the CSM subtraction. Figure 4-5 show some typical beamforming maps of the two methods. In both figures, the top left beamforming map shows the noise source localization of the Original signal. The top right beamforming map shows the noise source localization of the Broadband signal. The bottom beamforming maps show the noise source localization of the Tonal component after the removal of the broadband component. The result of Bahr and Horne's method on the left side and the noise source localization of the Beamform Interactive method on the right side. A frequency bin is considered as tonal, if the most dominant noise source belongs to a tonal noise generation mechanism, and broadband if it belongs to a broadband noise generation mechanism. In Figure 4, the beamforming maps of an originally tonal frequency bin can be seen. This frequency is associated with an interaction tone frequency, calculated from rotational frequencies of the rotors. The noise source localization on the Broadband map is completely different from the map of the Original signal. Therefore, the removal of the broadband component has no effect on the noise source localization, and hence the noise source localization on the beamforming map of the Original signal belongs to a tonal noise source, which appears in the Tonal beamforming maps as well. In the frequency bin of Figure 5, a tonal noise source should be the most dominant (shaft order below the shaft of the CROR) according to the rotational frequency calculations. But in the beamforming map of the Original signal, a broadband noise source appears with the same level (above the shaft of the CROR). The noise source localization of the Broadband signal shows the localization of this broadband noise source. As a result of CSM subtraction methods, the level of the broadband noise source decreased and the tonal component become the most dominant noise source of the investigated frequency bin.
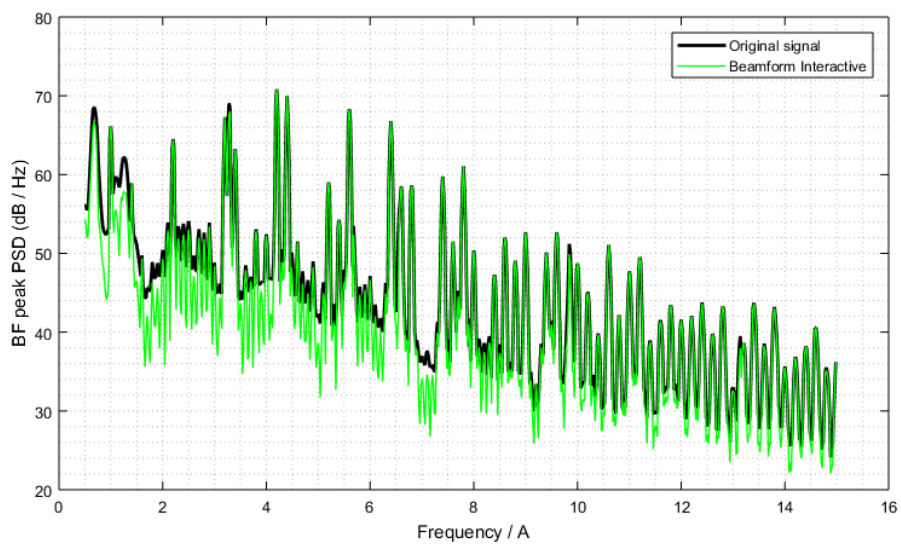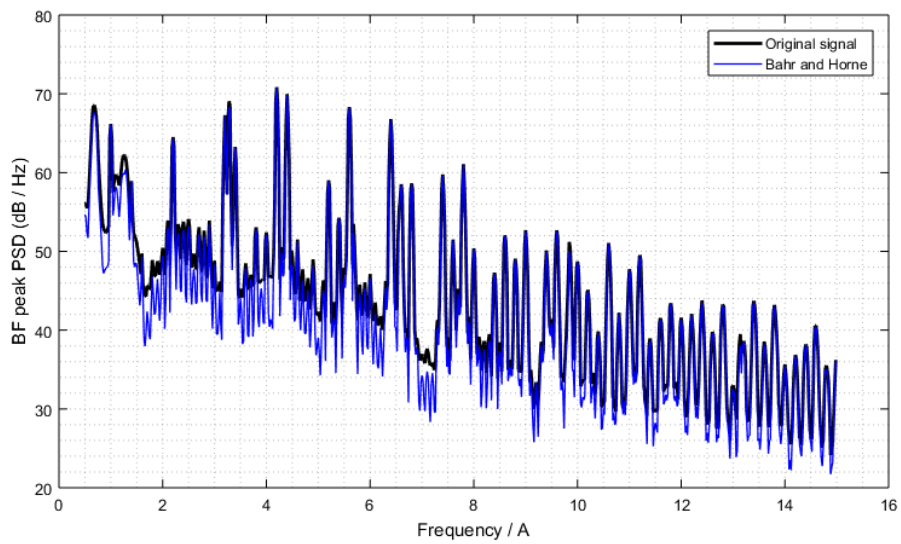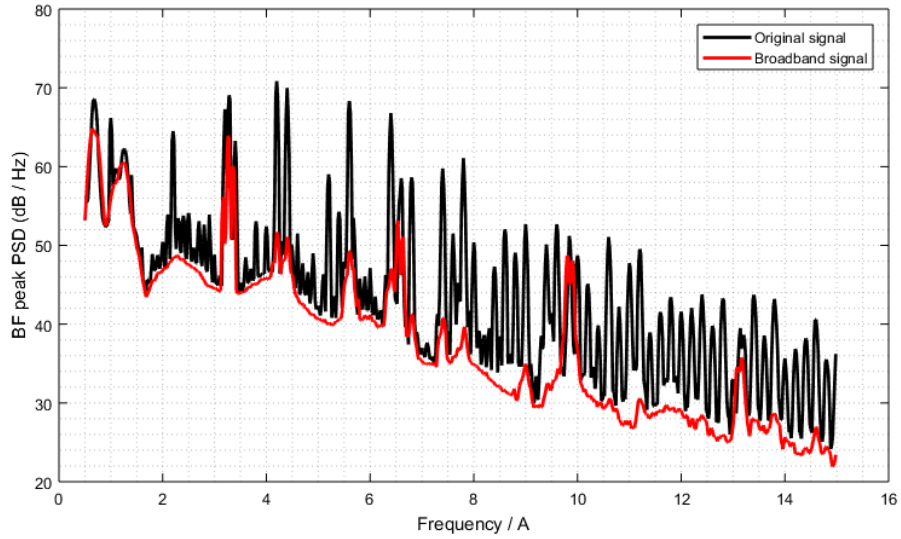
Figure 3. The spectral results with the spectrum of the Original signal; top: Broadband signal; middle: Bahr and Horne method; bottom: Beamform Interactive
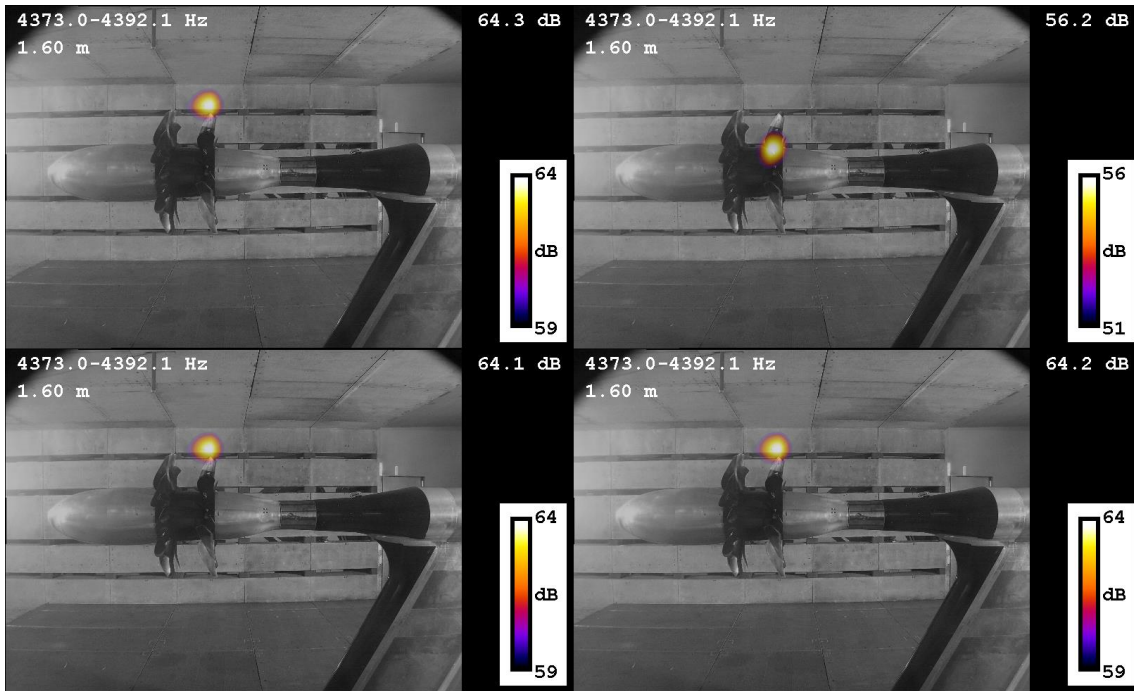
Figure 4. Beamforming maps of an originally tonal frequency bin in the case of the Original signal (top left), Broadband signal (top right), Bahr and Horne method (bottom left), Beamform Interactive (bottom right)
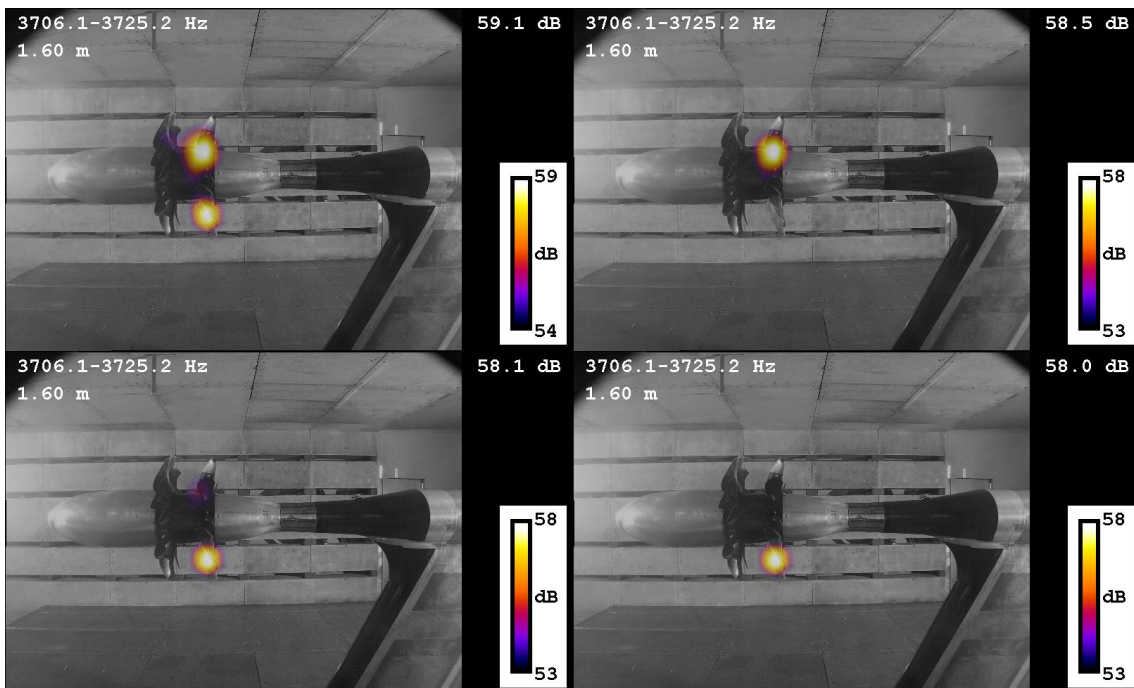

