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A 3 MICROPHONE METHOD TO SEPARATE DIRECT AND INDIRECT COMBUSTION NOISE INSIDE A TURBOFAN JET ENGINE ANNULAR COMBUSTOR.

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Greater fuel efficiency is a key area in the development of a new generation of turbofan engines. It is currently unclear as to how modifications to the combustor to achieve higher levels of efficiency will affect the combustion noise that reaches the far field. To understand this, it is necessary to be able to identify the contribution of both the direct and the indirect combustion noise to the far field level. The contribution of these two combustion noise sources is unknown for the current generation of turbofan engines. This paper presents a 3 microphone method for the separation of the direct and indirect combustion noise signals inside the combustor of a turbofan jet engine. The effects of transfer function error and coherence of unwanted noise on the performance of the technique are examined. This technique is then used as an input to the current combustion noise measurement method, called '3S Array', to examine the effect of transfer function error on the coherence with the far-field. It has been found that the separation is only weakly dependent on transfer function error and is therefore a reasonable technique to apply to real engine data. All of the data presented in this paper uses models of the problem rather than measurements.

Keywords: Combustion noise, Measurement techniques

1. Introduction

Greater fuel efficiency is a key area in the development of a new generation of turbofan engines. It is currently unclear as to how modifications to the combustor to achieve higher levels of efficiency will affect the combustion noise that reaches the far field. Also, with the advancements in the reduction of jet and fan noise in turbofan jet engines, combustion noise is becoming a more prominent noise source. It is, therefore, becoming more important to understand how much combustion noise propagates to the far field.

Current measurements of combustion noise in the far field use coherence based measurement techniques. These techniques use two or more microphones to obtain the part of measured signal at one of the microphones that is coherent with the other microphone signals. For measuring combustion noise, these methods assume that the only signal that is coherent between the microphones is combustion noise. There are, however, two types of combustion noise called the direct and the indirect combustion noise. The direct combustion noise is produced by the unsteady heat release in the combustor which is caused by the combustion of the fuel. The combustion of the fuel also produces entropy waves which convect with the flow through the engine until they undergo an acceleration which produces acoustic waves which is the indirect combustion noise (or sometimes called entropy noise). The indirect noise will then propagate both upstream and downstream of the location at which acceleration occurd. The presence of both direct and indirect combustion noise is a problem when using coherence based measurement methods as there will be direct combustion noise that is coherent between all of the measurement microphones and indirect noise that is coherent between some, or all, of the microphones. Separating the direct and indirect combustion noise would provide a greater understanding of combustion noise.

2. Literature Review

Harper-Bourne et al. [1] used a coherence based measurement technique called the Coherence Output Power (COP) to measure the combustion noise produced by the Rolls-Royce ANTLE engine at the INTA facility in Spain. The COP method, originally developed by Halvorsen and Bendat [2], can be used to obtain an estimate of the combustion noise in the far field by multiplying the autospectra of a far field measurement by the coherence between the far field microphone and an in-engine sensor. The method suffers from a bias error if the signal to noise ratio is not sufficiently large. Harper-Bourne et al found that the estimate obtained when using the combustor and far field probes was smaller than when using a probe near the hot nozzle outlet and far field probe. They concluded that this difference was due to indirect noise being present at the nozzle position but not at the combustor position.

Miles [3] has also used the COP method to measure the combustion noise that propagates to the far field from a Honeywell TECH977 engine. The test setup consisted of a far field polar array and a number of in-duct sensors. To improve the coherence between the sensors, he used a method to calculate the phase delay of the cross spectra between the two microphones and used this to time align the signals. In doing this he noted that in the frequency range of 0-200 Hz, a delay of 90.027 ms provided maximum coherence with the microphone at 130° to the nozzle while 86.975 ms provided the maximum coherence in the 200-400 Hz frequency range. Miles concluded that the difference in delay is due to the direct and indirect noise taking different times to propagate to the far field. He stated that the 0-200 Hz band must be where indirect combustion noise is dominant as the entropy waves will convect with the flow speed to the turbine stages, which is slower than the sound speed, where it will then undergo an acceleration to produce indirect combustion noise.

