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Broadband Noise Source Location in Turbomachinery using a Conditioned Spectral Analysis Technique Coupled with Modal Decomposition

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Abstract
Methods are presented for the identification, *viz.*, relative magnitude and spatial origin, of broadband and tonal noise sources within aeroengines. The methods require dynamic pressure measurements from sensors located within the engine. These techniques can be used to assess the contribution of internal noise sources to sound radiated from an aeroengine exhaust, for example, to the far field. Three coherence based techniques are evaluated: the coherent output power, the signal enhancement technique and a five sensor partial coherence method. The techniques are applied to data generated by a small scale experimental rig within an EU FP7 programme – TEENI. The experimental test rig design simulates the most relevant acoustic features of the downstream part of a turbo-shaft engine, i.e. the combustion noise source, the turbine stages and the relevant propagation processes to the exhaust exit. The application of these techniques to turbo-shaft engines is of particular interest where corenoise is a far more significant contributor to far field sound than jet noise. Results show how broadband noise from a rotor/stator stage, broadband noise from a single loudspeaker (simulating the combustor) and a tone from the rotor/stator stage can all be decomposed from measurements and how these contributions can be localised. In addition, the five sensor method is significantly enhanced to include acoustic modal decomposition. This allows the contribution of sources to individual radial modes to be measured and the source location identified. Specific radial modes were generated and measured with upstream loudspeaker and downstream microphone arrays respectively.

Keywords: Broadband noise, modal decomposition, noise source identification, turbo-shaft.

1 Introduction

Broadband noise generation has become a subject of significant interest in the design of turbomachinery in recent years. For aeroengines, exhaust broadband noise is produced at the many rotor-stator stages of the turbines and by the combustor stage in direct and indirect

(also called entropy nise) form. This noise is usually a significant contributor to the overall sound level during aircraft landing.
Coherence based noise-source identification techniques can be used to identify the contribution of core noise to near and far field acoustic measurements in turbomachinery. The Coherent Output Power technique, reported initially by Halvorsen and Bendat [1], has been reported extensively in aeroacoustics literature utilising the ordinary coherence function between internal measurements at a source and far-field measurements. Chung's [2] flow noise rejection technique (Signal Enhancement), using three microphones to remove extraneous noise from a far-field measurement of a single noise source, was used by Shivashankara [3] to identify the internal core noise contribution to far-field measurements. A partial coherence technique was developed by Hsu and Ahuja [4] using five microphones which can separate out the contributions of two sources in the presence of extraneous noise. Previously published work in this area from the 1970's and 1980's has been revisited in more recent years by Hsu and Ahuja [4] and Nance [5]. In Bennett and Fitzpatrick [6] techniques which can be used to identify the contribution of combustion noise to near and far-field acoustic measurements of aero-engines were evaluated. In the papers by Bennett and Fitzpatrick [7] and by Bennett et al [8] analysis techniques which allow the contribution of linear and non-linear mechanisms to the propagated sound to be identified was reported for tonal and narrow band noise respectively.

2 Coherence Based Noise Source Identification

An acoustic measurement of a system of interest will most often be the summation of a number of separate acoustic sources along with some extraneous noise *n(t)*. For the case where it is not possible to remove individual sources without affecting the behaviour of the others, the challenge is to decompose the measurement signal *y(t)* into its constituent parts. For acoustic sources that are considered to be stationary random processes with zero mean and where systems are constant-parameter linear systems, Figure 1, a multiple-input/single output model, can be used to represent the system.

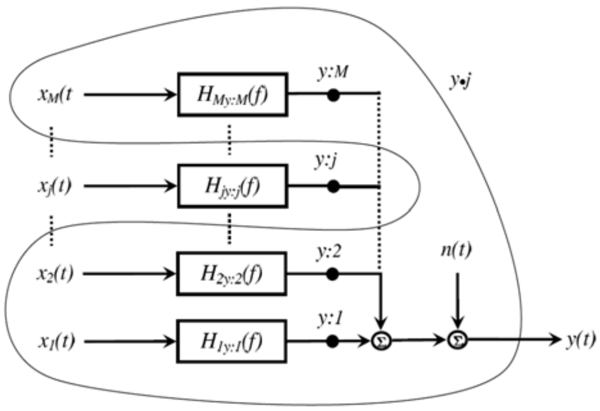

Figure 1: Multiple Source Acoustic Measurement

The coherence squared function between two signals x(t) and y(t) is defined by:

$$\gamma_{xy}^2 = \frac{|G_{xy}|^2}{G_{xx}G_{yy}} \leq 1 \tag{2.1}$$

and can be used to measure the contribution of x(t) to y(t). If the coherence function is greater than zero but less than unity, one or more of three possible physical situations exist:

