# DEVELOPMENT OF DESIGN TOOLS FOR REDUCED AERODYNAMIC NOISE WIND TURBINES (DRAW)

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# 1 Abstract

The major aim of the present project was the development of new prediction models for the aerodynamic noise generation at wind turbine blades. These models should be transferred to computer codes and should be sensitive enough to consider even small changes in the airfoil geometry. This accuracy is needed in order to allow potential users in industry and research establishments to design silent airfoils and consequently blades and wind turbines.

The two main noise mechanisms - trailing-edge noise and inflow-turbulence noise - were treated separately with a mixture of experimental, theoretical, and numerical work. A prediction model for trailing-edge noise was developed which uses the spectrum of the pressure fluctuations beneath the turbulent boundary layer as an intermediate step. The model requires detailed information on the structure of the boundary layer close to the trailing edge. This information can result from Navier-Stokes simulations or from measurements. The model was validated on the result of acoustic measurements on airfoil sections and a good agreement was achieved. A fast and user-friendly Navier-Stokes code was developed which will serve as a future basis for the prediction of trailing-edge noise.

A new prediction model for inflow-turbulence noise is based on an acoustic analogy and makes use of the boundary-element method. The model is able to accurately predict the difference in noise production which is due to airfoil shape. A first design of a silent airfoil turned out to be successful. Both prediction models are believed to be useful also in related areas like fan or propeller noise.

Additional experiments on two different tip shapes revealed that a sword-like shape is more silent than a commonly used rounded tip. Furthermore, tip noise is limited to relatively high frequencies. However, the experimental techniques which were available did not allow to judge whether a distinct contribution of the tip to the total noise level of a wind turbine can be expected or whether it will be masked by the noise coming from the rest of the blade.

Measurements were carried out on two commercial wind turbines in the Netherlands. For this different techniques were applied, i.e. ground boards and an acoustic parabola which allows to discriminate between different parts of the blades.

Another objective of the project was the development of a design tool for wind farms. The resulting computer code (dB DRAW) allows to predict the noise, which results from an arbitrary distribution of wind turbines, at several immission points. The handling of the code is based on a graphical user-interface which enables the user to locate turbines in a wind farm using simple mouse operations. The program is therefore extremely user-friendly.

# 2 Partnership

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# 3 Objectives

The major objective of DRAW was the development of prediction schemes for the main noise mechanisms on wind turbine blades which are accurate enough to be useful as a design tool for silent airfoils and consequently blades and wind turbines. In order to achieve this goal a mixture of theoretical, numerical and experimental work was carried out. The second major objective was the development of a user-friendly computer tool for the acoustic layout of wind farms.

The objectives of DRAW can be summarized as follows:

- Development of an improved model to predict trailing-edge noise,
- Development of an improved model to predict inflow-turbulence noise,
- Analysis of extra noise production at the tips (tip noise),
- Development of a design tool for wind farms.

# 4 Technical Description

There are two important mechanisms which are considered to be responsible for the aerodynamic noise generation at wind turbine blades. These mechanisms are trailing-edge noise and inflow-turbulence noise.
This section starts with a brief description of the two noise mechanisms. It further tackles the experimental techniques which were used on a variety of wind tunnel models. The main part deals with the new prediction models and with the design tool for wind farms. Finally, additional measurements on blade tips and large modern wind turbines are reported.

## 4.1 Noise mechanisms on wind turbine blades

Aerodynamic noise is a by-product of the flow around wind turbine blades. A variety of mechanisms can be responsible for this noise. However, in case of a modern wind turbine only two mechanisms are considered to be important for the generation of broadband noise. These are in the order of importance trailing-edge noise and inflow-turbulence noise. A special problem is the noise generation at the blades tips. There is currently no agreement among scientists whether there is a significant extra noise production at all and what is the mechanism. The research in this project focused on the two important noise mechanisms which were treated separately. Some experiments were also carried out to investigate tip noise.

## 4.2 Outline of measurement program

The measurements within DRAW were performed in two wind tunnels of the National Aerospace Laboratory NLR[1]. The Low Speed Aerodynamic Tunnel (LST) was used for flow measurements on the 3D models and the Small Anechoic Tunnel (KAT) was used for the acoustic measurements and additional flow measurements. The whole measurement program was coordinated with the STENO project (Serrated Trailing Edge Noise, JOR3-CT95-0073).