Hultgren and Miles [4] compared the combustion noise measurements performed by Harper-Bourne and Miles. They concluded that the difference in the two estimates made by Harper-Bourne is due to an inherent bias error in the COP technique which is caused by high levels of uncorrelated noise present in the measured combustor signal. They also found that the estimated direct noise measured by Miles is at a higher frequency than the indirect noise while Harper-Bourne found the opposite.

It is possible that the indirect noise is also present in the combustor. No researchers have attempted to separate the direct and indirect combustion noise in the combustor as it is believed that the indirect noise is generated at the turbines. Dowling and Mahmoudi [5] describe a combustion instability called ‘rumble’ which can occur in the combustor at low operating powers. It is believed that this instability is generated via a feedback mechanism and the frequencies of the rumble occur below the acoustic resonances of the combustor. They state that rumble occurs when entropy waves, produced by the combustion process, convect to the Nozzle Guide Vanes (NGV) and get accelerated resulting in the production of indirect combustion noise. The indirect noise then propagates upstream to the flame and interferes with the generation of entropy waves which results in the low frequency rumble.

If the indirect combustion noise propagates upstream from the NGV, then the combustor measurement will contain both direct and indirect combustion noise. Figure 1 is a simplified diagram of a section of an annular combustor indicating the various noise sources. The output of coherence based measurement techniques in this case would provide an estimate of the total far field combustion noise. A coherence based measurement technique developed by Rodríguez-García et al. [6] called 3S Array uses two sensors in the engine and an array of microphones in the far field to provide an estimate of the combustion noise that propagates to the far field. 3S Array does not suffer from the inherent bias error that the COP method does and so, provides more accurate estimates of the total combustion noise that propagates to the far field. To be able to gain a better understanding of the combustion noise generation mechanism, the direct and indirect noise needs to be separated. The following sections will outline a method for separating direct and indirect combustion noise inside the combustor of a turbofan jet engine, the output of which can be used as an input to the 3S Array technique.

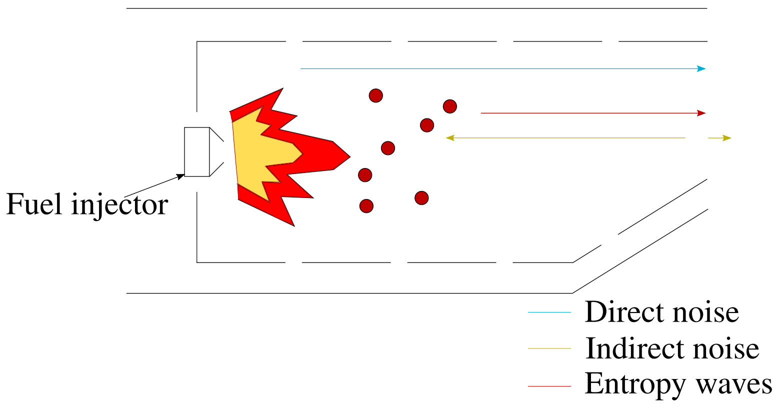

Figure 1: A simplified diagram of a section of an annular combustor.

3. Model for noise in the combustor

The sound field in the combustor will comprise the sum of direct and indirect noise. Pressure fluctuations in the combustor also contain contributions due to the hydrodynamic pressure field. The flow through the NGV can be expected to be choked which will result in an absence of reflections of sound from this end of the duct. There is a hard reflective surface near the fuel injector, however, which will result in a single reflection of the direct and indirect noise.