1) extraneous noise is present in the measurements; 2) the system relating x(t) and y(t) is not linear; 3) y(t) is an output due to an input x(t) as well as to other inputs.

2.1 Coherent Output Power (COP)

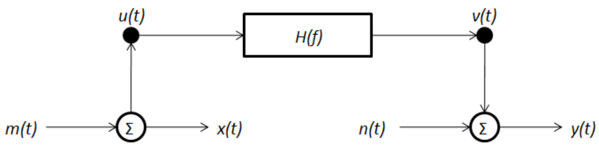

Figure 2: Input/Output relationship with noise.

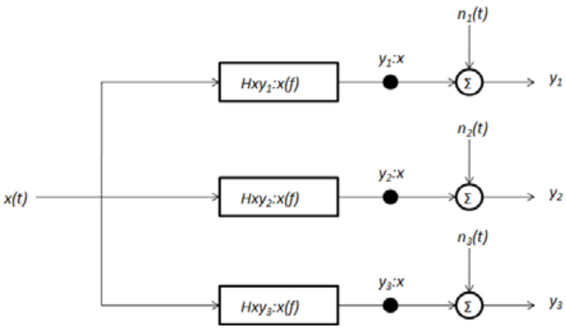

Figure 3: Signal Enhancement Model

The coherent output power can be used to identify a source's contribution to an output measurement. With reference to Figure 1, the contribution y:j of input $x_j(t)$ to a measurement y(t) can be identified. This is an ideal case of the general input/output model of Figure 2, where *y(t)* = *v(t)* + *n(t)*, and given that the source measurement *x(t)* measures the source only u(t) with no contaminating noise (*m(t)* = *0*). In this model n(t) might include all other sources uncorrelated noise with u(t). In the frequency domain, the COP can be calculated with equations 2.2 and 2.3.

$$G_{vv} = \gamma_{xy}^2 G_{yy} \tag{2.2}$$

$$G_{nn} = (1 - \gamma_{xy}^2) G_{yy} \tag{2.3}$$

If there is noise present in the input measurement (*m(t)* > *0*), there will be the following error in the measured COP:

$$G_{v'v'} = \gamma_{x'y}^2 G_{yy} = G_{vv} \frac{G_{xx}}{G_{xx} + G_{mm}} \leq G_{vv} \tag{2.4}$$

The signal enhancement technique addresses this case.

2.2 Signal Enhancement (SE)

Unlike the COP, which requires a noiseless measurement of the input signal, Chung [2] developed a technique for extraneous noise rejection at the input using a minimum of three measurements. This technique can therefore be applied when a direct measurement at the source is not possible. The assumptions made in the model are: 1) The system is linear, 2) The signal of interest is received with perfect correlation at each measurement point, 3) Extraneous noise at each measurement position is completely uncorrelated with each other and the signals, 4) If there are a group of sources, as opposed to a single source, and they are not completely correlated with each other, then the transducers must be located close together relative to the distance from the group (related to condition two).
The desired spectra can then be found using these equations:

$$G_{v_1v_1} = \frac{|\gamma_{y_1y_2}||\gamma_{y_1y_3}|}{|\gamma_{y_2y_3}|} = \frac{|G_{y_1y_2}||G_{y_1y_3}|}{|G_{y_2y_3}|} \tag{2.5}$$

