In-situ Characterisation of Ducted Sources of Airborne Sound

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ABSTRACT
This paper concerns the development and application of an in-situ characterisation method for in-duct sources. Such sources may be attributed to many of the noise problems faced by acoustic engineers, and therefore reliable methods for the analysis and prediction of sound generation and propagation due to in-duct installations are of interest. Based on the concept of an equivalent field representation the in-situ method presented allows for the determination of an independent source strength, thus providing a transferable data set that may be used within a wide range of modelling schemes, including Virtual Acoustic Prototypes. The method itself may be subdivided into three complementary methods each targeting a specific region of the duct’s response, namely: planar, modal and diffuse regions, thus offering the potential for full bandwidth characterisation. Experimental validation is provided through the in-situ characterisation of a compact compressor unit housed within varying lengths of duct. The transferability of data between assemblies is demonstrated through the prediction of operational pressure responses.

1. INTRODUCTION

The overall context of this paper concerns the development of an in-situ characterisation method for in-duct sources (i.e. fans, compressors, etc.). With such sources being attributed to many of the noise problems faced by acoustic engineers, reliable methods for the analysis and prediction of sound generation and propagation due to in-duct installations are of interest. Key to the implementation of these methods is the ability to successfully characterise a noise generating component as an acoustic source. The aim of any characterisation method is to determine some quantity that describes a source’s behaviour with respect to some physical parameter. Depending on the method used this quantity may or may not be an independent property of the source. An independent quantity may be defined as one that is invariant to changes in acoustic loading and is therefore an intrinsic property of the source in question. Such an independence is beneficial in that it allows for source data to be transferred between assemblies and used in the prediction of sound propagation. A prevalent application of such independent characterisation methods, particularly in recent years, is in the development of virtual acoustic prototypes (VAPs), whereby acoustic emissions are predicted and auralised for subjective analysis [1]. The general aim of this paper is therefore to present an independent characterisation methodology suitable for the prediction and auralisation of acoustic emissions as a result of in-duct sources.

The characterisation of in-duct sources has been a focus of attention within acoustic research for many decades. Much of the early work concerned the development of the one-port, two-port and multi-port methods [2–6]. Hailing from 4-pole electrical network theory, these methods work on decomposition schemes whereby a set of unknown source strengths are solved for by use of a measured ‘scattering matrix’. This scattering matrix describes the interaction between forward and backward travelling waves due to the presence of a source. Although a fairly simple procedure in the one and two-port cases, these only enable characterisation in the plane wave region. A further extension to cater for higher order modal contributions is provided via the multi-port approach. Unfortunately, the hardware required for it’s implementation is proportional to the order of the highest mode being accounted for, making full bandwidth characterisation an expensive procedure. Furthermore, due to their modal nature, characterisation or prediction within a geometrically complex assembly is not supported and specially designed test rigs are required.

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Other less invasive methods have been investigated such as [7], in which Weidmann’s acoustic similarity law was used to determine a source’s characteristics by isolating the acoustic loading of the test rig. Implementation of this method requires the source to be operated at multiple speeds whilst a measured pressure is decomposed into the product of a source function and acoustic frequency response function using a computer implemented algorithm. Although an independent characterisation is achieved, the frequency range is limited to the planar region. Other methods, including the only standardised in-duct measurement method (BS EN ISO 5136), are based on the determination of acoustic power [8, 9] and therefore have limited application particularly with regards to auralisation. Moreover, these methods often require the use of anechoic terminations, which are not only large and expensive, but often questionable in their reliability.

It appears most work in the field of in-duct source characterisation has been focused on the prediction of sound pressure within duct-like networks. However, in many cases, such as desktop fans, fridges and other domestic products, we instead concern ourselves with the determination of sound pressure at a given position exterior to the source housing, for example that of a listener. In such cases the aforementioned methods are no longer suitable as they do not appear to provide clear methods for the prediction of acoustic emissions exterior to the source housing. Although not necessarily a problem if diagnostic information is all that is of interest, the capability of predicting the acoustic emissions at any given point is a valuable tool, particularly within the field of virtual acoustic prototyping.

