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**Comparison of measured and predicted airfoil
self-noise with application to wind turbine
noise reduction**

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ABSTRACT			
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Abstract: In the ongoing JOULE-III project *Development of Design Tools for Reduced Aerodynamic Noise Wind Turbines (DRAW)*, prediction codes for inflow-turbulence (IT) noise and turbulent boundary layer trailing-edge (TE) noise, are developed and validated.

It is shown that the **differences** in IT noise radiation between airfoils having a different shape, are correctly predicted. The first, preliminary comparison made between predicted and measured TE noise spectra yields satisfactory results.

NOMENCLATURE

c	chord length	m
c_0	speed of sound	m/s
f	frequency	Hz
k	wave number	1/m
L_p	sound pressure level (re. $2 \cdot 10^{-5}$ Pa)	dB
M	Mach number (U/c_0)	-
PWL	sound power level (re. $1 \cdot 10^{-12}$ Watt)	dB
u'	rms-value of horizontal, longitudinal velocity fluctuations	m/s
v'	rms-value of horizontal, transversal velocity fluctuations	m/s
U	tunnel flow speed	m/s
y	distance to model surface	(m)
ε	rate of dissipation	s^3/m^2
ϕ_{pp}	pressure spectral density (re. $2 \cdot 10^{-5}$ Pa)	dB
ω	angular frequency ($2\pi f$)	rad/s

1 INTRODUCTION

The allocation of new, on-shore sites for wind turbines is becoming a serious problem, mainly as a result of wind turbines producing aerodynamic noise. Especially for a further growth of wind energy in densely populated areas like f.i. the Netherlands and parts of Germany, more silent turbines have to be developed.

The efforts spent thus far have seen limited success, mainly revealing that the understanding, prediction and reduction of wind turbine noise is not a simple task. As a result, generally applicable design tools are not yet available, although several prediction models and noise-reducing concepts are reported (see f.i. [1]).

In the research project *Development of Design Tools for Reduced Aerodynamic Noise Wind Turbines (DRAW)* [2],

it is aimed to develop acoustic prediction codes which take into account the true shape of the airfoil(s) used on wind turbine blades. This is attempted by a mixture of analytical and numerical work. Empiry is introduced only in case the wide applicability of the models is maintained. Another aspect of the work is the use of state-of-the-art CFD (Computational Fluid Dynamics) codes for the generation of detailed information of the airfoil boundary layers. Furthermore, an extensive series of wind tunnel measurements is performed, with the aim to allow for the validation of each step of the development of the prediction codes.

In this paper, the basic principles of the codes developed will be explained. Furthermore, the measurements and the way these are used to validate the codes will be discussed. A preliminary assessment of the capabilities of the codes will be made.

2 MODELLING

Based on the current insights, trailing-edge (TE) noise followed by inflow-turbulence (IT) noise are the main contributors to the overall level of aerodynamic noise of modern wind turbines. Both IT and TE noise occur in two-dimensional flows, in case turbulence is present in the inflow or in the boundary layer along the airfoil, respectively. IT and TE noise are proportional to the effective flow velocity with an exponent of about 5 to 6, meaning that, in the case of a rotating wind turbine blade, the noise radiated from the tip regions (outer 20% of the blade) determines the overall wind turbine noise level.

As a result of this, much confusion exists about the existence and importance of 'tip noise', which is considered to result from the strongly three-dimensional flow at the very tip of the rotating blade. Due to the limited spatial resolution of outdoor measuring techniques and due to the limited



prediction capabilities, it is not clear to what extent 'tip noise' can be considered as an additional source of noise which can not be described with IT or TE noise models. Only in a limited number of cases, tips exhibit outrageous noise radiation, absolutely not matching the IT and TE noise predictions. At this moment, no generally applicable guidelines for 'silent' tip design are available, despite the fact that several, mostly experimental, investigations have been carried out [3-6].