$$G_{n_1n_1} = G_{y_1y_1} - G_{v_1v_1} \tag{2.6}$$

2.3 Conditional Spectral Analysis (CSA)

2.3.1 Three-Microphone CSA Method

One of the limitations of the SE technique is that for measurement locations within the same pressure field, the technique may only be applied when there is a single correlated source between the records. Minami and Ahuja [9] discuss the errors resulting from using the Signal Enhancement technique when two sources, as opposed to only one source, are buried within extraneous noise. For the situation where there are only two correlated sources, and a measure of one of them is attainable, the COS and the SE techniques may be used in conjunction with each other and with conditional spectral analysis to successfully identify both sources and the extraneous noise. This approach is presented by Hsu and Ahuja [4]. The problem case is illustrated in Figure 4(a). The first stage consists of separating out the part correlated with the measurable source, using the COS technique, and thus identifies its contribution. The second stage uses a partial coherence form of the SE technique on the residual to remove the extraneous noise, see Figure 4(b). A measure of at least one of only two sources and three output measurements are required for this technique.

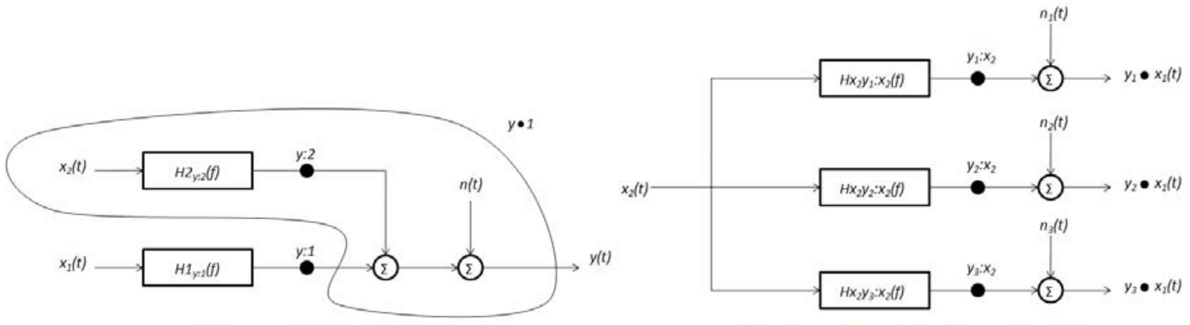

Figure 4: Three-Mic Conditional Spectral Analysis Model

2.3.2 Five-Microphone CSA Method

Hsu and Ahuja [4] modified the 3-mic CSA method to accommodate the situation where measurements of the single source are contaminated by uncorrelated noise. With reference to Figure 5, and noting that microphone measurements y_4 and y_5 are such that they measure the single source $x_1(t)$ and uncorrelated noise only, the source spectra: G_k and G_v can be deduced using the following equations (for $y_1(t)$ only for brevity):

$$G_{k_1k_1} = \frac{\left|G_{y_1y_2} - \frac{G_{y_1y_4}G_{y_5y_2}}{G_{y_5y_4}}\right|\left|G_{y_1y_3} - \frac{G_{y_1y_4}G_{y_5y_3}}{G_{y_5y_4}}\right|}{\left|G_{y_2y_3} - \frac{G_{y_2y_4}G_{y_5y_3}}{G_{y_5y_4}}\right|} \tag{2.7}$$

