THE USE OF CAUSALITY METHOD FOR DETECTING NOISE SOURCES IN ISOLATED TURBOMACHINERY AIRFOILS AND CASCADE.

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ABSTRACT

This paper describes an experimental investigation on the interaction noise from a jet investing isolated airfoils. The region of interest focused on the tip region of an isolated cambered airfoil, in use in subsonic axial fans. The Mach number, Reynolds number and blade incidence angles are set in the static frame of reference in order to reproduce flow field condition kinematically similar to that in the rotating frame. Far-field noise measurements were correlated to simultaneous near field pressure measurements taken at different chord-wise positions on the blade surface. The aim was to find, through the use of a cross correlation technique, a causal relationship between the aerodynamic sources and noise emissions to establish the role of airfoil self-noise associated with turbulent structures produced by interaction of the turbulent inflow and highly cambered blade tip geometry. Because the importance of the noise originating from the interaction of unsteady disturbances in fan or compressor blades, as a fundamental contributor to rotors' overall acoustic emission, there is interest also in the development of an estimation of the noise sources by the mean of experimental surveys not directly dedicated to the noise measurements. The technique of cross-correlation represents a good compromise in the study of the blade noise sources, especially when the rig set-up is not dedicated to a proper noise investigation (*i.e.* HPC compression tube facilities).

INTRODUCTION

There is an historical interest on developing physical understanding for the problem of a solid body invested by a steady flow, but in practice, propellers and fans operate under non-uniform inflow. When a turbulent eddy passes the sharp edge of a solid body, the turbulent fluctuations radiate even more strongly, scaling with the Mach number's fifth power as Ffowcs Williams and Hawkings[1] showed. Therefore, due to this scaling, in absence of other noise-generating mechanisms, the trailing edge and the tip gap are the most significant aerodynamic noise source, especially at low Mach number. In stationary tests, engineers have deduced that the dominant noise component arises from the interaction between ingested turbulence and the rotor blades, as demonstrated by Magliozzi and co-authors[2]. These authors worked on understanding the physical mechanisms that are responsible for the noise due to unsteadiness in the impinging flow.

The base for this approach is the linearised aerodynamic theory of an isolated airfoil[3]. The far- field noise, which an airfoil radiates, is related to the turbulent velocity field by transfer function independent of the aerodynamic flow characteristics; when determined for an isolated airfoil to rotating blades. The only limitation in this case, being the neglecting for the blade aerodynamic interaction among the other blades. Winkler *et al*.[4] first proposed this approach for the trailing edge noise study of a highly cambered NACA five digit airfoil at zero degrees angle of attack with and without a boundary layer tripping.

Measurement technique

The data analysis in this paper came from a comprehensive broadband noise experiment for stationary airfoil. Testing parameters included flow average velocity, blade pitch angle, and angle of incidence of the incoming flow and the tip leakage flow control through a new aerodynamic tip end-plates compared with a *datum* impeller geometry.

The authors tested the airfoil in the core of a round free jet blowing into an anechoic chamber at the Fläkt Woods facility in Colchester, UK. They blew the jet through a circular nozzle at the end of a convergent duct onto the airfoil. They aligned the jet's upper part 50 mm from the fan's inlet bell-mouth edge which blew the jet centreline approximately to the blade's tip region (Figures 1.a and 1.b). The relative position of the round jet to the blade assured an aerodynamic behaviour as close as possible to the rotating conditions. The authors used two microphone types for the far-field and the near-field measurements. They obtained the measured time series from positioned probes to give an acceptable trade-off between signal-to-noise ratio and directivity according to Winkler et al.[4] and Bianchi et al.[5].

a)

b)