In DRAW, some measurements on the flow in the tip region of a generic wind tunnel model of a blade tip are carried out, mainly to get an indication for the noise generating mechanism. Additionally, some measurements on the 'tip noise' of a scaled model are performed. At this moment, the measurements are not yet analyzed to a degree necessary for model development. Therefore, only the work on IT and TE noise will be discussed in this paper.

2.1 Inflow-turbulence noise

The noise originating from the interaction of turbulence in the flow with the rotating blades is called inflow-turbulence (IT) noise. Here, the noise results from the passage of convected, turbulent eddies which induce pressure fluctuations at the blade surface.

Many of the existing IT noise models are based on a model described by Amiet [7] which is based on the response of an infinitely thin flat plate of large aspect ratio to incident gusts. In most cases, this model gives satisfactory results after it is empirically adjusted to account for the differences which arise from the fact that wind turbine blades, at higher frequencies, cannot be considered as infinitely thin. As a consequence, the value as a design tool is limited since these adjustments are determined by measurements on one turbine, or on a small number of turbines.

Only after wind tunnel measurements had been introduced for studying aerodynamic noise of wind turbine blades [8], research could be performed more systematically, among other things showing that IT-noise depends on the airfoil thickness and airfoil shape [9]. It were these experimental findings which raised the interest in the further development of the prediction models for IT noise.

In the approach followed by the Institute for Aerodynamics and Gasdynamics, the turbulence is modeled as vorticity which is passively convected along the streamlines of the mean flow. This flow is assumed to be inviscid, irrotational, and incompressible. The latter is justified because the Machnumber is rather low ($M^2 \ll 1$). The separation of the problem into a base flow and an additional acoustic field simplifies the analysis considerably and allows to treat both by employing the boundary-element method. The sound generation due to vorticity is described by a so-called acoustic analogy.

In the simulations the airfoils are subjected to skewed harmonic gusts of vorticity. As a consequence a fluctuating pressure field on the airfoil surface is generated which is radiated into the far-field. An additional sound production is due to the fact that the gusts are distorted while they pass the airfoil. This effect is not considered in the model by Amiet which considers the airfoils as infinitely thin plates. However, from simulations it is found that the distortion, caused by the finite thickness of the airfoil, is essential and cannot be neglected. The reader interested

in more details is referred to [10].

2.2 Trailing-edge (TE) noise

The noise generated by the boundary layer turbulence when it is convected past the trailing edge is called trailing-edge (TE) noise.

The many, semi-empirical models available to predict TE noise can mostly be related to the models of Chase and Howe [11,12]. In these models, use is made of a description of the turbulent velocity fluctuations in terms of their wavenumber components. Furthermore, a semi-infinite flat-plate airfoil is considered. In this case, the distribution in the pressure jump across the plate can be related analytically to the amplitude of an incident sinusoidal gust. From the pressure distribution, the far-field sound can be calculated rather straightforwardly using a flat-plate 'response function'. Just like for existing IT noise prediction models, empirical adjustments have to be made additionally to fit predictions to experimental findings.

After, again, wind tunnel measurements had revealed that the general airfoil shape and the boundary-layer structure as well as the detailed trailing-edge shape may have an important influence on the noise emitted [13], interest was raised to improve the prediction models.

In DRAW, attention is focussed on the modelling of the distribution of surface pressures in case of turbulent velocity fluctuations as present in 'real' boundary layers.

In another, complementary JOULE-III project called STENO [14] attention is paid to the evaluation of the trailing-edge response function in case of a serrated trailing edge.

The work performed by the Institute for Applied Physics TPD-TNO roughly follows the approach of Blake [15]. This approach results in a confined expression for the so-called wave-number ($k-\omega$) frequency spectrum of the unsteady surface pressures. The $k-\omega$ spectrum is presented in terms of

- a mean velocity gradient,
- the rms-value of the velocity fluctuations,
- an integral length scale of the turbulence, and
- a (turbulence) spectrum function.