### 4.2.1 Wind tunnel models

A number of models was produced and tested in the wind tunnels of NLR. 7 cylindrical airfoil sections were used for the investigation on trailing-edge and inflow-turbulence noise. Additional models with two different tip shapes were used in order to study the relationship between tip flow and noise radiation. The first tip is the rounded reference tip which has already been used in former projects, the second tip has a sword-like shape (see Figure 1). All tip models have a fillet into which a small strip with 23 pressure transducers can be mounted.

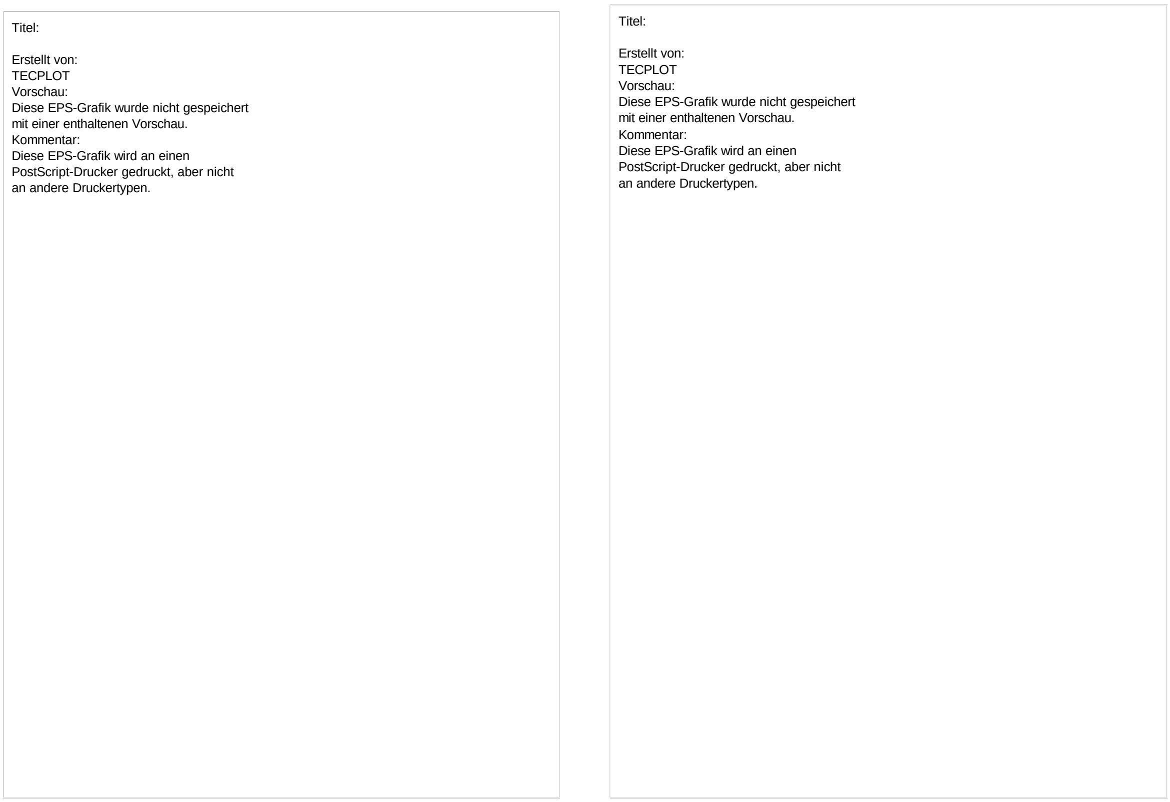


**Figure 1:** Overview of 3D models (left) and 2D airfoil sections (right).

### 4.2.2 Measurement techniques

Different aerodynamic and aeroacoustic measurement techniques were applied:

- Hot-wire, $P_s$-, $P_t$-tube measurements to characterize the turbulent boundary layer (velocity profile, distribution of turbulent kinetic energy, Reynolds-stresses); these data were used for developing and validating the new model for trailing-edge noise,
- Measurements with miniature pressure transducers (KULITE) to determine the wave-number-frequency ($\mathbf{k}$-$w$) spectra of the surface pressure fluctuations; these data were again used for the trailing-edge noise model,
- Measurements with a rake of five-hole probes to determine the path of the tip vortex behind the tip models,

- Flow-visualization with oil-soot and liquid crystals to determine surface streamlines, separation, reattachment lines and transition,
- Measurements of forces and moments,
- Measurements with an acoustic antenna in order to determine the noise radiation; these data were used to validate the new noise prediction models.