Figure 5. Beamforming maps of an originally broadband frequency bin with an expected tonal noise source in the case of the Original signal (top left), Broadband signal (top right), Bahr and Horne method (bottom left), Beamform Interactive (bottom right)

Examining the whole frequency range (500 Hz-14000 kHz, 725 frequency bins), the following can be observed: For some frequency bins, where a tonal noise source was expected, the effect of the dominant broadband noise source can be decreased and removed from the beamforming maps, resulting in a tonal noise source localization. In

the case of the originally tonal dominant beamforming maps, the CSM subtraction does not change neither the level nor the localization of the noise source. In the case of the originally broadband dominant frequency bins, the level of the noise sources decreased, but the noise source localization remained unchanged. At higher frequencies, the efficiency of the broadband removal decreases and it has moderate effect on the beamforming maps. Generally, both applied CSM subtraction method behave similarly, but in this case study the Beamform Interactive method seems to be more efficient.

6. Conclusion

The broadband noise component of turbomachinery can be generated. Applying Cross Spectral Matrix subtraction methods, the CSM of the tonal component can be generated from the CSM of the original signal and the CSM of the Broadband signal. Bahr and Horne published an advanced method, which is based on eigenvalue decomposition. Beamform Interactive also includes CSM subtraction. Counter-rotating open rotor data was used to examine the effectiveness of the CSM operations. Both of the methods worked, although the method of Beamform Interactive performed more effective. The originally tonal dominated frequency bins remained unchanged. In the originally broadband dominated frequency bins the level of the broadband component can be decreased and if a tonal noise source is present, its localization can be improved. In many frequency bins, mostly for higher frequencies, the broadband component has not been remove by the applied methods. This study showed that the CSM subtraction algorithms can be used in order to obtain purely the tonal component from the Original signal and the Broadband component, but the method has to be improved in order to work more effectively.

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