All these parameters can be obtained either from measurement or from calculations (see section 2.3 and 3.3). The second part of the model consists of the translation of surface-pressure fluctuations into an acoustic excitation of the airfoil surface, and subsequently, the far-field noise produced by this excitation. Here, the approaches of Chandarimani [16], and Brooks and Hodgson [17] are followed. In these approaches the finite thickness and sharpness of the airfoil at the trailing edge are neglected. An experimental justification for this approach had been established by wind tunnel measurements carried out before the beginning of DRAW [13].

2.3 Boundary-layer calculations

With the aim to obtain information about the velocity gradient, the rms-value of the velocity fluctuations and the integral length scale of the turbulence in the boundary layer, a Navier-Stokes (NS) code with various turbulence models has been used by the Department of Fluid Mechanics of the Vrije Universiteit van Brussel (VUB). The NS code called EURANUS/TURBO solves the time-dependent Reynolds averaged Navier-Stokes equations, with either the algebraic turbulence model of Baldwin-Lomax or a two-equation (linear and non-linear) $k-\epsilon$ model for closure.



NS boundary-layer calculations are performed on the 500 mm chord NACA-63612 airfoil measured in the KAT and on the 200 mm and 800 mm chord FX79-W-151A airfoils measured in the LST. In this way a Reynolds number range from 0.85 up to 3.4 million is covered.

3 MEASUREMENTS

The experimental part of DRAW consists of aerodynamic and acoustic wind tunnel measurements, both performed on generic models of wind turbine blade sections. As a result of the overlap in the measuring techniques used in DRAW and in another, closely-related JOULE project (STENO, [14]), measurement campaigns as well as the manufacturing and use of test models could be combined.

3.1 Test facilities and experimental set-ups

The majority of the flow measurements were carried out in the Low Speed Wind Tunnel (LST) of the National Aerospace Laboratory NLR. This tunnel is a closed circuit wind tunnel with a 3×2.25 m² closed test section. In this section, wind speeds up to 85 m/s can be attained.

In the LST, the model supports were placed on a balance, situated below the test section floor. For this, a recess was made in the test section floor. In order to enable model rotation, both the model, balance and a circular, rotatable part of the tunnel floor was mounted on a turn-table underneath the test section.

All the acoustic measurements, and a smaller part of the flow measurements were carried out in the Small Anechoic Wind Tunnel (KAT) of NLR. This tunnel is an open circuit wind tunnel. The open jet test section is situated in a room completely covered with 0.3 m long sound absorbing wedges, yielding a cut-off frequency (99% acoustic energy absorption) of 500 Hz. With the 0.4×0.5 m² exhaust nozzle used, flow speeds up to 80 m/s can be attained.

In the KAT a special set-up is available for performing measurements of the aerodynamic noise of 'airfoils' (see also [13]). In this set-up, airfoils can be placed between end-plates which are mounted on the upper and lower lip of the wind tunnel exhaust nozzle. For IT noise studies, a grid, increasing the turbulence of the flow, can additionally be mounted on the tunnel nozzle. Just outside the flow, an acoustic antenna, consisting of 36 microphones, is placed. With respect to previous investigations, the antenna has now been changed on two points. For getting spatial resolution in two directions, the antenna is now extended with a vertical array. Furthermore, the spacing between the microphones is no longer equidistant. More to the centre of the antenna the distance between the microphones is 4 cm; more to the periphery, this distance is 8 cm. With this configuration, a higher resolution can be obtained for a larger range of frequencies.

A picture of the antenna set-up for airfoil self-noise measurements in the KAT is shown in Figure 1.

3.2 Models

Within DRAW, a large series of models with chord lengths varying from 200 mm up to 800 mm were used. For the investigations reported here, it is relevant to mention the models which were used for the IT and TE noise studies. For the investigations on IT noise three 250 mm chord



Fig.1 Acoustic antenna set-up for airfoil self-noise measurements in Small Anechoic Wind Tunnel

models of the type NACA-63612, NACA-63618, and one newly designed one, were measured in the KAT. The new airfoil was designed to yield minimal IT noise without increasing the relative thickness, based on the insights at the beginning of the project.