As a consequence of the relatively low levels of noise emanating from aerodynamic bodies, an acoustic antenna technique had to be used for the acoustic measurements[2]. It is applied first of all to filter off the tunnel background noise, and secondly to enable the separate measuring of noise radiated from different parts of a model.
A typical acoustic image resulting from the acoustic antenna technique is shown in Figure 2 (left). These images can be obtained in different frequency bandwidths and show the locations and contributions of the dominant sources. In the image shown, the noise radiated from the leading edge (left) and the trailing edge (right) can be recognized as well as some influence of reflection from the end-plates.


**Figure 2:** Examples of measurement results: acoustic image (left); **k**-*w* spectrum (right).

Another important technique was the measurement of **k**-*w* spectra using a strip with 23 miniature pressure transducers (KULITES). These spectra form an important intermediate step in the trailing-edge noise model (see Section 4.3). A typical picture of a wave-number-frequency spectrum is shown in Figure 2 (right).

## 4.3 Prediction of trailing-edge noise

Trailing-edge noise as well as inflow-turbulence noise has been an important field of research in the aeroacoustic community for many years. Both mechanisms are related to the basic problem of turbulence interacting with an edge. In case of trailing-edge noise this turbulence interacts with the *trailing* edge and originates from the boundary layer around the blade which is usually turbulent for the Reynolds numbers under consideration ($Re \approx 1–6 \cdot 10^6$). For inflow-turbulence noise the turbulence is present in the incoming wind and interacts with the *leading* edge of the airfoil. Both mechanisms are also important for a number of other applications such as low-pressure fans, propellers, turbo-fans of aircraft engines, etc.

### 4.3.1 Outline of Prediction Model

A new prediction model for trailing-edge noise was developed at TNO-TPD[3,4]. The prediction model consists of two major steps. The first is the computation of the **k**-*w* spectrum of the surface pressure fluctuations beneath the turbulent boundary layer. The second is the prediction of the far-field sound.

As a consequence of the velocity fluctuation in a turbulent boundary layer there will be a pattern of pressure fluctuations at the surface which is somehow convected with the flow. The **k**-*w* spectrum of the surface pressure fluctuations is a space-time Fourier transform of this pressure pattern. Recall that a usual Fourier transform decomposes an arbitrary signal in time or space into a number of harmonic signals of different frequency or wave number, respectively. A combined space-time transform decomposes a signal which depends on space *and* time into a number of *harmonic waves* of different frequency and wave number.

Since no pressure pattern at the surface is known from simulations (this would require a direct numerical simulation or a large eddy simulation) a model was developed which gives directly the **k**-*w* spectrum as a function of mean flow quantities such as the velocity distribution in the boundary layer and the structure of the turbulent kinetic energy.

### 4.3.2 Prediction of *k*-w spectrum

Following the approach by Chandiramani[5] an expression for the **k**-*w* spectrum of the surface pressure fluctuations was derived which can be written down as an integral along the coordinate $x_2$ normal to the surface:

$$P(k,w) = 4\,r_0^2 \frac{k_1^2}{k_1^2 + k_3^2} \int_0^{\infty} \Lambda_2(x_2)\bar{u}_2^2 \left( \frac{\partial U_1(x_2)}{\partial x_2} \right) f_{22}(k,w)\, f_m\big(w - U_c(x_2)k_1\big) e^{-2|k|x_2}\, dx_2 \qquad (1)$$

Here **k** denotes the wave vector of a single wave with $k_1$ and $k_3$ being the components in flow and crossflow direction, respectively. $U_1$ is the mean velocity in the boundary layer, $\overline{u_2^2}$ the root mean square of the velocity fluctuations normal to the surface, and $\Lambda_2$ the vertical correlation scale for turbulent motions. Finally, $f_{22}$ describes a dimensionless spectrum of the vertical velocity fluctuations and $f_m$ is a moving axis spectrum.

### 4.3.3 Prediction of boundary-layer characteristics

In order to complete the prediction scheme, expressions for all unknown quantities in Eq. (1) must be derived. This can be accomplished by using a number of assumptions such as the mixing length hypothesis. In the end the only input required is the distribution of mean chordwise velocity and turbulent kinetic energy. These quantities can be extracted from a solution of the Reynolds-averaged Navier-Stokes (RANS) equations.