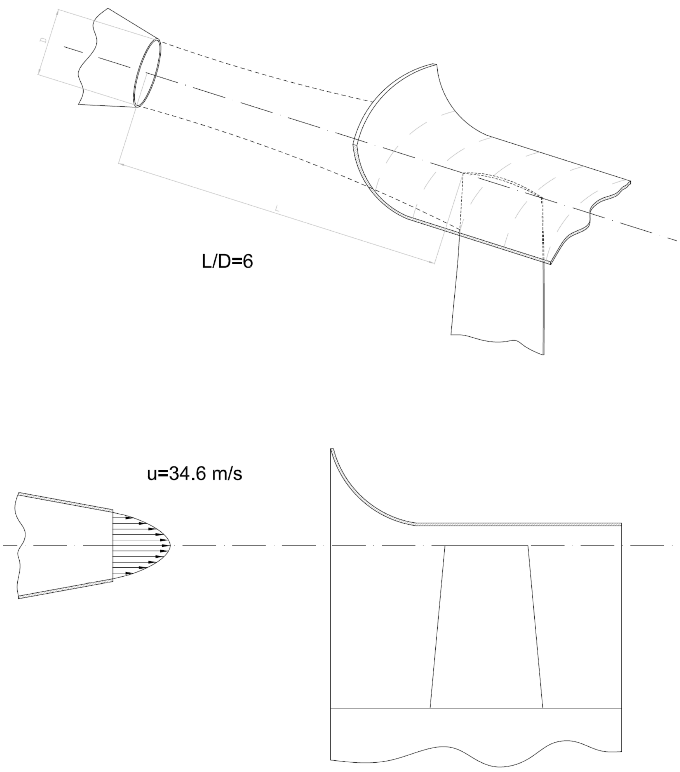


Fig. 1: schematic arrangement of the sector rig.

The far-field microphone was a free-field standard Bruel & Kijaer 1/3" protected with a foam- ball. The microphone was located in the anechoic chamber 1.2 fan diameters off the blade trailing edge, with an angular anomaly θ = 30° from the centreline of the jet plume as recommended by Bianchi et al. [5], Winkler et al. [4] and by Leggat and Siddon[6]. The probes in the near-field unsteady pressure measurements on the blade surface are GRAS Type 40PS surface microphones (Figure 2), designed for measurements on planar and curved surfaces. These probes are 2.8 mm thick with a useful frequency range up to 20 kHz and a dynamic range topping at around 136 dB. The signals from all microphones were acquired using a dBFA-AREVA Symphonie acquisition card. The authors used the near- and far-field signals to compute auto- and cross-spectra. They obtained all the spectral data with 3.125 Hz bandwidth where normalised under the impinging jet parameters to the St number; defined as.

$$St = fL / U_j$$

Where f is the considered frequency, L is the airfoil chord and U_j is the jet average velocity.

The airfoil under investigation is representative of a fan blade section which the engineers had previously developed and which the authors refer to as the *datum* blade configuration. The *datum* blade in the tip region was a modified ARA-D 6% airfoil, British Aeronautical Research type D for subsonic tip propellers. Table 1 provides the *datum* fan's specifications and airfoil section.

The authors present the experimental results *'as measured'*, whilst the theoretical aeroacoustics on the turbulence/airfoil interaction include correction to account for the jet shear layer presence through which the sound must pass before reaching the far-field microphone. Note that there were no adjustable parameters in the theory, which the authors could have used to improve the agreement between theory and experiments for the tested airfoil type.

After the measurement, the authors appropriately processed the instantaneous pressure data in order to derive some quantitative data on the the tip noise. The authors recorded all measurements at a sampling rate of 50 kHz, thus the Nyquist frequency was f = 25 kHz. To avoid signal aliasing, they filtered all data at 20 kHz and analysed it in the range below 20 kHz. The resulting Nyquist-Rate was 2 kHz which was largely below the sampling frequency, thus verifying the second condition in the Nyquist problem on signal aliasing.

The authors estimated the overall uncertainty on unsteady pressure measurements as: i) $\Delta V = 1000$ mV ± 12 mV (20:1) on the voltage and ii) $\Delta G = 200$ dB ± 2.4 dB (20:1) for the row signal gain in the frequency ranges. The error in the Fourier transform was in the range of 0.1-0.2 dB at 1 kHz and 2 dB at 10 kHz, as given by the calibration certification on the microphones and the acquisition system.