The approach adopted within this paper is based on an inverse method similar to that given in [10, 11], by which a set of unknown source strengths are obtained via the inversion of a measured transfer function matrix. Unlike the aforementioned multi-port methods, the inverse approach defines the source in terms of a finite number of discrete elementary sources, opposed to radiating modes. Such a discrete representation allows for source data to be transferred easily between assemblies, particularly those of complex geometry. There have been attempts at applying similar methods to the characterisation of compressor units and fans in which the transfer functions were obtained from analytical models [12, 13], however it seems that little has been done with the use of measured transfer functions, especially with the VAPs in mind.

2. INVERSE APPROACH

It can be shown from the equivalent field representation of Bobrovnitskii [14] that an independent source quantity, similar in concept to that of a mechanical free velocity, may be determined from in-situ measurements made on a coupled assembly. This quantity represents a relative oscillatory displacement between source and receiver sub-structures which when applied at the coupling interface generates an identical response field in the receiver to that of the active source.

In theory, this relative displacement is applied over the continuum that separates the two sub-systems. However, in reality one can not measure over a continuum. As such, some form of discretization is required if a viable characterisation method is to be developed. It is proposed that a number of elementary sources, i.e monopoles, may be used as a means of discretization. A monopole, being defined as a harmonically expanding rigid sphere, imparts a relative displacement wherever positioned, and is therefore in accordance with Bobrovnitskii’s equivalent field representation. It is further proposed that from the application of an interface excitation, whereby a known velocity differential (i.e. volume velocity) is introduced, the ‘free velocity’ of a source may be determined via an inverse approach similar to that used in the characterisation of structural sources [15].

It is perhaps worth noting that a second equivalent representation presented by Bobrovnitskii, based on a constrained interface, has since gone on to form a well established structural source characterisation method known as the in-situ blocked force approach [15].

Let us first consider the general case whereby the velocity differential over the continuum is represented in terms of an arbitrary number volume velocities $q_m$, that contribute to a pressure field sampled at an arbitrary number of positions $p_n$. The contribution of each volume velocity to the pressure at a given point is determined by the transfer function, $H_{nm}$, that relates the two. From this we are able to construct the following set of
3. EQUIVALENT MONOPOLES

The implementation of equation 5 requires a two part measurement procedure whereby the operational pressure vector \( \vec{p} \), and passive transfer function matrix \([H]\) are measured. With the form of \([H]\) determining the form of \( \vec{q} \), choosing to define a source in terms of a number of elementary point sources requires the measurement of transfer functions relating pressure \( \vec{p} \) to volume velocity \( \vec{q} \). A similar procedure is encountered when determining the contribution of air-borne sources in Transfer Path Analysis (TPA) procedures. Transfer function measurements of this form have been of particular interest to those within the fields of building acoustics [17] and NVH [18], this has consequently led to the development of commercially available volume velocity sources. Unfortunately, due to the technical challenges associated with compact source size and VAP implementation, currently available tools and methodologies are not suitable. Such limitations have prompted the development of a new volume velocity source. Although key in the successful implementation of the proposed method, the development of this volume velocity source will not be covered in this paper, however, it will likely form the basis of a future publication.

For the equivalent monopole description, the general case outlined in equations 1-4 is simply reduced to 2 unknowns, and a solution found via the pseudo-inverse. In the following section a reduced form of equation 5 is used to independently characterise a compact compressor unit housed in a number of different length ducts. Equivalent source strengths are compared and subsequently used to predict the response in different assemblies.

3.1 Test Set-up

The equivalent inlet and outlet source strengths of a compact compressor unit have been measured using the inverse method presented above. The test rig used consisted of a sample holder, figure 1a, to which varying lengths of duct, figure 1b, were be attached. The sample holder and additional sections of duct were all 0.14m in diameter with their lengths given in table 1.

For the equivalent monopole representation the position of the equivalent sources were chosen to be at the radial centre of the pipe, approximately 1 inch away from the compressor’s furthest extremities. The test procedure was carried out as follows:

1 A given test rig configuration (see figure 1 and table 1) was set up in an acoustically idealized space (University of Salford’s hemi-anechoic chamber).
2 An array of 8 microphones were placed around the test rig (see figure 2). 4 by the inlet and 4 by the outlet (thus allowing a 4 fold over-determination). Outlet microphones were positioned out of the way of any strong air flow which may have disrupted measurement.

3 The transfer functions between the inlet/outlet source positions and the microphone array were measured using the calibrated volume velocity source.

4 The compressor was then run and the operational pressures at the 8 microphone positions measured. For auralisation purposes, when measuring the operational data it is important to record the raw time signal of each channel.