Assuming that the only mode propagating in the combustor is the plane wave mode, the direct combustion noise can be modelled as a plane wave source at a position d_d and the indirect combustion noise can be modelled as a plane wave source at a position d_i. If a number of microphones are placed in the combustor, at a single frequency, the pressure at the m^{th} microphone in the combustor can be expressed as

$$p_m(f) = H_{d,m}(f)p_d(f) + H_{i,m}(f)p_i(f) + n_m(f) \tag{1}$$

where $p_d(f)$ and $p_i(f)$ are the plane wave pressures of the direct noise at d_d and indirect noise at d_i respectively, $H_{d,m}(f)$ and $H_{i,m}(f)$ are pressure-to-pressure transfer functions that describe the propagation from the direct and indirect source locations to the microphone and $n(f)$ is the unwanted noise measured by the microphone. The transfer functions can be expressed as

$$H_{d,m}(f) = (\sigma_{d,m}(1+M))^{-\frac{1}{2}}\left(e^{jk^+(d_m-d_d)} + R(f)e^{j(k^-d_d+k^+d_m)}\right) \tag{2}$$

and

$$H_{i,m}(f) = (\sigma_{i,m}(1-M))^{-\frac{1}{2}}e^{jk^-(d_i-d_m)} + (\sigma_{i,m}(1+M))^{-\frac{1}{2}}R(f)e^{j(k^-d_i+k^+d_m)} \tag{3}$$

where $\sigma_{d,m}$ and $\sigma_{i,m}$ are ratios of the cross-sectional area at the source location to the cross-sectional area at the m^{th} microphone location, $M = V/c$ in which V is the local bulk flow speed and c represents the local speed of sound, $R(f)$ is the reflection coefficient of the wall and $k^{\pm}$ is the wavenumber depending on whether the sound is travelling upstream (+) or downstream (−). The wavenumber in a duct with only the plane wave mode cut on is

$$k^{\pm} = \frac{k_0}{(1 \pm M)} \tag{4}$$

where $k_0 = \omega/c$.

For a number M_T of microphones, Eq. (1) can be expressed in vector form

$$\mathbf{p}(f) = \mathbf{H}(f)\mathbf{q}(f) + \mathbf{n}(f) \tag{5}$$

where $\mathbf{q}^T(f) = \begin{pmatrix} p_d(f) & p_i(f) \end{pmatrix}$ and $\mathbf{H}(f)$ is a matrix of transfer functions between each microphone and each of the sources.

4. Separation method

Equation (5) is an expression for the acoustic pressure signal at a particular microphone location assuming the source signals, transfer functions and the noise signals are known. However, in practise $\mathbf{p}(f)$ can be measured and $\mathbf{q}(f)$ remains to be determined.

4.1 Single frequency source separation

For the case where there are two microphones inside the combustor, Eq. (5) becomes

$$\begin{pmatrix} p_1(f) \\ p_2(f) \end{pmatrix} = \begin{pmatrix} H_{d,1}(f) & H_{i,1}(f) \\ H_{d,2}(f) & H_{i,2}(f) \end{pmatrix} \begin{pmatrix} d(f) \\ i(f) \end{pmatrix} + \begin{pmatrix} n_1(f) \\ n_2(f) \end{pmatrix}. \tag{6}$$

In this instance, assuming the transfer functions are known, there are four unknowns and two equations. Estimates of the direct and indirect noise can be deduced from

$$\begin{pmatrix} H_{d,1}(f) & H_{i,1}(f) \\ H_{d,2}(f) & H_{i,2}(f) \end{pmatrix}^{-1} \begin{pmatrix} p_1(f) \\ p_2(f) \end{pmatrix} = \begin{pmatrix} d(f) \\ i(f) \end{pmatrix} + \begin{pmatrix} H_{d,1}(f) & H_{i,1}(f) \\ H_{d,2}(f) & H_{i,2}(f) \end{pmatrix}^{-1} \begin{pmatrix} n_1(f) \\ n_2(f) \end{pmatrix} \tag{7}$$

the accuracy of which is dependent on the level of unwanted noise present.