The authors processed the auto- and cross-spectra using a signal post-process suite in the frequency range 25 Hz to 20 kHz with a constant bandwidth of 3.15 Hz. A 01-dB Symphonie digital signal processor acquired the signals from the far-field microphone and performed the cross correlation with the near-field blade surface pressure.

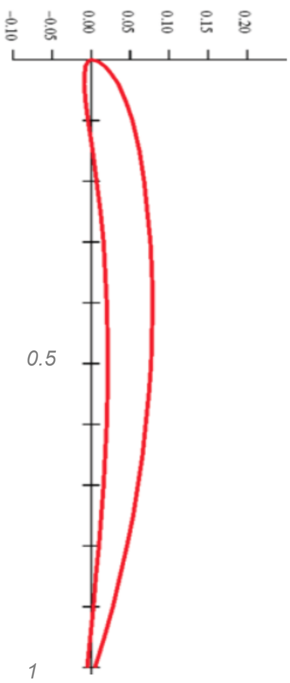
Causality Method Analysis

A transfer function that couples the pressure fluctuation (due to the unsteady flow in the near- field) with perceived noise in the far-field (which constitutes the response of the system) governs aeroacoustics emissions. Pseudo sound can degrade the results; however, in an anechoic chamber, the pseudo sound's transfer function has a shorter decay time than the same function transmitting the genuine noise emission to the far-field.[7] In accordance with Leggat and Siddon's[6] method, the authors chose the distance of the far-field probe from the fan as the optimum to avoid pseudo sound becoming coherent.

In the present study, the authors correlated the tip pressure measurements of the near-field with the measured noise at the far-field. In diagnosing acoustic sources, engineers find identification of the proper correlation domain useful for assigning flow regions in the near-field controlling the sound in the far-field. The cross-correlation between near- and far-field signals reveals a causal relationship between individual noise-source phenomena and the overall radiated sound in a given direction, thereby yielding quantitative information about acoustic source distribution, their local spectra and the scale of their coherence. If a strong harmonic coupling between a source in the near- field and far-field spectra exists, the resulting correlation function does not decay quickly, but is periodic in nature.

Table 1: ARA-D 6% rotor metrics.

	AC90/6 fans	
blade geometry	*hub*	*Tip*
ℓ / t	1.32	0.31
pitch angle (deg)	36	28
camber angle (deg)	46	41
solidity	1.24	0.3
fan rotor		
blade number	6	
blade tip pitch angle (deg)	16 ÷ 28	
hub-to-casing diameter ratio ν	0.22	
tip diameter (mm)	900.0	
rotor tip clearance τ (% span)	1.0	
rated rotational frequency (rpm)	935	



Thus, the authors derived a coherence function for the data set. In accordance with Mile's suggested procedure[8], the authors set the threshold for signal coherence at 95% of the calibrated noise source and used this to confirm the anechoic chamber's acoustic performance. The authors used a white noise Brüel & Kjær Type 4204. This procedure ensured that only coherent sources contributed to the cross-spectra; whereas, the auto-spectra remained as a consequence of coherent and incoherent sources. Correlating near- and far-field data was a good solution for facilitating an improvement in pseudo sound correction.

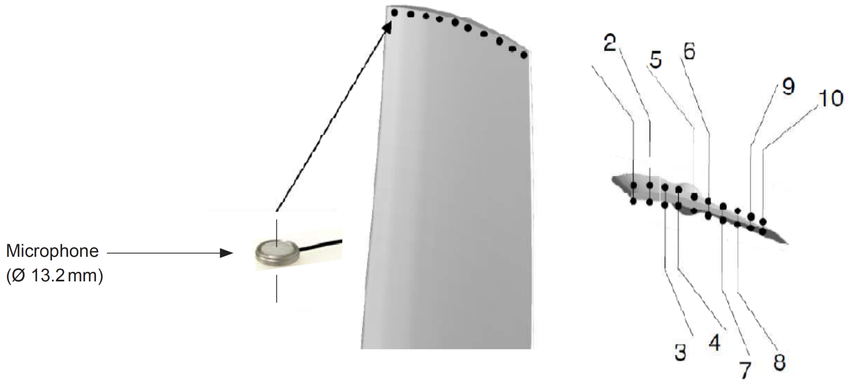


Fig. 2: arrangement of the near-field pressure probes.