5 Data exported and analysis carried out in MATLAB.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duct</strong></td>
<td><strong>Length</strong></td>
</tr>
<tr>
<td>A</td>
<td>0.61m</td>
</tr>
<tr>
<td>C</td>
<td>0.29m</td>
</tr>
<tr>
<td>D</td>
<td>0.33m</td>
</tr>
</tbody>
</table>

Table 1: Duct lengths and test rig configurations.

It is worth noting the importance of signal processing methods used in the inverse procedure. In order for the inverse approach to be used successfully the operational terms, in our case the pressures, \( \{p_n\} \), must have some common phase reference. The classical approach to this is to use a time averaged operational auto-spectrum (real with no phase) and assign it a phase relative to the time averaged cross-spectrum. This approach not only restricts the time domain reconstruction with respect to our aim of auralisation, but often performs poorly. As an alternative, a hybrid time/frequency approach has been adopted, as discussed in section 6.

Figure 1: Test rig parts.

Figure 2: Measurement set-up layout. A number of microphones were set up around the inlet and outlet of the test rig. Equivalent sources were defined either side of the compressor unit approximately 1 inch from furthest extremity.
3.2 Source Strengths and Validation

Figure 3 shows a set of inlet and outlet source strengths obtained whilst the compressor was mounted in rig 1 (see table 1). The colour plots correspond to a set of determined solutions. Each of these were calculated using two operational pressures, one at the inlet and one at the outlet. Since a total of 8 microphones were used a set of 4 determined solutions could be obtained. The fifth plot, shown in black, corresponds to the solutions of the over-determined problem. These source strengths were calculated using all 8 operational pressures. Let us first consider the determined solutions. The results show a strong agreement between all of the source strengths, particularly below approximately 1.5kHz. Above this it can be seen that the source strengths begin to behave differently, displaying artefacts that are unlikely to belong to the compressor. The over-determined solutions tend to agree well with the determined strengths up to about 1.5kHz. Beyond this the over-determined source strengths can be seen to follow the general trend of the determined source strengths, although less of the questionable artefacts. This result suggests not only that the over-determination of the problem can help reduce potential errors, but that above 1.5kHz the source strength is perhaps not sufficiently defined by a single pair of monopoles, i.e. the transfer function measurement is unable to excite all of the modes that contribute to the external sound pressures. Due to the central positioning of the equivalent sources it is unlikely that any of the azimuthal modes are excited, as the source would have been placed at a nodal point. Knowing the diameter of the duct we are able to estimate the cut-on frequency of the first few modes, as shown in table 2.

It can be seen that the cut-on of the first azimuthal mode \((n = 0, m = 1)\) occurs at \(\approx 1.4kHz\), roughly where the agreement between source strengths begins diverge. Figure 4 shows the over-determined inlet and outlet source strengths calculated from measurements made on 3 different test rigs. It can be seen that the agreement between the 3 rigs is good across the majority of the frequency range, even above the cut-on of the first azimuthal mode.

![Figure 3: Source strengths obtained from rig 1 using different microphone pairs and over-determination. E.g. OP 1 + 8 is the source strength determined using inlet and outlet pressures from microphones 1 and 8, respectively. All OPs is the over-determined source strength obtained using all 8 measured pressures.](image)

<table>
<thead>
<tr>
<th>(m)</th>
<th>0</th>
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<td>2382</td>
<td>3276</td>
<td>4157</td>
</tr>
<tr>
<td>1</td>
<td>2988</td>
<td>4158</td>
<td>5230</td>
<td>6251</td>
<td>7239</td>
</tr>
<tr>
<td>2</td>
<td>5471</td>
<td>6657</td>
<td>7775</td>
<td>8848</td>
<td>9890</td>
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<tr>
<td>3</td>
<td>7934</td>
<td>9129</td>
<td>10271</td>
<td>11375</td>
<td>12450</td>
</tr>
</tbody>
</table>

Table 2: Cut-on frequencies for duct of \(d = 0.14m\) (Hz).
mode. Some small discrepancies can be seen at the lower frequencies between rig 1 and 2/3, and at the higher frequencies, namely between, 6-7kHz for the inlet prediction and 4-5kHz for the outlet prediction. Regardless of these errors the results show quite clearly that the proposed inverse method provides a set of source strengths that are consistent between test rigs, i.e. independent.