Obtaining an estimate of the direct and indirect combustion noise will be possible so long as the number of microphones is equal or greater than the number of source terms. Generalising Eq. (7) to M_T microphones and writing in vector notation yields

$$\mathbf{q}(f) = \mathbf{H}^{-1}(f)\mathbf{p}(f) - \mathbf{H}^{-1}(f)\mathbf{n}(f). \tag{8}$$

For the case where there are more microphones than sources, the transfer function matrix will not be square and so the pseudo inverse

$$\mathbf{H}^{-1} = (\mathbf{H}^{\mathbf{H}}\mathbf{H})^{-1}\mathbf{H}^{\mathbf{H}} \tag{9}$$

will need to be calculated where $^{\mathbf{H}}$ is the Hermitian transpose.

4.2 Broadband source separation

The above single frequency source separation method can be rewritten for the more realistic case of random broadband noise. The Cross Spectral Matrix (CSM) of microphone pressures is defined as

$$\mathbf{S}_{pp}(f) = \frac{1}{2T} E\left[\mathbf{p}^{\mathbf{H}}(f)\mathbf{p}(f)\right] \tag{10}$$

where $\mathbf{p}(f)$ is given in Eq. (5) and $E[\,]$ is the expectation operator. Equation (5) can therefore be expressed in terms of CSM,

$$\mathbf{S}_{pp}(f) = \mathbf{H}(f)\mathbf{S}_{qq}(f)\mathbf{H}^{\mathbf{H}}(f) + \mathbf{S}_{nn}(f) \tag{11}$$

where $\mathbf{S}_{qq}(f)$ is the CSM of source signals and $\mathbf{S}_{nn}(f)$ is the CSM of unwanted noise. To separate the direct and indirect noise for the broadband case, the same inverse method can be used which yields

$$\mathbf{S}_{qq}(f) = \mathbf{H}^{-1}(f)\mathbf{S}_{pp}(f)(\mathbf{H}^{\mathbf{H}}(f))^{-1} - \mathbf{H}^{-1}(f)\mathbf{S}_{nn}(f)(\mathbf{H}^{\mathbf{H}}(f))^{-1}. \tag{12}$$

5. Configuration of simulation

Equation (11) can be used to simulate a CSM of microphone pressures inside a combustor so that the effectiveness of the separation method can be investigated. Figure 2 is a diagram of the configuration that is used from here onwards to evaluate the separation method.

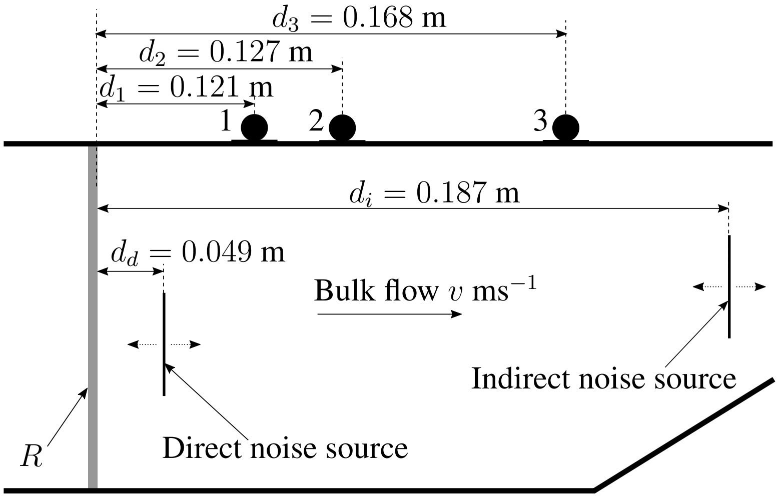

Figure 2: Configuration used to simulate microphone pressure signals and evaluate separation method.