For the investigations on TE noise, one 200 mm chord model of the type FX79-W-151A, and three 500 mm chord models, again of the type NACA-63612, NACA-63618, and a newly designed one, were used in this wind tunnel. In the LST a 800 mm chord, four times scaled-up, model of the FX79-W-151A type model, was used for boundary-layer measurements.

At the trailing edge of the 200 mm chord model a strip containing 24 miniature pressure transducers (see next section) could be flush-mounted. This strip could also be mounted at the trailing edge of the 800 mm model.

3.3 Measuring techniques

Both in the LST and in the KAT, boundary-layer measurements were performed using hot(cross)-wires and pressure tubes. These measurements were carried out at different chordwise stations of various models. Besides the distributions of the mean velocity, turbulence and the Reynolds stresses, spectra of the turbulence were determined. Unsteady surface pressures were measured using a strip with 24 flush-mounted miniature pressure transducers. 16 of these transducers were clustered in 3 chordwise arrays. The signals of all transducers of one array are cross-correlated and transformed both in time and space to give the so-called wave-number frequency ($k-\omega$) spectra. A wave-number frequency spectrum contains all the spectral information of the boundary-layer turbulence, like convection speed and intensity, and is used to predict the far-field TE noise [13]. In these spectra, the pressure fluctuations which are most important for the noise generation have the highest intensity and propagate with the local convective speed. The region in the $k-\omega$ spectra which represents these fluctuations is called the convective ridge. Two spectra of these pressure

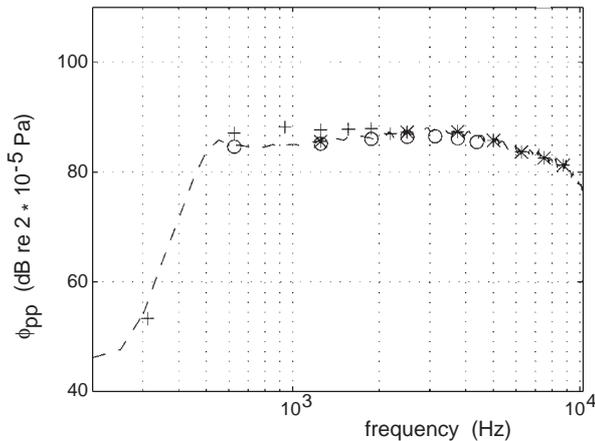


Fig. 2a Pressure distribution at the convective ridge ($c_l = 0.00$, $M = 0.22$)

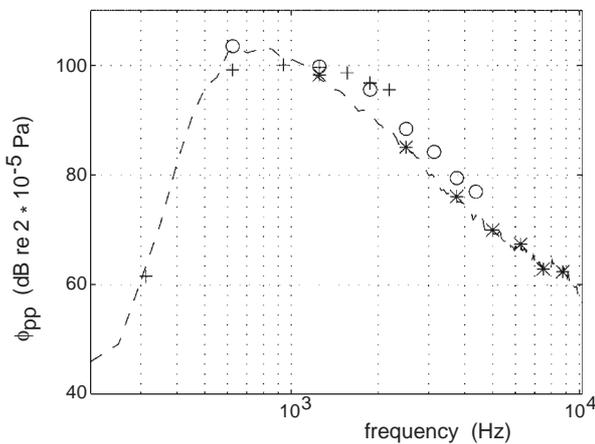


Fig. 2b Pressure distribution at the convective ridge ($c_l = 0.75$, $M = 0.22$)