As a further measure of the quality of the equivalent source strengths, two validation procedures have been carried out, an on-board validation, figure 5, and a transferability validation, figure 6. The on-board validation involves the prediction of an operational pressure using a set of source strengths obtained from the same test rig for which the prediction is carried out. The on-board validation concept may be defined as in equation 6, where \( p_{\text{rin}} \) and \( p_{\text{rout}} \) are a pair of reference pressures located at the inlet and outlet respectively. Subscript \( A \) corresponds to the assembly in which the marked quantity was measured. The on-board validation can therefore be seen to make a prediction for assembly A using source strengths obtained from assembly A.

\[
\begin{bmatrix}
    p_{\text{rin}} \\
p_{\text{rout}}
\end{bmatrix}_A = 
\begin{bmatrix}
    H_{11} & H_{12} \\
    H_{21} & H_{22}
\end{bmatrix}_A 
\begin{bmatrix}
    q_1 \\
    q_2
\end{bmatrix}_A
\]  

(6)

In a similar manner the transferability validation involves the prediction of a pair of operational pressures using a set of source strengths obtained from a different test rig than the one being predicted for, as shown by equation 7.

\[
\begin{bmatrix}
    p_{\text{rin}} \\
p_{\text{rout}}
\end{bmatrix}_B = 
\begin{bmatrix}
    H_{11} & H_{12} \\
    H_{21} & H_{22}
\end{bmatrix}_B 
\begin{bmatrix}
    q_1 \\
    q_2
\end{bmatrix}_A
\]  

(7)

Since the on-board validation requires a prediction on the same assembly in which the source strengths were measured, the over-determined source strengths have been calculated using 3 pairs of operational pressures, with predictions being made for the 4th. For the transferability validation the fully over-determined source strengths have been used.

It can be seen that for both the on-board and transferability validations there is excellent agreement between prediction and measurements up to roughly 1.5kHz, corresponding to the cut-on of the first azimuthal mode. Above this the prediction begins to fall short of the measured response, suggesting that there are additional sources of energy not accounted for in the source characterisation.

Regardless of the error associated with the cut-on of higher order modes, it has been shown that the source strengths are transferable between assemblies and can be used to make pressure predictions with high accuracy providing the source is sufficiently defined. The next section aims to improve upon the results presented here by introducing a set of equivalent multi-pole source strengths.
4. EQUIVALENT MULTIPOLe

In an attempt to extend the frequency range of the proposed inverse method the following section investigates the use of equivalent multi-pole source descriptors. The equivalent multi-pole approach is based upon the same inverse procedure as before, the only difference being the number of monopoles used in the discretisation. For the results presented in this section the inlet and outlet were each defined by a set of 5 equivalent monopoles. By choosing sensible source positions it is proposed that the first few higher order modes, namely the first 2 azimuthal, the first radial and their respective cross modes, may be accounted for and thus according to table 2 extend the working frequency range to approximately 3kHz.

The volume velocity vector being solved for is now of dimensions $10 \times 1$. Consequently we require a transfer function matrix of at least dimensions $10 \times 10$ and an operational pressure vector of dimensions $10 \times 1$. Unfortunately, due to hardware limitations only 10 operational pressures could be measured simultaneously, thus prohibiting any over-determination. Initial results appeared severely contaminated by what was likely inversion error as a result of the larger $10 \times 10$ matrix involved. Techniques such as over-determination and regularisation [19] are often used in an attempt to reduce errors of this sort. With the inability to over-determine the problem, some light regularisation was therefore required. A common form of regularisation consists of the discarding of small singular values of matrix $H$. These small singular values often contain minimal information, that is they are largely composed of noise. When inverted these small terms become dominant and can result in considerable error. Therefore, by discarding or applying some form of restriction to these small singular values it is possible to reduce the severity of this error.

Shown in figure 7 are a pair of transferability validations for the multi-pole source descriptor approach. Figures 7a-7b show an operation prediction of test rig 1 using source data determined from test rig 2. Figures 7c-7d show an operational prediction of test rig 3 using source data also obtained from test rig 2. Source strength data was determined using an absolute singular value threshold of $10^{-6}$, below which all values are discarded. Such a value was chosen somewhat arbitrarily by comparison between predicted and measured responses.