$$G_{v_1v_1} = \frac{|G_{y_1y_4}||G_{y_1y_5}|}{|G_{y_4y_5}|} \tag{2.8}$$

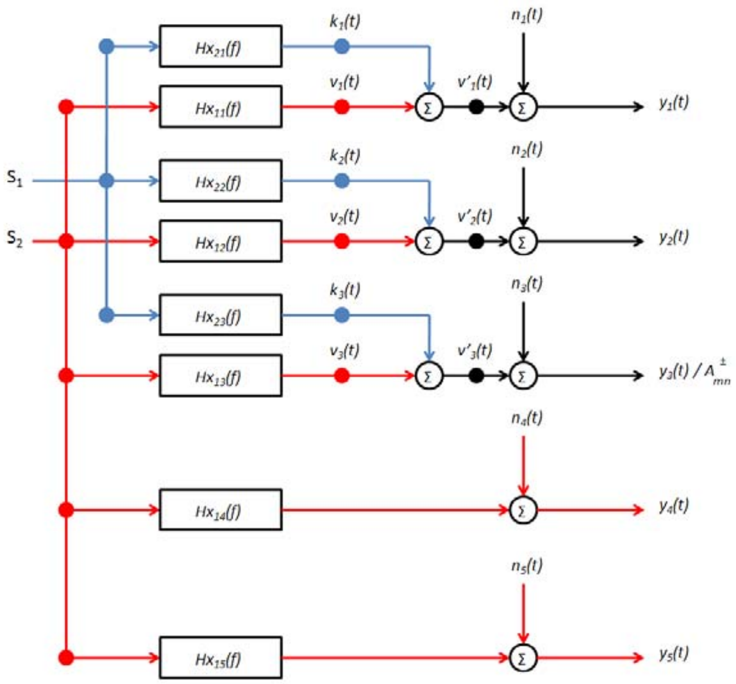

Figure 5: Five-Mic Conditional Spectral Analysis Model

3 Modal Decomposition in Hard Walled Circular Ducts

Modal decomposition is an advanced technique which can provide detailed information as to the modal content of sound propagating in ducts. When applied to aero-engines, the technique can be used as a diagnostic to determine which of the many rotor-stator stages contribute most to the overall radiated sound power. The modal decomposition performed in this paper is based on the approach proposed by Abom [10]. This technique was implemented by Bennett [11] for experimental data, and the pressure field decomposed such that:

- Incident and radial modes can be identified.
- A mean flow can be accommodated.
- A frequency response function technique may be employed.
- Radial and azimuthal modes can be identified
- Duct-wall flush-mounted microphones only are used for the decomposition.
- The decomposition is performed for all frequencies (within the range of interest).
- Data is acquired at all locations simultaneously.

The complex pressure field is commonly expressed with the functional form of $A_{m,n}$ expressed explicitly (see Enghart *et al.* [12] and Tapken and Enghardt [13]) and the complex circumferential mode distribution is isolated as a function of φ only.

$$p(x, r, \varphi) = \sum_{m=-\infty}^{\infty} A_m e^{jm\varphi} \tag{3.1}$$

The amplitude of each circumferential mode of order *m* separates out into a series of radial modes as follows:

$$A_m = \sum_{n=0}^{\infty} [A^+_{m,n} e^{-jk^+_{m,n}x} + A^-_{m,n} e^{+jk^-_{m,n}x}] f_{m,n}(r) \tag{3.2}$$

Equation 3.2 may be expanded such that the complex pressure may be written as:

$$p(x,r,\varphi) = \sum_{m=1-M}^{M-1} \sum_{n=0}^{N-1} [A^+_{m,n} e^{-jk^+_{m,n}x} + A^-_{m,n} e^{+jk^-_{m,n}x}] f_{m,n}(r) e^{jm\varphi} \tag{3.3}$$

M and *N* are the number of azimuthal and radial modes cut-on respectively. The azimuthal index *m* may be positive or negative due to the possibility of the modes spinning in either direction. Abom's method of modal decomposition is carried out in two steps. Firstly an azimuthal decomposition is carried out with microphones equi-azimuthally spaced around the duct. By repeating this stage at different axial locations, these modes can be decomposed into incident and reflected radial modes. A full description of this method including the terms above may be found in Bennett [11].

4 Experimental Rig and Instrumentation

To test the techniques proposed in the proceeding section an experimental rig designed by DLR was used. The experimental test rig design simulates the most relevant acoustic features of the downstream part of a turbo-shaft engine, i.e. the combustion noise source, the turbine stages and the relevant propagation processes to the exhaust exit. On the other hand, in order to gain as much insight as possible into the performance of the different coherence-based source identification techniques and to optimally investigate sound scattering effects, the setup was kept as simple as feasible. The combustor is the main noise source of interest and is modelled with a loud speaker-array in the duct. The basic acoustic scattering effects caused by a turbine stage are simulated by simple stator and rotor blades of an axial fan, although the flow conditions are not representative (which is of minor importance in the current investigations). The part denoted with 'inlet' in Figure 6 corresponds to the exhaust of the turbo-shaft engine. It should be noted that a hub, (hub-to-tip ratio, η = 0.56) in the 0.5m diameter duct, was introduced upstream of the stator/rotor stage with the purpose to modify the conditions for mode propagation, which allows a more differentiated verification of the methods. The sources of noise in the rig are the single rotor-stator stage consisting of 24 rotor blades and 5 stator vanes and the array of sixteen loudspeakers which can be used to generate broadband or tonal noise. The rotor induces a mean flow in the positive x-direction of 9m/s at the inlet. The duct terminates anechoically at the downstream end.