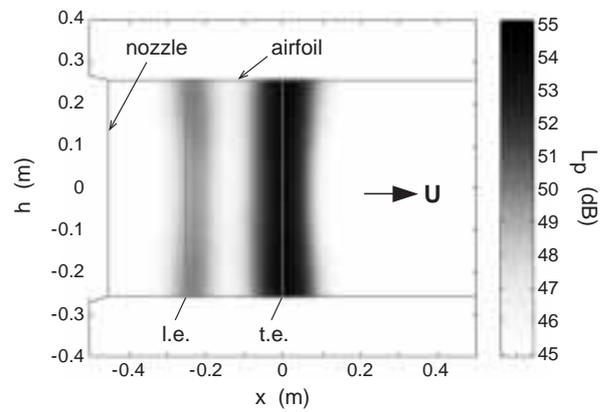


Fig. 3 Acoustic mapping of 250 mm chord model ($f = 2$ kHz, $c_l = 0.75$, $M = 0.22$)

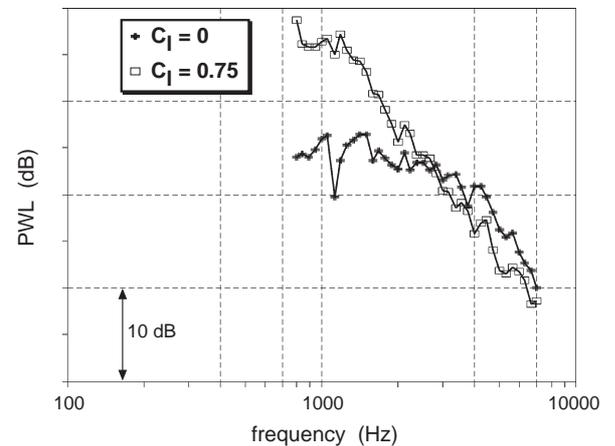


Fig. 4 Spectra of TE noise of 200 mm chord model ($M = 0.22$)

fluctuations as measured at the trailing edge of the 200 mm chord FX79-W-151A airfoil, are shown in the Figures 2a-b.

The ‘focusing’ algorithm employed for the antenna measurements consists of ‘comparing’ the microphone signals with respect to amplitude and phase. In literature, several focusing techniques, all with their specific pros and cons, are described. In DRAW, a so-called conventional (sum-and-delay) technique is used to ‘scan’ source planes. A typical result of such a scan, the mapping of the acoustic sources is shown in Figure 3.

From these scans, spectra of the noise emitted from the leading and trailing edge of a model, are determined. A typical example of these spectra is given in Figure 4, showing the measured TE noise of the 200 mm chord FX79-W-151A airfoil in case of $c_l=0.00$ en $c_l=0.75$, $M=0.22$).

It has to be noted that the antenna technique is well-suited for determining differences in noise radiation between different models. The determination of spectra in an absolute sense however is much more complicated and inaccuracies up to 6 dB may be expected for some frequencies.

3.4 Measuring conditions

All measurements are performed for at least 3 different tunnel flow speeds ($M=0.12$, 0.18 and 0.22), and for at least four angles of attack (yielding $c_l=0$, 0.25 , 0.5 and 0.75).

4 VALIDATION

4.1 Inflow-turbulence noise

Predictions have been validated against results of measurements on the 250 mm chord models for all conditions. The results for $M=0.18$ are shown in Figure 5 (left side: prediction, right side: measurement). In this figure, all levels are presented in 1/3rd octave bands and normalized by the sound levels found for the NACA-63612 airfoil at $c_l=0.25$. At higher frequencies (> 2 kHz), no measured levels are shown for the NACA-63618 and the newly designed airfoil due to the fact that the (low) noise levels could not be measured accurately.

Both measurements and predictions show that the NACA-63618 airfoil radiates less noise than the NACA-63612