The regularized predictions can be seen to agree well with that of the measured pressure up to approximately 3kHz, i.e. the cut-on of the 3rd azimuthal mode. Above this it seems that the regularisation has little to no effect. It is proposed that the over-determination of the problem would help further reduce the error associated with the matrix inversion and provide better quality source strength data. Comparing the above results to those obtained using the equivalent monopole approach it can be seen that at lower frequencies the use of multiple equivalent sources introduces some error. However, this is not considered a problem as in this region these additional sources may simply be discarded, and a good result obtained from the remaining equivalent monopoles.

An error can be seen to occur across all regularized predictions at approximately 2kHz. This error is likely due to the poor coherence between the volume velocity source and the external microphones. This poor coherence is a result of the limited dynamic range of the internal volume velocity source sensor. It is believed that
use of a more sensitive microphone would alleviate this error.

Regardless of these errors, the above results confirm not only that the equivalent monopole approach was limited by the cut-on of non-planar modes, but that the multi-pole approach allows the frequency range to be extended up to the highest captured mode. However, with the principle aim of this work being to produce realistic auralizations, the implementation of this approach will quickly become unrealistic and expensive due to the number of microphones and source positions required to account for the higher order modal contributions. The following section aims to provide an alternative method suitable for the characterisation of high frequency content.

5. EQUIVALENT ENERGY

It would not be unreasonable to expect the synthesis of sufficiently realistic source auralizations to require predictions up 20kHz. If such be the case, the methods presented above may no longer be suitable for obtaining an independent source strength quantity, be it due to hardware limitations, insufficient source definition or inversion error. In order to sufficiently capture all of the radiating modes using the equivalent multi-pole approach, a considerable amount of instrumentation would be required, and the simplicity of the method would be lost. Instead we aim to find a sufficiently accurate method based on energy. The move to an energy basis is justified by the assumption that at higher frequencies the modal behaviour of the assembly becomes complex enough that the phase relation between modes becomes more or less random, similar to the concept of a diffuse field. In this region it is proposed that the inverse method be carried out using magnitudes only. It is further proposed
This allows the higher frequency region to be defined in terms of two equivalent volume velocity ‘energy’ sources.

\[
\begin{bmatrix}
\tilde{q}_{in} \\
\tilde{q}_{out}
\end{bmatrix} = \begin{bmatrix}
|\tilde{H}_{p_1,q_{in}}| & |\tilde{H}_{p_1,q_{out}}| \\
|\vdots| & |\vdots| \\
|\tilde{H}_{p_n,q_{in}}| & |\tilde{H}_{p_n,q_{out}}|
\end{bmatrix}^+ \begin{bmatrix}
|p_1| \\
|\vdots| \\
|p_n|
\end{bmatrix}
\]

(9)

where $|\tilde{H}_{p_i,q_{in}}|$ represents the averaged transfer function between the 5 inlet monopole sources and the pressure at microphone 1. Shown in figures 8a and 8b are a pair of transferability predictions for test rigs 1 and 3 based on the energy approach outlined above. It can be seen that although there are significant discrepancies in the lower frequency range, above approximately 1 to 2kHz agreement is quite good, certainly better than that of figures 5, 6 and 7.

Using a combination of the 3 methods (equivalent monopole up to the first cut-on, equivalent multipole up to $N$th cut-on and the energy approach above) it is possible to characterise the compressor across the full range of interest (see figure 9). However, if the source data is to be used for the prediction and subsequent auralization of an assembly it is important to assign a random phase to the equivalent energy source strength spectrums. This
may be done by multiplying the source terms by a complex exponential as follows,

$$
\begin{bmatrix}
q_1 \\
q_2 \\
\vdots \\
q_n
\end{bmatrix} =
\begin{bmatrix}
\bar{q}_1 \\
\bar{q}_2 \\
\vdots \\
\bar{q}_n
\end{bmatrix} \cdot e^{i\theta}
$$

(10)

where $\theta$ is a randomly generated phase angle. Although results based on the energy approach appear to successfully predict the response above 1.5kHz, it is suggested that it only be used above the cut-on of the highest captured mode, as the random phase required for auralization is not ideal in the presence of tonal features. An alternative auralisation approach is presented in [20].