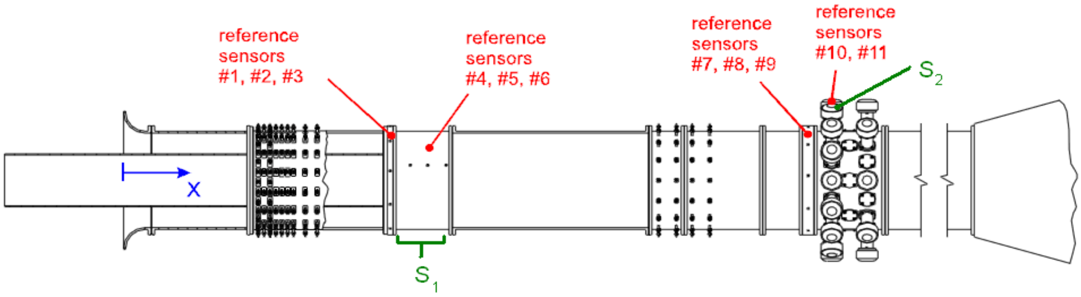

Figure 6: Reference Sensor and Source Locations. S_1 = rotor-stator stage at 1500 rpm. S_2 = single loudspeaker generating broadband noise, or a single ring of eight loudspeakers generating tonal noise at 800 Hz.

Data was acquired at a sampling frequency of 16 kHz with 24 bit resolution. High quality condenser microphones were used to acquire the acoustic pressures at the two arrays of receivers, one of which was located at the hub of the rig. Reference sensors were also located in the duct close to the loudspeakers and close to the rotor-stator stage.

5 Coherence Based Noise Source Identification on a Modal Basis

To test the coherence based noise source identification techniques discussed, two fundamental test cases were chosen: 1) rotation speed of 1500 RPM (giving a blade pass frequency of 600 Hz) and a single loudspeaker generating broadband noise; 2) Same RPM with eight loudspeakers in a single axial ring generating tonal noise instead of the single loudspeaker. The objective in applying these techniques is to identify the contributions of one or more sources to the measurement at a receiver location using the reference sensors. The two sources present during the tests, S_1 and S_2, could represent the turbine and combustor stages of a real turbo-engine. It is important to note that source S_1, representing the turbine, stage consists of a tonal and broadband part and that source S_2, simulating the combustor, is either be broadband or tonal depending on the test case. The techniques tested were the Coherent Output Power (COP), Signal Enhancement (SE) and the Five-Microphone Conditional Spectral Analysis (CSA) technique – standard and modal. The latter (modal) is a novel technique whereby the acoustic modes decomposed at the inlet bank are used (upstream), in turn, instead of one of the output microphone measurements, say $y_3(t)$ in Figure 5. To achieve this, a modal decomposition (see section 3) was performed at the inlet receiver bank in order to identify the complex modal amplitudes at mode orders in the cut-on range. The aim of this technique was to further enhance the identification of each source's contribution at a receiver location by allowing the modal content also to be determined. Thus for test case 2. by controlling the relative phases of the eight loudspeakers in a single axial ring, specific targeted azimuthal modes (TAM) at a specific tonal frequency could be generated. Use of the second ring of eight speakers could allow specific radial modes also to be excited.

To illustrate the application of these techniques, the results of the following test points are presented in this paper:

Table 1. COP Identifier of the single sensors at S_1 (rotor-stator), y(t), and S_2 (single loudspeaker) as input x(t). Test case 1-single loudspeaker.

Test	S_1	S_2	Technique	x	y
1	-	BBN	COP	10	6
2	Tones + BBN	BBN	COP	10	6

Table 2. SE-figure3. An arbitrary sensor (y_3) at inlet and the two reference sensors as in Table 1. Test case 1-single loudspeaker.

Test	S_1	S_2	Technique	y_1	y_2	y_3
3	Tones + BBN	BBN	SE	10	6	Inlet

Table 3. Five-Microphone CSA (standard). Two sensors at the rotor-stator stage (y_1 and y_2), two reference sensors in the loudspeaker cone as pure source measurements (y_4 and y_5) combined with an arbitrary sensor of the inlet array (y_3). Test case 1-single loudspeaker.