The simulated direct and indirect combustion noise will both consist of white noise with a level of 117 dB SPL. The indirect noise will be present between 0 - 200 Hz and the direct noise will be present between 100 - 400 Hz. Initially, the bulk velocity is $v = 60$ ms^{-1} and the reflection coefficient $|R| = 1$. The speed of sound in the combustor was chosen to be 600 ms^{-1} due to the average temperature in the combustor. The unwanted noise is uncorrelated between measurement locations and the direct and indirect noise. The uncorrelated noise signal for each microphone signal is white and has a level of 94 dB SPL.

6. Results

Figures 3 and 4 show the estimated direct and indirect combustion noise respectively using 2 microphones (1 and 3) without unwanted noise, 2 microphones with unwanted noise and 3 microphones with unwanted noise. The addition of the unwanted noise severely effects the estimate of the direct and indirect noise. At very low frequencies, the estimates provided by the 2 microphone and the 3 microphone separation with the unwanted noise are very similar. At higher frequencies the estimates begin to differ significantly, especially for the indirect noise where there are two discontinuities in the 2 microphone separation which are not present in the 3 microphone separation.

The variation in the estimate where direct and indirect noise are not present (in this case above 400 Hz) is due to

$$\mathbf{H}^{-1}(f)\mathbf{S}_{pp}(f)(\mathbf{H}^{\mathbf{H}}(f))^{-1} = \mathbf{H}^{-1}(f)\mathbf{S}_{nn}(f)(\mathbf{H}^{\mathbf{H}}(f))^{-1}. \tag{13}$$

As all of the unwanted noise signals have flat autospectra with a level of 94 dB, the discontinuities and level variation in the estimate must be due to the inverse of the transfer function matrix. The inverse of the 2×2 transfer function matrix is defined as

$$\begin{pmatrix} H_{d1} & H_{i1} \\ H_{d2} & H_{i2} \end{pmatrix}^{-1} = \frac{1}{H_{d1}H_{i2} - H_{i1}H_{d2}} \begin{pmatrix} H_{i2} & -H_{i1} \\ -H_{d2} & H_{d1} \end{pmatrix}. \tag{14}$$

where $H_{d1}H_{i2} - H_{i1}H_{d2}$ is the determinant of the transfer function matrix. The inverse of the matrix is undefined for the case where

$$H_{d1}H_{i2} = H_{i1}H_{d2} \tag{15}$$

which results in the discontinuities in the estimate.

The 3 microphone method has fewer discontinuities in the direct estimate and no discontinuities in the indirect estimate. As there are 3 microphones, the pseudo inverse is calculated which results in many more terms in the determinant and therefore, fewer instances where the determinant is zero. Using 3 microphones to estimate the direct and indirect noise in the combustor results in a more accurate estimate than using 2 microphones.

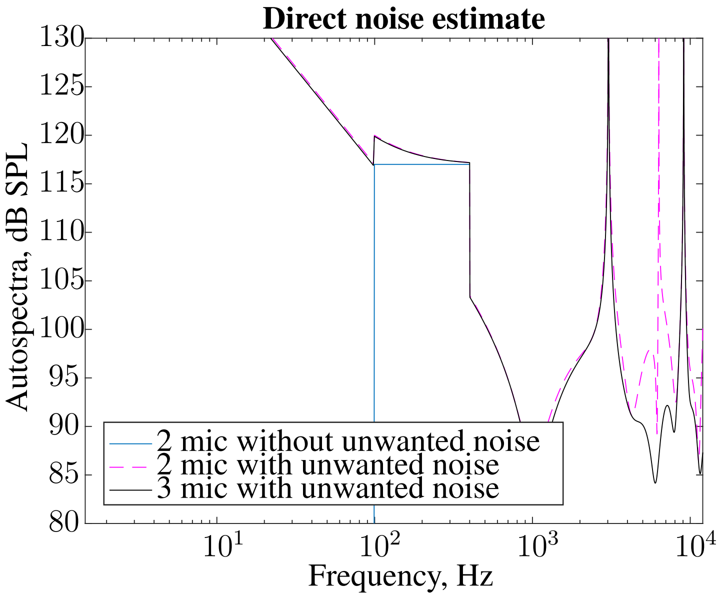

Figure 3: Estimated direct combustion noise.