REMARKS ON THE METHODOLOGY

The measurement of instantaneous pressure in the airfoil near field raises questions about the consequences of using such measurements to dissect noise-source activity. Previous work[3] has established that, in addition to the 'purely hydrodynamic' contributions, the near-field also comprises an 'acoustic' component limited to the progressive pressure fluctuations put towards the reach of the far field. Several studies on subsonic jet noise have reported on near field pressure measurements under similar velocity gradients to those in the outflow from fan rotor[8]. With regard to the relationship between the near field pressure and noise-source dynamics, Ribner[9] observed that the first-order approximation of the Lighthill source term is formally related to the pressure Laplacian in incompressible flows. Moreover, Laurendeau *et al.*[6] noted that the spectrum in the near-field combines a low frequency range dominated by the aerodynamic signature and a high frequency range that senses acoustic-pressure fluctuations. The pressure in the near-field senses both the 'aerodynamic cause' and the 'acoustic effect' in different frequency ranges. Applied far field filtering provides insights into the source-noise emission coupling mechanisms. From this perspective, the paper aims to correlate the local pressure fluctuations on the blade surface, measured for three chord positions in the tip zone, with the noise at the far-field measured in the different azimuthal angles which the experiments considered. This 'causality method' is no less than a high precision source localisation technique, which identifies the coupling mechanism's structure via which the largely redundant wall pressure dynamic drives the far-field pressure field.

Cross-Correlation Method

Generally speaking, cross-correlations help identify variables (*e.g.* wall pressure) which are leading indicators of other variables (*e.g.* noise) or how much one variable is predicted to change in relation the other variable. This analysis will provide a correlation between two time series or two waveforms. The cross-correlation of two complex functions $f(t)$ and $g(t)$ of a real variable t, denoted $f * g$ is defined by:

$$f * g \equiv \overline{f} = (-t) \otimes g(t)$$

where $\overline{f}$ is the complex conjugate and $\otimes$ denotes here the convolution of the function.

It follows that

$$[f * g](t) = \int_{-\infty}^{\infty} \overline{f}(-\tau) g(t-\tau) d\tau = \int_{-\infty}^{\infty} \overline{f}(\tau) g(t+\tau) d\tau$$

We can use the relation above to determine the relative sizes of sound field intensities radiated from given blade surface positions at given flow speeds. It is understood that the results from the cross-correlation function are to be interpreted as the fraction of the overall intensity radiated from the eddy located at the position of the pressure probe measuring wall static pressure in the near-field.

As the flow velocity ratio increases to higher Mach numbers, since a finite averaging time is employed in the calculation of the cross-correlation function, there exists a noise fluctuation riding on the function itself which gives the uncertainty in the true value of the cross-correlation function. Different studies[12, 14] reported very little difference in the magnitude of peaks pressure of the fundamental tones, but these peaks are shifted to higher frequency. Twofold elements contributed to this evidence: the background tunnel noise, which is greater at high frequencies, and the distance between the near-field and the far-field probes. This effect is partly due to the semi-reverberation environment of the wind tunnel. This increase in frequency for the shear region as compared with that for the mixing region, is supported by other work[14], as the present survey represents a first attempt with the simple case-study of low Mach number flow. In that work[14] a relatively slow jet is disturbed by high intensity sound fields produced at various frequencies, it Is found that the maximum instability within the shear layer occurred for a Strouhal number of 18 to 20. If we compare this with the typical Strouhal number for the mixing region, St = 0-3, one obtains a ratio of approximately St = 6-7 for the critical frequencies for these two regions, agreeing qualitatively with our observations of the actual pressure fluctuations. Because of the increased importance of the shear layer in cross-flow sound-radiation, this has the effect of increasing the frequency of the spectrum maximum for the radiated sound under cross-flow conditions. This frequency shift should be accounted for in any experiment of confined supersonic flow. The reflected correlation pulses can be found experimentally; they will be separated from the first arrival— sound travelling directly from the source position to the far field position — so long as the far field probe is more than a wavelength from the nearest wall of the tunnel. The important measurement is the maximum of the correlation function. The 'noise' evident in this theoretical sketch is composed, depending on test condition, of:

a) Wind tunnel noise.

b) Flow self-noise at the i^{th} microphone.

c) Higher order reflections of jet noise from the tunnel walls.