Test	S_1	S_2	Technique	y_1	y_2	y_3	y_4	y_5
4	Tones + BBN	BBN	5-Mic CSA	2	6	Inlet	10	11

Table 4. Five-Microphone CSA (standard & modal). Using the inlet sensor or the decomposed modes for y_3, two sensors at the rotor-stator stage (y_1 and y_2) and two reference sensors in a ring near loudspeaker array as pure source measurements (y_4 and y_5). Test case 2-eight loudspeakers.

Test	S_1	S_2	Technique	y_1	y_2	y_3	y_4	y_5
5	Tones + BBN	TAM = 0, at 800 Hz	5-Mic CSA	2	6	Inlet	7	9
6	Tones + BBN	TAM = 0, at 800 Hz	5-Mic CSA	2	6	$A^-_{m,n}(inlet)$	7	9

6 Discussion of Results

The procedure of evaluation was to acquire data for when each source was turned on individually and then when both were turned on at the same time. This allowed the true autospectra for each source at any output sensor location of interest to be known and could thus be compared with the results from the techniques. An example of this can be seen in Figure 7 where we see for one of the sensors located in the loudspeaker cone, the influence of the source S_1 from the rotor/stator is low compared to the overall signal when both sources are turned on. The results from the COP technique are given in Figure 8. The objective here is to measure the contribution of S_2 (the combustor) to a measurement taken in the vicinity of the rotor/stator (S_1). We can see that even though the S_2 contribution at this point is very small the technique does an excellent job at separating out the S_2 contribution from the overall signal measured at sensor 6. Some small evidence (20dB lower than peak) of a 2BPF tone is seen in the conditioned signal as this is also present in the reference microphone placed at the loudspeaker – Figure 7. This is the classical example of how the COP is used and is seen here to perform very well when a noiseless input signal is provided.

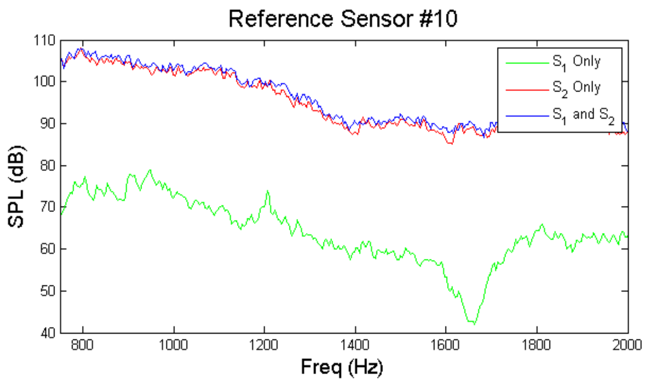

Figure 7: Spectra of input sensor 10 (x) beside S_2 used in COP technique

The results from the SE technique is given in Figure 9. This technique has been demonstrated to work well by this author and others and by others in the literature for similar test set-ups but it can be a difficult technique to implement. The main reason for this is the requirement that only one coherent source be present in each of the three signals. The same two sensors of the COP technique are used here with the addition of a third sensor located in the inlet of the duct. This latter sensor will measure a similar acoustic field to sensor 6 and thus measures both S_1 and S_2. As a result it performance for these sensors is reasonable but with errors. Primarily, the conditioned signal is neither S_1 nor S_2 but a mix of both. More judicious location of the sensors would result in a better decomposition.

The five sensor technique allows for two signals in the acoustic field providing an identification of one related to the single source reference signals (v(t) in Figure 5 associated to S_2) and the second source also (k(t) in Figure 5 associated to S_1). The noise incoherent with both signals is also identified. The results of this technique are provided in Figure 10 and are extremely promising. The part related to S_2 (v_2 cond) is identified as accurately as the COP technique with a slight improvement at the 2BPF. However, unlike the COP technique, the residual signal is further decomposed into two parts. One related to the tonal content of the rotor/stator stage and a second related to its broadband component. We see the magnitude and frequency of the tone is accurately identified and the broadband level of the fan, n_2, is equal to that of the S_1 only case in Figure 8a. It is extremely significant that two broadband signals over the same frequency range have been identified and separated from each other, not to mention a third tonal source.