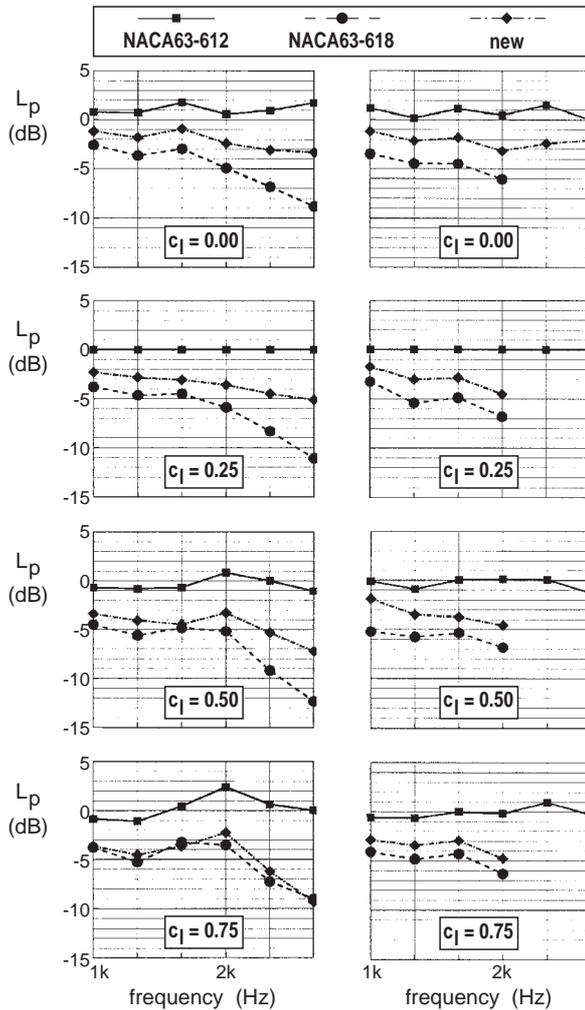


Fig. 5 Normalized prediction (left) and normalized measurement (right) ($M = 0.18$)

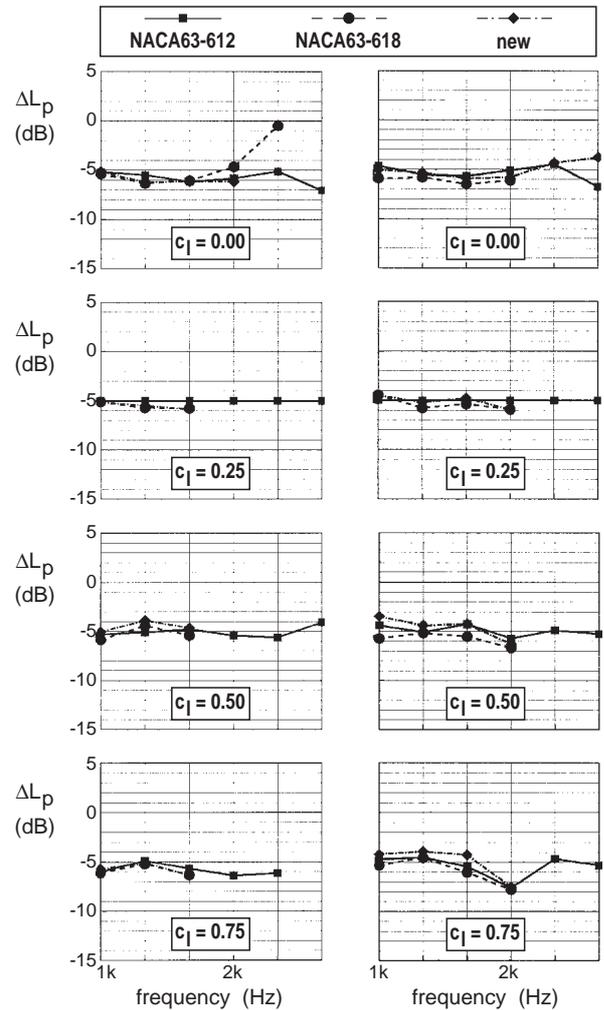


Fig. 6 Difference between normalized prediction and measurement for $M = 0.15$ (left) and $M = 0.18$ (right)

airfoil. The newly designed airfoil shows to yield 2-5 dB less noise than the equally-thick NACA-63612. In general, predicted and measured spectra have a satisfactory similar shape.