In the framework of the DRAW project a RANS solver from the Free University of Brussels (VUB) was used for this purpose[6]. Additionally, an existing Navier-Stokes solver for laminar flows was extended to treat also turbulent flows. This was done at the Institute of Computer Applications (ICA)[7]. The code uses a finite volume formulation on unstructured grids. Different two-equation turbulence models are implemented, i.e. several low-Reynolds *k-e* models, the *k-w* model from Wilcox (low and high Reynolds number version), and the shear stress model from Menter. The code is integrated in the UG-library developed at ICA and includes a lot of pre- and postprocessing tools[8]. Simulations can be carried out by using a powerful script language which makes the code very user-friendly (see <u>Figure 3</u>).

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**Figure 3:** Illustration of RANS simulation; contour plot of velocity in x-direction, computation mesh, pressure distribution.

### 4.3.4 Prediction of far-field sound

Once the **k**-*w* spectrum is known the far-field sound can be computed by evaluating a diffraction integral at the trailing edge. This is greatly simplified by treating the airfoil as a semi-infinite flat plate, an assumption which is normally valid for the frequencies of interest. The pressure power spectral density $S(w)$ is then given by

$$S(w) = \frac{L}{4pR^2} \int_{-\infty}^{\infty} \frac{w}{c_0 k_1} P(k_1, w) dk_1 . \qquad (2)$$

Here, $R$ denotes the distance of the observer to the trailing edge and $L$ is the span of the trailing edge.

### 4.3.5 Validation of prediction model

Navier-Stokes simulations were carried out by VUB[6] and ICA[7]. The following results were obtained for the airfoil FX-79-W151 at a Reynolds number of $1.52 \cdot 10^6$ using the code developed at ICA with the Wilcox *k*-*w* model. Figure 4 shows the distribution of mean chordwise velocity and turbulent kinetic energy (TKE) at the trailing edge for three incidence angles ($a$ = 0, 4, 8 deg). The results show some typical features, such as a thickening of the boundary layer and an increase of TKE at the suction side at higher incidence angles. The opposite trend can be found on the pressure side. As described above the outcome of the RANS simulations can be used to compute the **k**-*w* spectra. Figure 5 shows the results for suction and pressure side at 0 deg incidence angle.
The prediction model is able to give absolute sound levels. However, in order to be useful as a design tool for reduced noise airfoils, it is more important that the *differences* in sound level

between different airfoil shapes are predicted correctly. Sine no clear difference was found in the measurements we will consider different cases of airfoil loading in the following. This can be illustrated by plotting the difference between the *measured* spectra at $c_l = 0.25$ and $c_l = 0.75$ against the difference between the *predicted* spectra at $a = 0$ deg and $a = 4$ deg. Note that these two angles give a similar lift of $c_l = 0.29$ and $c_l = 0.73$, respectively. Figure 6 shows that there is a good agreement between the two curves. Apparently, there is a common trend that increasing the incidence angle gives higher noise levels at lower frequencies and vice versa.

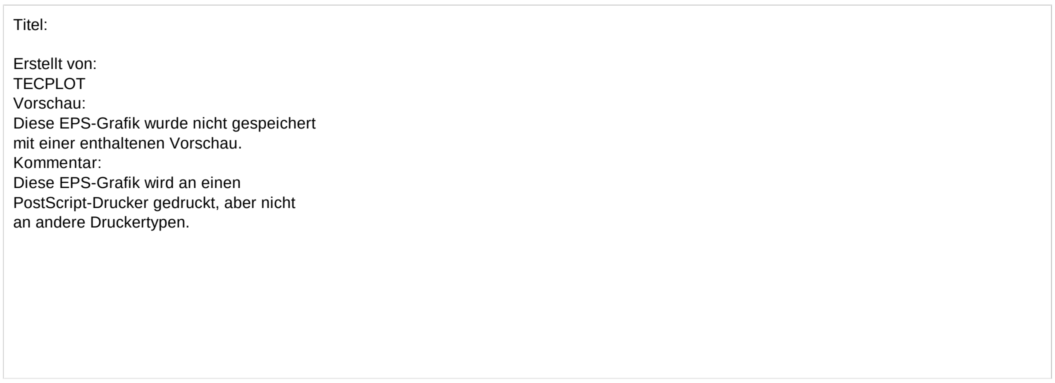


**Figure 4:** Results of RANS simulations: velocity and turbulent kinetic energy profiles at the trailing edge (99 % chord).