All of these noises are uncorrelated (for small values off) with the main aerodynamic noise of airfoils — which is what we want to measure.

The authors chose the position of the near-field microphones at ten positions along the airfoil's chord to cover the three most important regions responsible for the tip noise emission: the leading edge (LE), the mid-chord (MD) and the trailing edge (TE). This is an important point given the aforementioned difficulty associated with identify the radiating part of a source in the near-field. Because the formal identity between the source far-field correlation and the integral solution of the Lighthill's equation, the filtering operation by which the said solution sorts and extracts acoustically matched source activity, is inherently present in the source far-field correlation. This is most effective when the source fluctuation frequency matches with the far-field noise pressure. Other researchers have reported the same deduction in past studies on the jet noise source correlations[10].

The second important consequence of using near-field pressure is that we are dealing with more than just the signature of a causal pressure dynamic. We also sense the beginnings of the acoustic response for certain frequencies, as the radiation extent of the airfoil wall pressure field's 'hydrodynamic' component is a function of frequency. The authors could sense low frequency 'hydrodynamic' pressure fluctuations further in the airfoil surface than the high frequencies due to their reflection on the rigid wall surface. The spectrum of the near pressure field thus comprises a low frequency range where the perturbations are largely dominated by the hydrodynamic signature of the largest scale of the jet turbulence and a high frequency range dominated by progressive, acoustic, fluctuations. So, the same near-field measurement both senses the cause and the effect, in different frequency ranges. When we correlate them with the far-field measurements, which are sensitive only to the acoustic effects, it is possible to obtain valuable information related both to the mechanism by which the hydrodynamic cause couples with the far-field, but also to how the new-born far-field sound field at higher frequency radiates to the various far-field microphones. This also provides insight into the sound waves' directional character issuing from the airfoils rigid surface.

Certain difficulties exist, however, concerning physical interpretation of the pressure field in this near-field region, and in particular when relating it to the sound production mechanisms. On one hand, the near pressure field is dominated by dynamics which are best described by a linear hyperbolic differential equation; whereas, it is essentially driven by a nonlinear hydrodynamic pressure field which is well approximated by elliptic equations. There is, however, a further difficulty related to the hyperbolic dynamics of the near field, and which hinders clear interpretation of near-field measurements. Nevertheless, together with the hydrodynamic signature of the turbulence in the high rotational region, as it is for an airfoil near wall region, the near-field also contains the beginnings of a sound field which is destined to reach the far-field. As we are dealing with a jet investing an airfoil, in addition to those discussed above, we have further complications which arise on account of the existence of different shear layers. We characterise these by different velocity gradients, turbulence scales, and characteristic convection velocities.

Guitton *et al.*[11] presented an empirical model which accounted for both the different flow velocity dependence, and the different spectral decay of the hydrodynamic and acoustic components of the near pressure field. They proposed the following criterion to predict the point at which we can observe transition from hydrodynamic to acoustic dominance.

On the base of the above model, Laurendeau[6, 12] convincingly showed that for a jet flow with similar aerodynamic characteristics with the one that the authors used in this measurement campaign, the transition region, from the hydrodynamic and the acoustic regime, lie somewhere in the region of St = 1.3 for a near-field to far-field microphone distance equal to the one that the authors used in these experiments. With respect to the most amplified frequency of the transition region, Laurendeau[12] clearly indicated this value as St = 0.7. This means that, in terms of cause-effect relationship, we seek to probe the limit of St=5, imposed for the similarity of the noise emission of a static airfoil invested by a round jet with respect to a real rotating blade. This limited the value in understanding the details of source dynamic in providing information of the *cause-effect* regime, but informed to the directivity of the high frequency sound field emanating from the three locations at which the authors performed the near-field measurements. Nevertheless, this is strictly true for the cross-correlation analysis, as the tool of coherence analysis is still useful in order to highlight the *cause-effect* relationship. Indeed, because the coherence function involves a normalisation by frequency band, it tends to highlight events that are highly coherent even if their energy is low, also inside the hydrodynamic regime. On the other hand, an analysis using the correlation coefficient, such as cross-correlation, will tend to suppress the low energy events and to highlight the *effect-effect* relationship that we associate with the most energetic events. The coherence analysis is better suited to highlight the near-field acoustic relationship to the far-field domain and gives a feel for the directivity of the sound field issuing from different regions of the airfoil tip. In addition, the cross-correlation analysis informs with regard to that precious information related to the subtle details of the coupling mechanism via which the airfoil wall pressure energy excites the far-field in a particular direction.