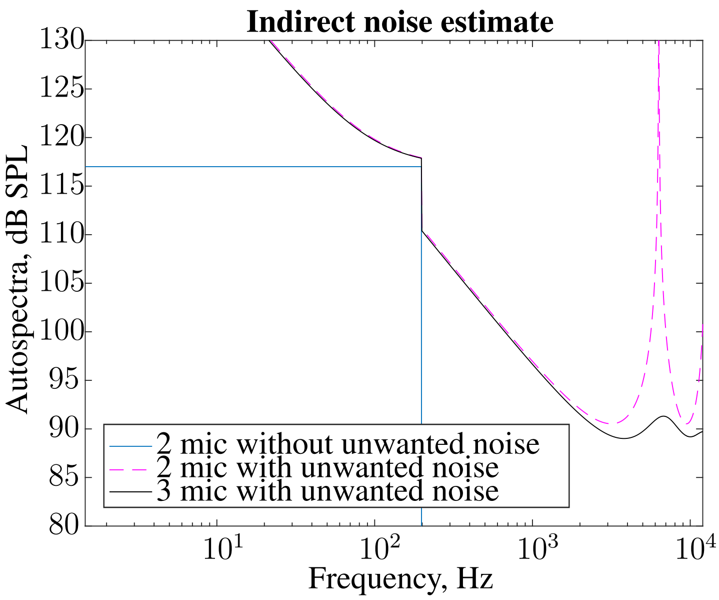

Figure 4: Estimated indirect combustion noise.

Up to this point, it has been assumed that the transfer functions are known exactly. It is unlikely that this will be the case for measured data. The locations of the microphones may be known accurately, but there will be uncertainty in the estimates of bulk flow velocity and reflection coefficient. It is therefore necessary to examine how sensitive the estimated direct and indirect combustion noise signals are to errors in the velocity and reflection coefficient estimates.

Figure 5 is the estimates of the direct and indirect combustion noise for different estimated bulk flow velocities with the actual velocity being 60 ms^{-1}. From this, it is clear that the estimate is not very sensitive to error in the velocity estimate.

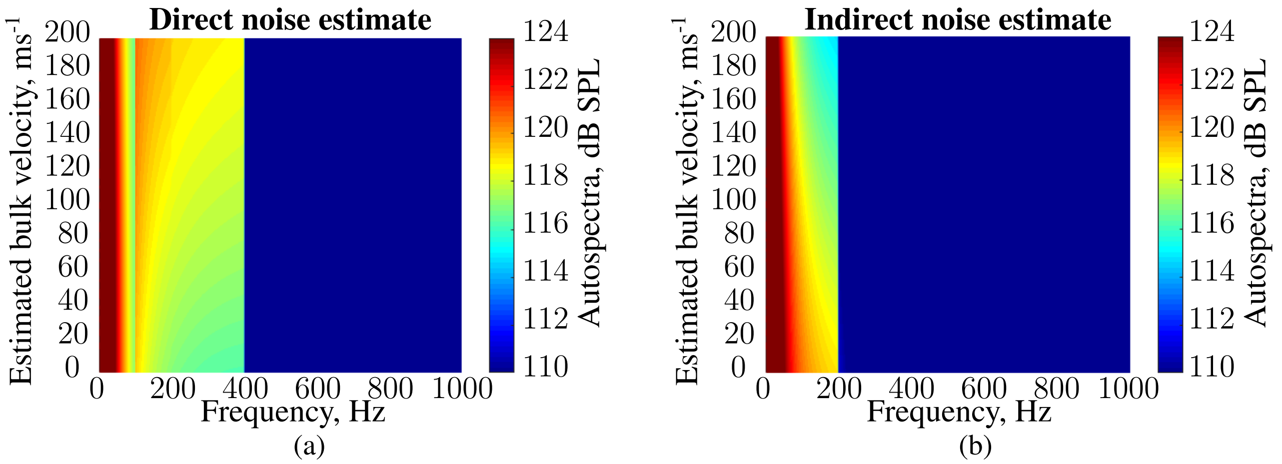

Figure 5: The direct and indirect noise estimates for different estimated velocities with the actual velocity being 60 ms^{-1}.