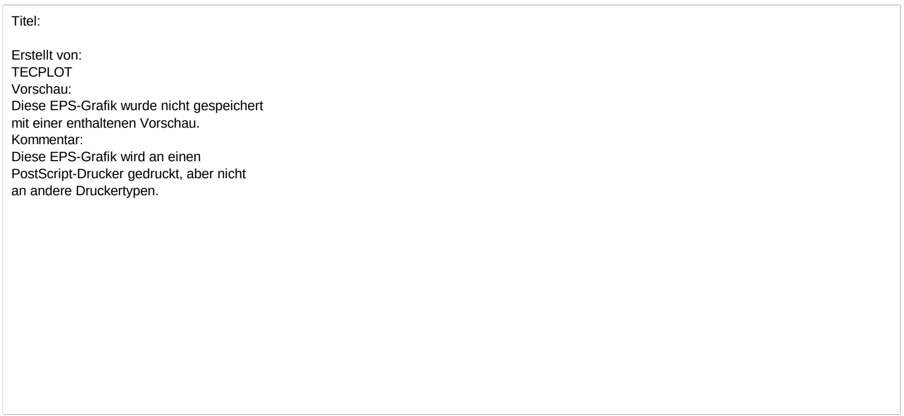


**Figure 5:** **k**-*w* spectra for 0 deg incidence angle.

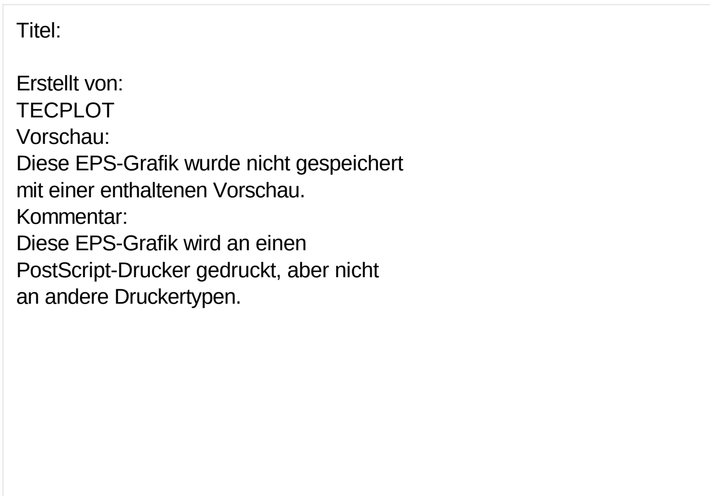


**Figure 6:** Measured and predicted trailing-edge noise; difference between $c_l = 0.25$ and $c_l = 0.75$.

## 4.4 Prediction of inflow-turbulence noise

A different approach is followed to predict inflow-turbulence noise. The model which was developed at IAG is based on an acoustic analogy and on the boundary-element method (BEM)[9]. The basic idea is to represent the turbulence in the incoming flow as a sequence of vortical gusts, i.e. vorticity which varies harmonically in stream- and crosswise direction. This vorticity is assumed to be passively convected along the streamlines of the mean flow around the airfoil. The latter is treated as inviscid and incompressible. In order to simplify the problem, the continuous distribution of vorticity is concentrated in thin sheets (vorticity waves) which coincide with the streamlines.

### 4.4.1 Acoustic analogy

The concept of an acoustic analogy was introduced by Lighthill in the fifties. He combined the momentum equation with the continuity equation in a way that the left-hand-side reduced to the classical wave operator and treated all the remaining terms on the right-hand-side as source terms which radiate sound. Lighthill showed that this source term is dominated in low-Mach number flows by the fluctuating Reynolds stresses which are present in every turbulent flow. The difficulty is that these source terms require a detailed knowledge of the turbulent flow which is normally not available.

Several acoustic analogies were derived in the following years. Among the most important are the ones by Powell and Howe. They introduced the concept of vortex sound by showing that the sound production is always related to the motion of vorticity[10]. This feature makes the analogy interesting for the present problem since it can be used to compute the sound that is radiated by the thin sheets of vorticity which in turn represent the turbulent gusts around the airfoil.

### 4.4.2 Boundary element method (BEM)

The interaction of the sound which is produced by the vorticity waves with the solid airfoil surface is a diffraction problem which is treated by the BEM. This allows to consider the exact airfoil shape without the need to simplify the problem. The BEM code allows to solve the Laplace equation which governs the steady mean flow and the Helmholtz equation which describes the propagation of sound waves. The code was developed at IAG. Its key features are (i) the surface is represented by cubic splines and (ii) the unknown surface distribution is approximated by cubic polynomials. The method can therefore be considered as a higher-order method.