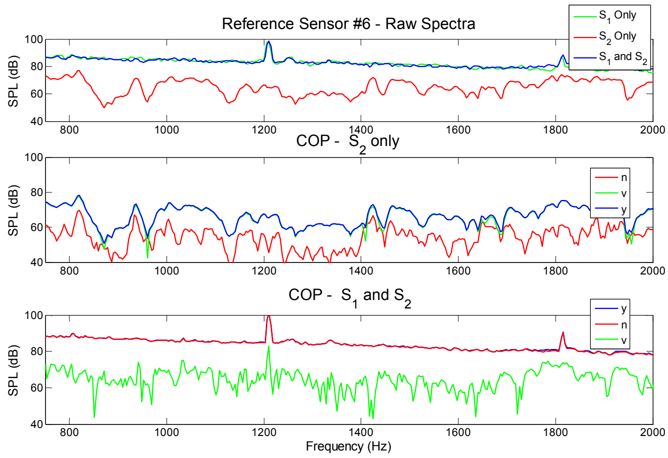

Figure 8: Tests One and Two - Coherent Output Power Technique

The five sensor technique was also applied to test case 2, where tonal noise at 800Hz radiated from eight speakers. In Figure 11 we see that the 800Hz tone is correctly identified (v_3) as being associated with S_2. The fan tone at 600Hz, however, is less clearly identified with S_1 however (k_3) and is of a comparable level to the other terms. This is partly due to the fact that this tone is of relatively low magnitude and not well defined. The problem is compounded also with vibration/structure borne noise related to multiples of the fan shaft RPM which manifest as additional peaks in the spectra some close to the BPF.

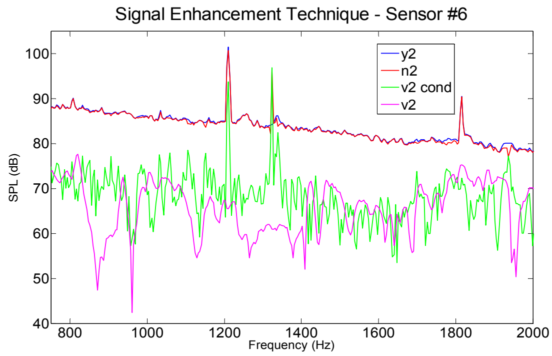

Figure 9: Test Three – Signal Enhancement Technique (sensor #6 shown only for clarity)

The enhanced modal five sensor technique was applied to the same data. To more thoroughly understand the acoustic field, a full modal decomposition was performed at the inlet for the S_1 and S_2 only sources, in turn, the results of which are shown in figure 12.Tyler-Sofrin theory [14] predicts that at the BPF the only cut-on mode excited by the 24 blades and the 5 stators should be m=-1 and corresponds very well with the mode identified in Figure 12a. Similarly, the targeted azimuthal mode of the eight loud speakers after phase adjustment was the plane wave mode or m=0, and is also correctly identified and verified in Figure 12b having the same legend as that in Figure 12a. The results from the application of the enhanced modal five sensor technique to the data when both sources are turned on are given in Figure 13 for the plane wave mode. This plot shows clearly that the energy at 800Hz is the plane wave mode and that its origin is from S_2. Similarly, Figure 14 shows that the m=-1 mode is the main contributor to the BPF whose source is S_1. The high peak at 800Hz can be explained by the fact that other modes are also excited by the speakers even when a specific mode is targeted – see Figure 12b. This peak is significantly lower than the targeted mode however. A waterfall plot of the spectra versus mode shows the plane wave mode to dominate at this frequency.