Figure 6 shows the estimates of the direct and indirect combustion noise for different estimated reflection coefficients with the actual reflection coefficient being 0.5. Again, while it does have an effect on the estimate, the estimate is only weakly sensitive to an error in the reflection coefficient.

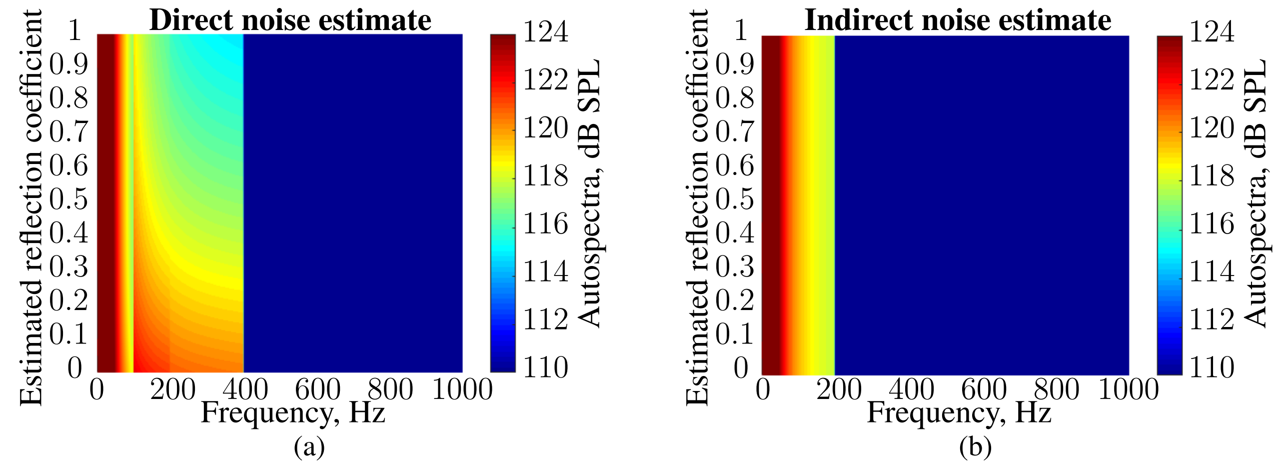

Figure 6: The direct and indirect noise estimates for different estimated reflection coefficients with the actual reflection coefficient being 0.5.

The main purpose of the separation technique is to use the estimated direct and indirect signals as inputs to a coherence based measurement technique. As such, it is the coherence between the separated signal and a microphone in the far field of the turbofan jet engine that is of interest. The pressure measured by the far field microphone is assumed to consist of direct and indirect combustion noise plus an unwanted noise signal which is not correlated with any other signal. For the purposes of a simple simulation, the far field microphone signal is simulated using

$$p_f(f) = H_{df}(f)p_d(f) + H_{if}(f)p_i(f) + n_f(f). \tag{16}$$

Figure 7 shows the coherence between the estimated separated signals and the far field microphone signal. From these coherences, it is clear that the estimated separated signals can be used in a coherence based measurement technique to isolate the direct and indirect combustion noise in the far field. If indirect noise is not present in the combustor, the separated signal will just be made up of the unwanted noise signals. The coherence with the far field should be 0 (assuming a large number of averages). This should confirm whether or not indirect noise is present in the combustor.