In Figure 6 the *differences* in sound level between the normalized measurements and the normalized predictions are shown for $M=0.15$ and $M=0.18$. Here, it can be seen more clearly that the model is able to predict the *differences* between the airfoils rather accurately. For some conditions, however, the difference due to the angle of attack is not captured correctly (see f.i. $c_l=0.75$, $M=0.18$).

4.2 Trailing-edge noise

The calculations carried out thus far, are based on an estimate of the $k-\omega$ spectrum of the turbulent boundary-layer pressure fluctuations. For boundary layers not too far from equilibrium, this estimate is based on a parametric description of the boundary layer.

Figure 7 shows a comparison of the measured sound pressure level and the predicted sound pressure level for the 200 mm chord FX79-W-151A airfoil ($c_l=0.5$, $M=0.18$). The predictions show that for low frequencies the spectrum

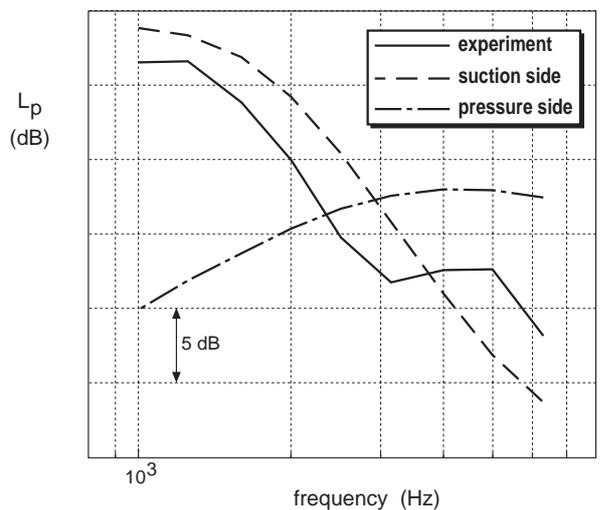


Fig. 7 Comparison of the predicted and measured sound pressure levels of the 200 mm chord model ($c_l = 0.5$, $M = 0.22$)



is dominated by the suction-side generated noise while for high frequencies it is dominated by the pressure-side generated noise. The figure suggests that the prediction of the spectrum produced by the suction side turbulence is satisfactory both with respect to the shape of the spectrum as the level of the spectrum. On the other hand, the high-frequency part of the spectra exhibits less agreement, due to an overestimation of the contribution of the pressure-side turbulence. This mismatch may be attributed to the asymmetry in the radiation pattern at the trailing edge. Another explanation may be given by the 'simple' parametric boundary layer description being not applicable to the thin pressure-side boundary layer.

4.3 Boundary layer calculations

Some typical results of the NS calculations are shown in Figure 8 (500 mm chord NACA63-612 airfoil, $M=0.18$, $c_f=0.5$). On first sight, it appears that the parameters shown are predicted well. However, when looking in more detail it shows that the positions where maximum turbulence intensities and Reynolds shear stress occur are rather inaccurate. At this moment, it seems that these inaccuracies will limit the use of the boundary layer calculations, due to the fact that these positions play a crucial role in the prediction of the noise.

5 CONCLUSIONS AND FUTURE WORK

In the ongoing JOULE-III project *Development of Design Tools for Reduced Aerodynamic Noise Wind Turbines*

(DRAW), a first comparison between predictions and measurements of airfoil self-noise is made. The predictions are obtained using newly developed predictions models which take into account the true airfoil shape.

It is concluded that the model developed for inflow-turbulence (IT) noise is capable of correctly predicting the differences in IT noise radiation between airfoils having a different shape. A first attempt to design an airfoil exhibiting more favourable IT noise radiation has led to a 2-5 dB more silent airfoil.

The model for trailing-edge noise prediction is still under development. A first, preliminary comparison made between predicted and measured TE noise spectra shows that the noise generation induced by the suction-side turbulence is accurately predicted while the noise produced by the pressure-side turbulence is slightly overpredicted. As the model for TE noise prediction requires reliable information about the boundary layer behaviour, it is investigated whether a state-of-the-art Reynolds-Averaged Navier-Stokes (NS) code is capable of delivering this.