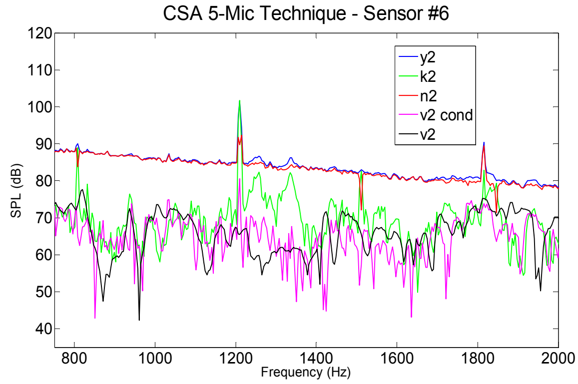

Figure 10: Test Four – Five-Microphone Conditional Spectral Analysis Technique (sensor #6 shown only for clarity)

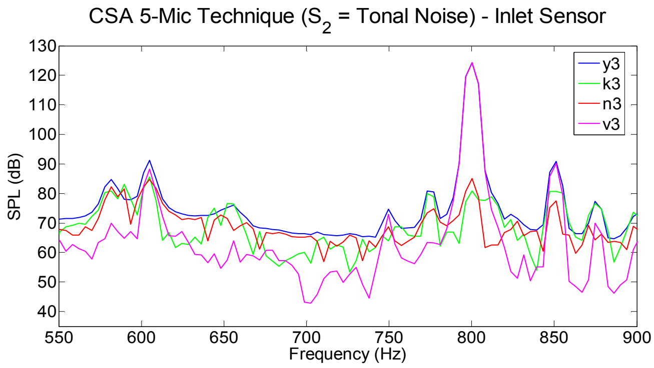

Figure 11: Test Five – Five-Microphone Conditional Spectral Analysis Technique, S_2 tonal noise (sensor #6 shown only for clarity)

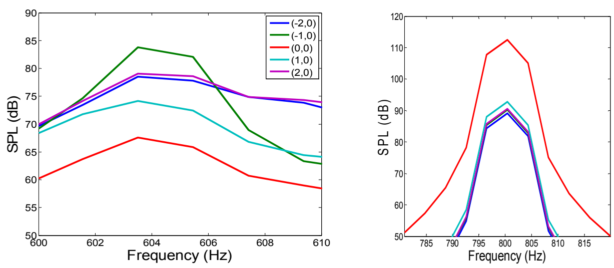

Figure 12: Modal Decomposition at Inlet Bank – S_1 only (left) and S_2 only (right)

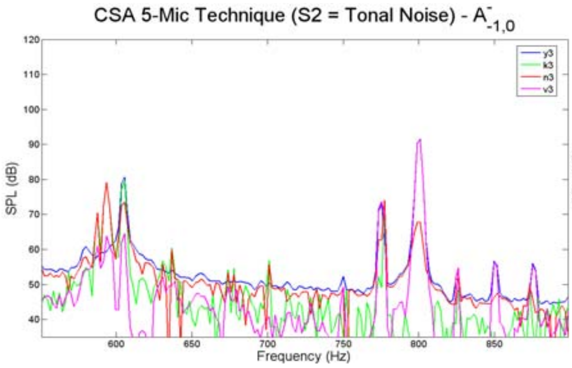

Figure 13: Test Six – $A_{0,0}$ mode

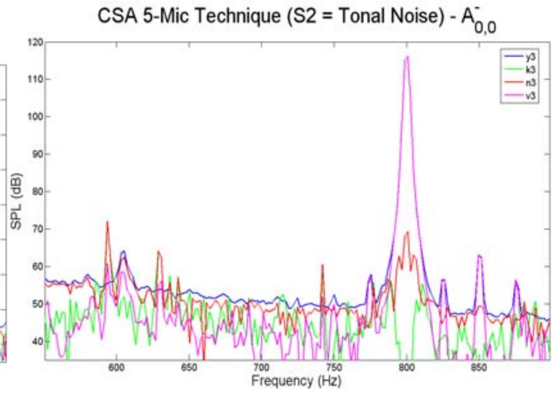

Figure 14: Test Six – $A_{-1,0}$ mode

7 Conclusions

- Coherence based noise source identification techniques have been applied to both broadband and tonal noise for one and two source models in an environment simulating the acoustics of a simplified turboshaft engine.
- The results illustrate the strengths and weaknesses of the techniques and provide recommendations for their use.
- The five microphone technique performs the best allowing two broadband signals to be separated from each other in addition to a third source.
- A novel enhanced five microphone technique method which incorporates modal decomposition is presented which allows source identification and localization to be performed as a function of Azimuthal (or radial) mode. Results from thjis technique are extremely promising.

8 Acknowledgements

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