### 4.4.3 Simulation procedure

As a first step the aerodynamic BEM is used to compute the steady mean flow around an airfoil. Based on this solution a large number of streamlines are determined. For each frequency under consideration a harmonic distribution of vorticity is prescribed and the sound production is computed according to the acoustic analogy equation. Finally, the acoustic BEM is used to compute the interaction of the airfoil surface with these sound waves. The results can be evaluated by computing the resulting pressure in the far-field.

### 4.4.4 Validation of prediction model

Simulation and measurements were carried out for a flat plate airfoil and a NACA-63612 airfoil both at zero incidence angle. The Mach number is $M$ = 0.15. The model is again applied only in a relative sense, i.e. it is checked whether it is able to predict the difference in sound radiation which is due to airfoil shape correctly. Figure 7 shows the measured and predicted difference in inflow-turbulence noise between the two airfoils (note that the flat plate makes more noise). It can be seen that the two curves match almost perfectly. Especially the trend that the difference increases for higher frequencies is captured. This confirms the accuracy of the model which has already proven to predict the difference between different airfoils with an error of 1-2 dB.

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**Figure 7:** Measured and predicted inflow-turbulence noise; difference between a flat plate and a NACA-63612 airfoil.

## 4.5 Measurement of tip noise

The mechanisms of sound production at the tip of a blade are still poorly understood. It is not even agreed that there is an extra noise production. In the past, three different explanations were suggested which can be summarized as follows: (1) Tip noise is a form of trailing-edge noise close to the tip which is determined by the highly turbulent and partially separated flow in this region[11]. (2) Tip noise is created by the cross-flow around the side edge of the tip[12]. (3) Tip noise is caused by oscillations of the tip vortex in the vicinity of the side edge[13].
It was not the aim of this investigation to develop a prediction model for tip noise similar to the models for trailing-edge and inflow-turbulence noise in Sections 4.3 and 4.4, respectively. However, a few interesting findings resulted from the noise measurements on the two tip shapes shown in Figure 1.
It should be noted that due to a fundamental problem concerning the calibration of the acoustic antenna, it cannot be decided whether a blade tip produces more or less noise than a 2D blade section of a given length, i.e. whether tip noise has an impact on the sound level perceived by an observer in the far-field. A conclusion that can be drawn from the measurements is that the sword-like shape (LST2 or KAT09) is more silent than the reference shape (LST1 or KAT08). This is remarkable because the reference shape was believed to be a relatively silent tip (compared to 2 'silent' tip shapes which were in reality more noisy, see WAGNER ET AL.[14], page 174). The sword-like shape was inspired by the shape of an LM Glasfiber blade which is however somewhat sharper (page 177). In a measurement campaign undertaken in another EU project, this blade was found to be the most silent on a full scale wind turbine[15].
Figure 8 shows the noise spectra of the reference tip (KAT08), the sword-like tip (KAT09), and a 2D-section of same chord and airfoil (KAT07) for a Mach number of $M_0$ = 0.22 and lift-coefficients of $c_l$ = 0.0, 0.25, 0.5, 0.75.

Bearing in mind that the spectra of a 2D section and a tip are not comparable in an absolute sense, it can nevertheless be observed that the ‘tip noise’ increases dramatically for higher blade loading, i.e. higher incidence angles. Another important observation is that tip noise seems to be limited to relatively high frequencies.