Shown in figure 9 are a pair of predictions for the free field sound pressure at the inlet and outlet of test rig 1. Predictions were obtained through a combination of the 3 methods; equivalent monopole, multi-pole and energy sources, presented in sections 3-5 respectively. Reasonable predictions are made across the entire range presented. Some small errors can be see at the low frequencies between 100-200Hz. These are likely due to experimental error as these results were obtained from the first attempt at multipole characterisation. It is believed that better results can be obtained through experimental practise. Regardless of this error the auralisations corresponding to figure 9 are remarkably realistic. It should be noted that the low frequency (equivalent monopole) results used in the combined methodology prediction are not the same as those presented in Section 3. The low frequency results presented in figure 9 have been obtained from the equivalent multipole measurement by using only the central source positions. This was due to potential changes in the positioning of the compressor within the sample holder between tests. All being well, the buttons below will allow you to listen to the auralised prediction and measured pressure response at the inlet of rig 3.

![Prediction vs Measured](image)

**Figure 8:** Inlet and outlet pressure prediction made on rig 1 using energy based source strength data from rig 3.

6. A NOTE ON AURALISATION FOR VAPS

A fundamental requirement of the inverse approach presented in this paper is the existence of a reliable phase relationship between the elements of the operational pressure vector. Classically, in both acoustic and vibro-acoustic applications, this operational vector is determined from measured auto and cross-spectra, whereby the cross-spectrum angle between each signal and a reference is assigned to the appropriate auto-spectrum, as in equation 11.

$$
\begin{bmatrix}
\hat{p}_1 \\
\hat{p}_2 \\
\vdots \\
\hat{p}_n
\end{bmatrix} =
\begin{bmatrix}
\sqrt{\hat{S}_{11}} \\
\sqrt{\hat{S}_{22}} \\
\vdots \\
\sqrt{\hat{S}_{nn}}
\end{bmatrix} \odot
\begin{bmatrix}
e^{i\theta} \\
e^{i\angle\hat{S}_{12}} \\
\vdots \\
e^{i\angle\hat{S}_{1n}}
\end{bmatrix}
$$

(11)
where \( \odot \) and \( \circ \) represent Hadamard (element-wise) product and time averaged quantities, respectively. Although a well established method, this cross-spectrum phase approach not only relies upon constant phase relationships, but assumes a steady state source behaviour. Although a fair assumption in most cases, with the aim of auralisation in mind such a method is not suitable. As an alternative it is suggested that a sequential Fourier spectrum approach be employed. Such a method makes no assumptions on the operational behaviour of the source in question and provides a time dependent source strength, from which realistic auralisations may be produced. The sequential Fourier spectrum approach may be formulated as in equation 12, where \( \mathcal{F}\{P_n(\Delta t_m)\} \) represents the Fourier transform of the \( n \)th time domain pressure signal \( P \) over the \( m \)th time window \( (\Delta t) \). For a given \( \Delta t \) the \( n \) Fourier spectrum are phase referenced to the beginning of that window and therefore a meaningful phase relationship is established between channels.

\[
\begin{bmatrix}
p_1 \\
p_2 \\
\vdots \\
p_n
\end{bmatrix}_m =
\begin{bmatrix}
\mathcal{F}\{P_1(\Delta t_m)\} \\
\mathcal{F}\{P_2(\Delta t_m)\} \\
\vdots \\
\mathcal{F}\{P_n(\Delta t_m)\}
\end{bmatrix}
\tag{12}
\]

The operational pressure vector of equation 5 is thus replaced by \( [p]_m = [p_1, p_2, \ldots, p_n]^T \) and the inverse procedure repeated for \( m \to M \), where \( M \) is the total number of time windows.

7. CONCLUSION

A simplified compressor characterisation method based on an inverse approach has been presented. The aim of this method was to provide an independent compressor source strength that was suitable for use within a general VAP framework. It has been shown that an equivalent monopole approach provides independent and transferable data suitable for external pressure predictions up to the cut-on of the first azimuthal mode. The frequency range was extended further via the inclusion of multiple equivalent source strengths, i.e. an equivalent multipole pair. Due to the larger matrix inversion and lack of over-determination the results where contaminated by inversion error. This was suppressed using some basic regularization and acceptable results obtained. A simple spatial distribution of sources allowed for independent and transferable data to be obtained up to the cut-on frequency of the \( n = 2, m = 3 \) mode. In an attempt to avoid the need for addition instrumentation for high frequency characterisation an alternate method based on an energy assumption was investigated. High frequency predictions appear to follow the general trend enough to allow for suitable auralisations to be produced. A combination of the three methods presented offers the potential for source characterisation and the prediction of external pressure across the entire frequency range of interest.
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REFERENCES