In the time remaining till the end of the project (end of 1997) the measurement data will be further analysed and partially re-processed, using several, recently programmed antenna 'focusing' algorithms. This, together with the use of antenna calibration data, will enable for a more accurate use of the measured spectra in an absolute sense. With respect to this, both IT and TE noise models will be developed and validated further. The use of NS calculations

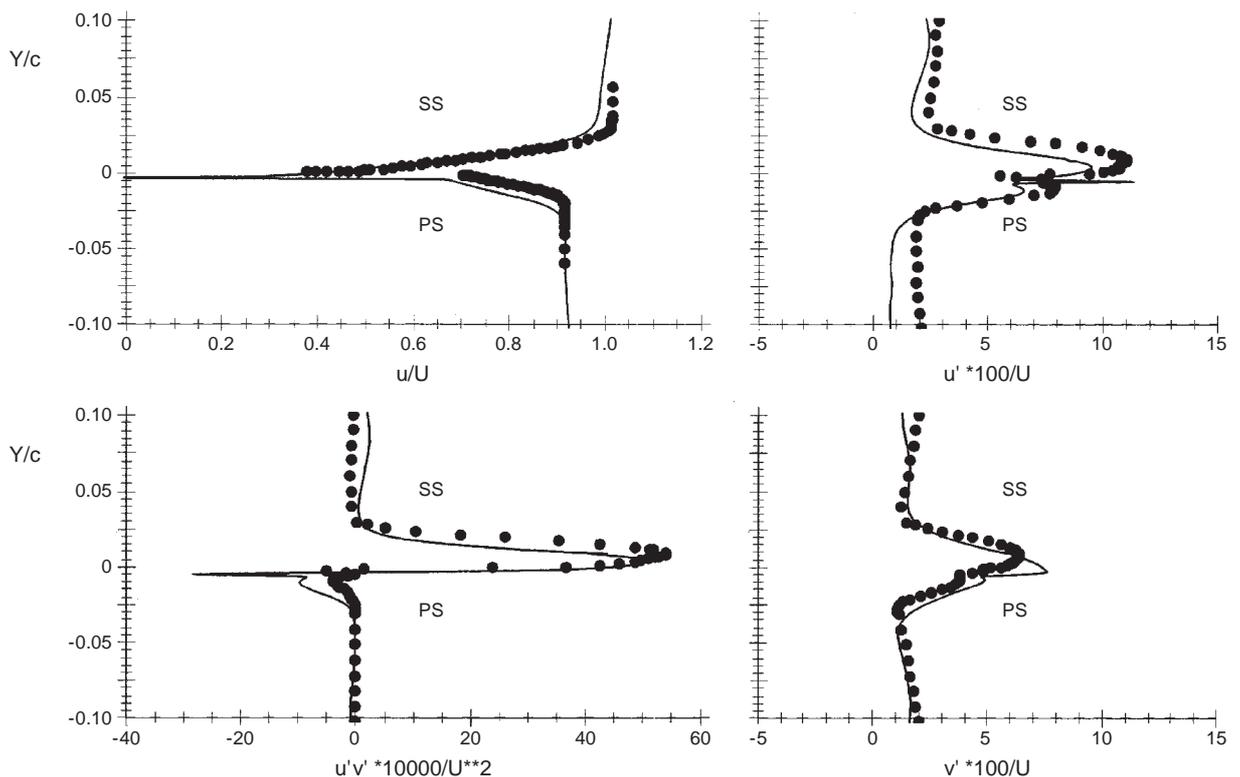


Fig. 8 Comparison of the predicted and measured mean velocity (up left), and Reynolds stresses in boundary-layer of NACA63-612 airfoil ($Re = 2.3 \cdot 10^6$, $c_f = 0.5$, $M = 0.22$)



for the generation of the boundary-layer parameters required, will further concentrate on the implications for the accuracy of the noise calculations. The use of outdoor, full-scale measurements will allow for a final assessment of the codes.

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