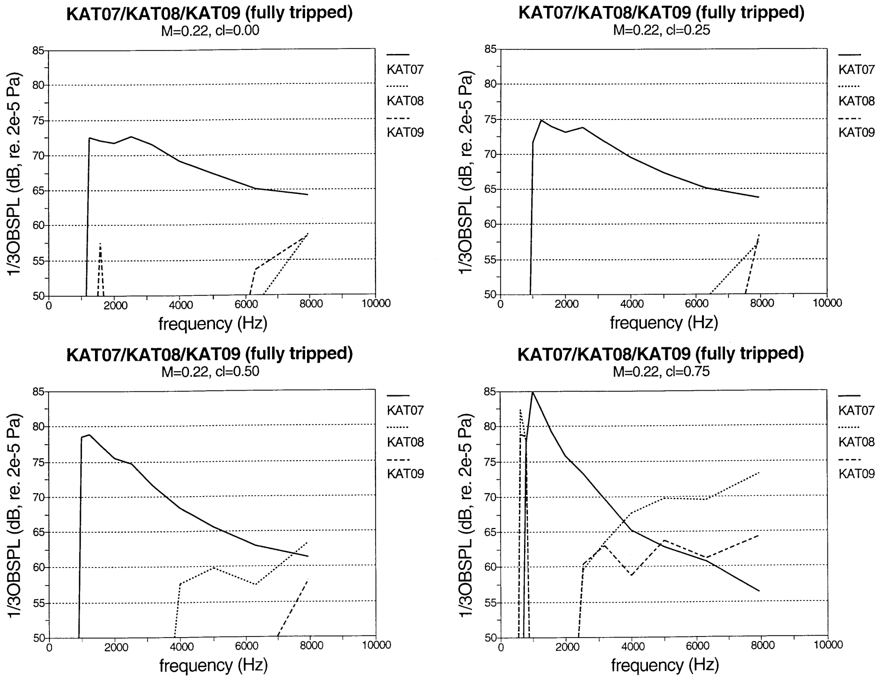


**Figure 8:** Noise spectra for three models at $M_0 = 0.22$.

## 4.6 Design tool for wind farms

Research on further minimizing the acoustic emissions generated by wind turbines is one important aspect for ensuring public acceptance of wind turbines and wind farms. This has been the major topic of the present project. However, a careful selection and analysis of possible sites is the other important aspect. In this context we are talking about a control of acoustic *immissions* at surrounding residential areas rather than the *emissions* of the turbine itself. All efforts in planning concentrate on searching for suitable sites while meeting a minimum required distance to farms or villages and placing the turbines in a reasonable distance to dwellings.

For this purpose a Windows-95-based software tool was developed. The program dB DRAW (Version 1.0) allows for sound-immission prognoses in the far-field of wind turbines or wind farms in Europe. It is applicable for planning authorities and companies in the planning stage or for the checking of windpark configurations (see the complete report[16] and the user’s manual[17]). dB DRAW includes several European regulations for the calculation of sound pressure levels in the surroundings of wind turbines, namely:

- German 'VDI 2714/2720',
- Dutch 'Handleiding meten en rekenen windturbinegeluid',
- Danish 'Statutory order 904',
- International 'ISO/DIS 9613-2'.

The program allows different possibilities of data input. It is compatible to other standard programs (e.g. WASP). The program is extremely user-friendly and allows siting of the turbines via mouse on a previously digitized map. It is possible to switch between the graphic display and the tables with input parameters and results. Changes that are made in one of the display modes are automatically transferred into the other mode. The display shows the location and characteristics of the sound sources and the immission points and acoustic iso-lines. Result tables can be printed out directly. Printing of result graphics has to be carried out with external graphic programs.
The simple structure of the program enables the user to quickly familiate himself with the possibilities of the program ensuring easy and efficient work. As an example Figure 9 shows the main frame which is the central element of the program from which all further screens and frames can be accessed.