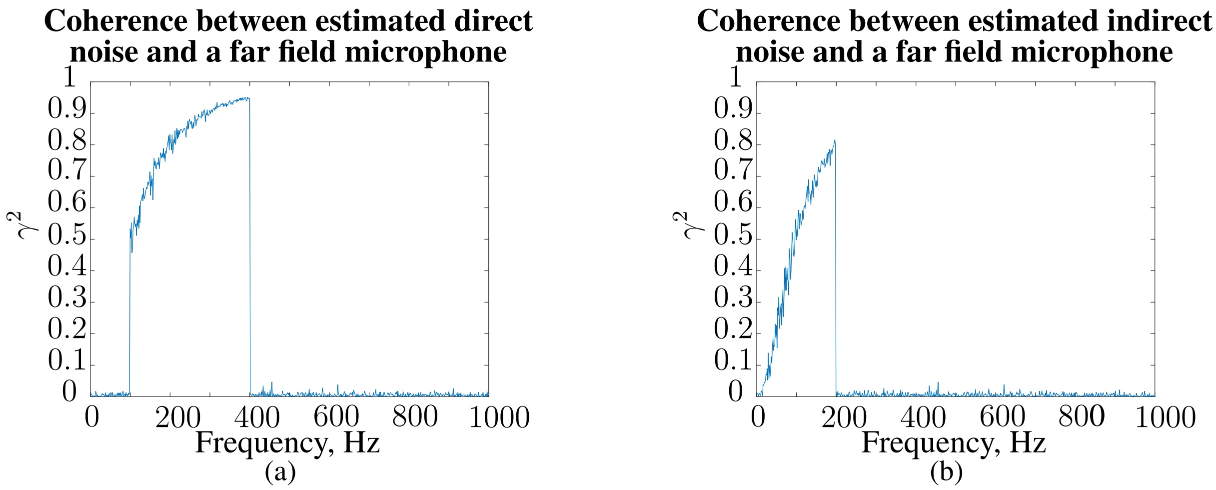

Figure 7: The coherence between the far field microphone and the direct and indirect noise estimates respectively.

7. Conclusions

Combustion noise is comprised of two components: the direct and the indirect combustion noise. A 3 microphone separation technique has been presented in this paper which can be used to provide estimates of the direct and indirect noise in the combustor. It has been found that:

- An estimate of the direct and indirect combustion noise using 3 microphones provides a significant improvement over using 2 microphones.
- The estimate of the direct and indirect combustion noise is only weakly sensitive to errors in the estimated bulk velocity and reflection coefficient.
- The separated signals can be used in a coherence based technique, even when the separated signals are significantly smaller than the unwanted noise.

Further work will be done applying this technique to measured data and on using this technique in combination with coherence based measurement techniques.

References

1. Harper-Bourne, M., Moore, A. and Siller, H., (2008), A Study of Large Aero-Engine Combustor Noise. *14th AIAA/CEAS Aeroacoustics Conference (29th AIAA Aeroacoustics Conference)*, Aeroacoustics Conferences, American Institute of Aeronautics and Astronautics.

2. Halvorsen, W. G. and Bandat, J. S. Noise Source Identification Using Coherent Output Power Spectra, *Sound and Vibration*, **9** (8), 15–24, (1975).

3. Miles, J. H., (2008), Spectral Separation of the Turbofan Engine Coherent Combustion Noise Component. *46th AIAA Aerospace Sciences Meeting and Exhibit*, Aerospace Sciences Meetings, American Institute of Aeronautics and Astronautics.

4. Hultgren, L. and Miles, J., (2009), Noise-Source Separation Using Internal and Far-Field Sensors for a Full-Scale Turbofan Engine. *15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference)*, Aeroacoustics Conferences, American Institute of Aeronautics and Astronautics.

5. Dowling, A. P. and Mahmoudi, Y. Combustion noise, *Proceedings of the Combustion Institute*, **35** (1), 65–100, (2015).

6. Rodríguez-García, P., Holland, K. and Tester, B., (2014), Extraction of Turbofan Combustion Noise Spectra Using a combined Coherence-Beamforming Technique. *20th AIAA/CEAS Aeroacoustics Conference*, AIAA Aviation, American Institute of Aeronautics and Astronautics.