EXAMPLES OF RESULTS

The authors applied the sequence of signal processing techniques, which the previous sections illustrated, to the pressure transducer signal located on the tip region's blade surface, and the far- field microphone noise signal. As already discussed, the complexity of the experimental set-up makes it impossible to use analytical Green's functions tailored to the actual geometry. Moreover, the authors expect that the noise sources distributed along the airfoil become non-compact around St = 6, thus a derivation of the Green's function is practically impossible for the frequency range of our interest. It is worth reminding that the conventional *dictum: "correlation does not imply causation"* means that we cannot use correlation to infer a strict causal relationship between the variables. As the introduction explains, do not interpret this *dictum* to mean that correlations cannot indicate the potential existence of causal relations for an aerodynamically produced noise. However, the causes underlying the correlation, if any, may be indirect and unknown, and high correlations also overlap with identity relations, where no causal process exists. For example, if the coefficient of the cross correlation is r = 0.1, as mainly occurs for the peak values in the emission of the studied airfoil, then the coherence g^2 = 0.50, which means that we can explain 50% of the total variation in noise by the linear relationship between this noise and the airfoil wall pressure (as described by the regression equation). The other 50% of the total variation in the noise remains unexplained.

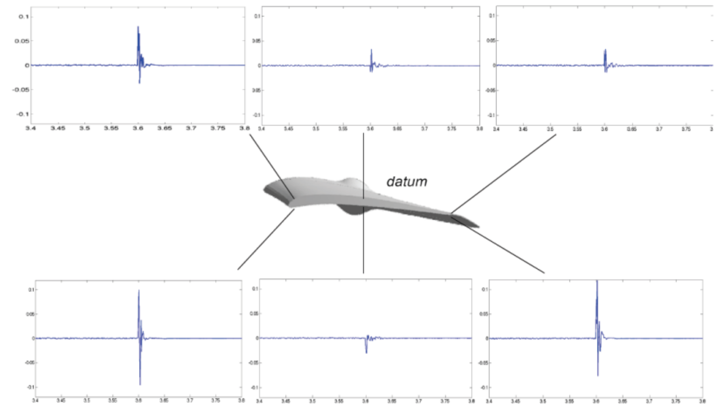


Fig. 3: Cross correlation coefficients of the airfoil in three different chord positions.

Bearing in mind the above stated limitations, the authors use cross-correlation and coherence analyses to discuss the causal relationship between the near-field wall pressure and the far-field sound domain. Figure 3 presents the coefficients of the cross-correlation. As usual for this analysis, if there is a perfect match of the two sets for the given near- to far-field time delay, a peak appears in the correlation function.

The plots in Figure 3 show the correlation coefficients in the time region from 3.4×10^{-3} *s* to 3.8×10^{-3} *s*, which contains the peak value. Turning our attention to the coefficients of the correlation function in Figure 2, a number of interesting observations drop off about the airfoil pressure side's source mechanisms. As Miles[8, 13] recently proved, the correlation coefficient's peak region in a near- to far-field cross correlation, is representative of different *cause-effect* and *effect-effect* mechanisms. The left side of the peak is determined by the direct correlated noise, which dominates the considered source and moves at acoustic speed along its full path to the far-field probe (Miles[8] dealt with the combustor pressure correlated noise in jet engines). The right side of the peak is in the region controlled by the indirect aerodynamic noise, which initially propagates with the mean flow velocity. Consequently, one might expect to see in Figure 3 a correlation function with one smeared peak, due to the direct wall pressure noise, and a smaller smeared peak due to indirect aerodynamic noise. From the examination of the correlation functions of Figure 3, it drops off that this is generally the case encountered.

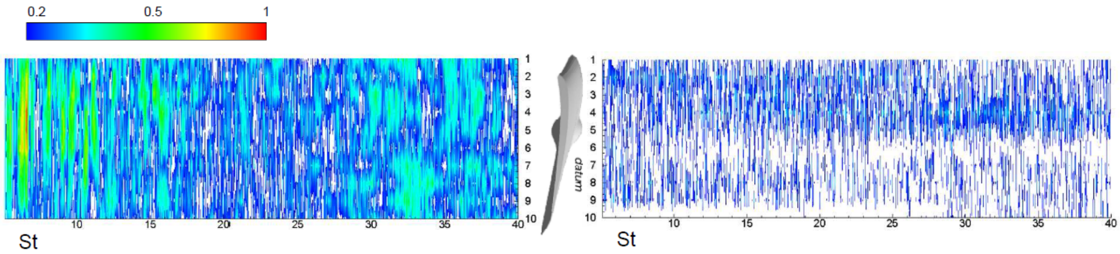


Fig. 4: chord-wise map of near-to-far-field coherence.

Figure 4 shows the chord-wise map of near-to-far-field coherence *(γ^2)* in the *datum* fan blade. The pressure measurements on blade pressure side (PS) indicate a significant coherence level distributed along the chord in a range of St up to 11. The tones of coherence produced at the leading edge region ($1 < c < 3$), in the frequency range St = 5 to St = 11, are due to the flow impingement as a result of the inflow's turbulent nature affecting the structures of the flow/leading-edge interaction. On the blade LE, the near-field probe merged in the boundary layer and was sensitive to the oscillatory pressure field mechanism. We can associate this highly fluctuating source with the Kelvin-Helmholtz mixing-layer structure, which became less efficient as the near-field probe position approached the airfoil's fully developed region.

In case the investigated blade might be placed inside a transonic jet, the derivation of the correlation factors from the measurement should be carefully evaluated, looking at the considerations discussed above and the experimental procedure should be designed properly[14]. The aerodynamic noise generated by a cascade of turbomachinery airfoils is generally 10 to 15 dB higher to the tunnel noise, except for the fundamental peak, which rises at about 19 dB. It is found that the presence of local overpressure due to the shock waves increases the fundamental peaks noise by 10 dB. Many of our measurements could have been improved (if the scope of the work had permitted) by such increased averaging times.

CONCLUSIVE REMARKS

The primary purpose of this work was to determine the effect on sound levels when a high cambered airfoil is immersed in a subsonic turbulent flow. A secondary purpose has been to develop, in a preliminary way, the concept for a measurement process employing correlation techniques, which could be used in a reverberant wind tunnel environment, for transonic cascade or rotors.

The cross correlation function and the coherence function methods provided a procedure to detect the presence of coherent indirect and direct aerodynamic noise, when both are present. However, the inherent smearing of the cross correlation that occurs as a consequence of the turbulence filtering renders the determination of the relative contribution of the indirect and direct noise to the total airfoil noise difficult.

The frequency of the full developed local turbulence of the datum airfoil is St=32. The components in the vicinity of the local mixing-layer frequency are at St=7.5 We can associate this highly directional source with the Kelvin-Helmholtz mixing-layer structure, which became less efficient as the near-field probe position approaches the airfoil's fully developed region.

Finally a comment concerning the cross-correlation measurement technique in a reverberant environment, like a pressure tube. The difficulties experienced in making sound measurements in high reverberant wind tunnel facilities are sufficiently known[14], but have not been investigated extensively. The pressure to noise correlation process has the advantage to eliminate background noise and the unwanted reflection noise. However, the smaller the signal to noise, referred to the direct radiated noise as the signal and all other sounds whether reflection or otherwise as noise, the greater is the averaging time needed in order to obtain a valid correlation function.

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