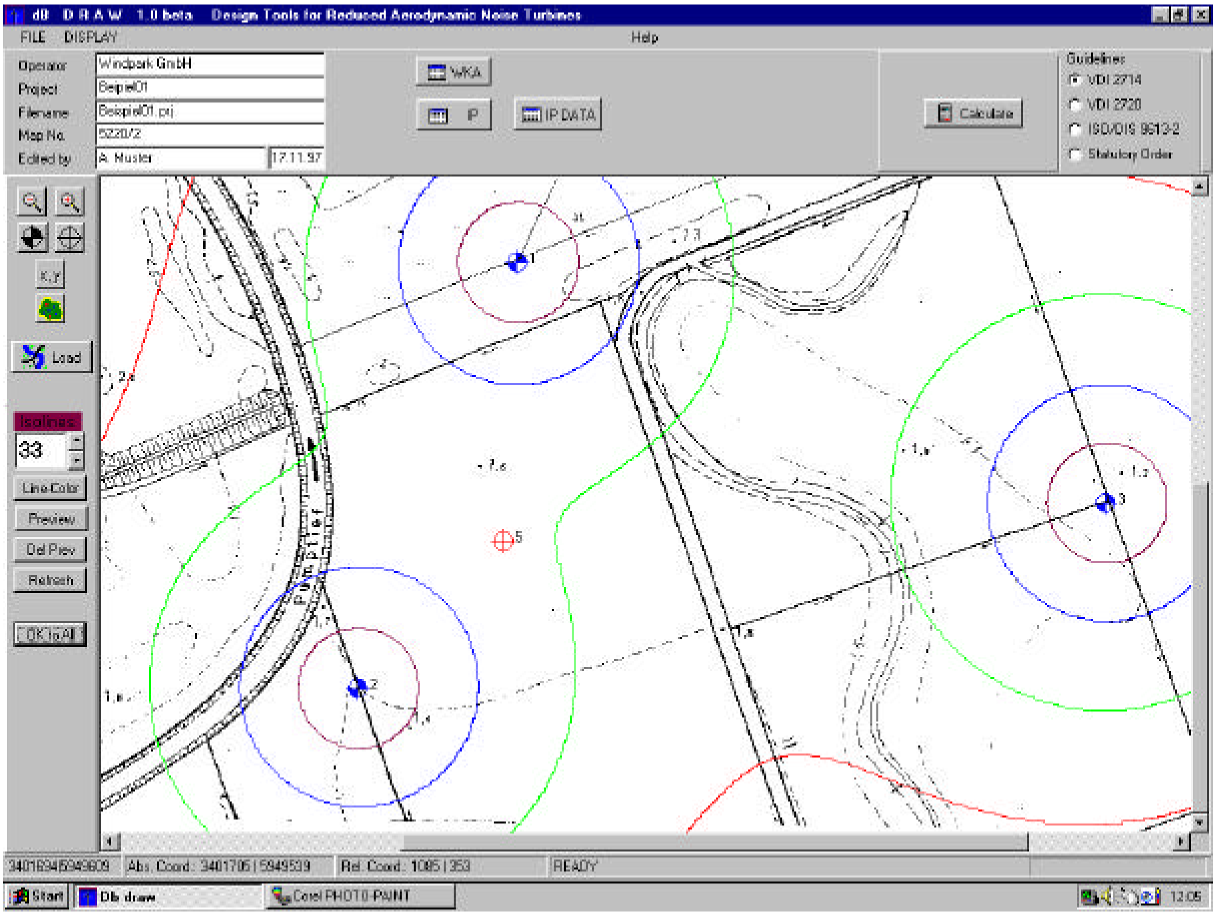


**Figure 9:** Main frame of dB DRAW V 1.0.

## 4.7 Outdoor measurements on wind turbines

Acoustic free-field measurements were performed on two wind turbines in the Netherlands, namely the Lagerwey LW45 750 kW prototype wind turbine at Nieuwe Tonge, and the Nedwind 30 250 kW test wind turbine at the ECN (Energieonderzoek Centrum Nederland) test site in Petten. Acoustical parabola measurements were carried out by ECN on the

Nedwind turbine (see complete report[18]). Ground board measurements were carried out by the VUB on the Lagerwey turbine[19], as well as parabola measurements by ECN[20].

# 5 Results and conclusions

There are two major results of the project.

1. Prediction models for trailing-edge and inflow-turbulence noise
2. Design tool for wind farms.

Prediction models for two important noise mechanisms on wind turbine blades (trailing-edge noise and inflow-turbulence noise) were developed. These models are accurate enough to consider the true airfoil geometry and can therefore be used for the design of silent airfoils.
The prediction models consist of a set of computer codes which are easy to use and can be applied on small workstations. The model for trailing-edge noise is based on a code which solves the Reynolds-averaged Navier-Stokes equations using different turbulence models. The only input which is needed is the contour of the airfoil and the operation conditions (incidence angle, Reynolds number, etc.). The code computes the viscous flow around the airfoil. The structure of the turbulent boundary layer close to the trailing edge of the airfoil is extracted and given as input to the acoustic prediction model. The far-field noise follows from a sequence of simple numerical integrations. The model gives absolute noise levels as function of the distance of an observer and the length of the airfoil.
The model for inflow-turbulence noise needs also the contour of the airfoil and the operation conditions (incidence angle, Mach number, etc.) as input. The code computes the sound spectra using a boundary-element method (panel method) both for the aerodynamics and the acoustics. Although no absolute levels of sound are computed the model is able to predict the difference between different airfoil shapes using the codes developed.
Both models were validated on a number of measurement results showing their ability to predict the absolute or relative sound levels radiated from airfoil sections. The models are therefore well suited for designing silent airfoil sections. To the best knowledge of the consortium this represents a step beyond the current state-of-the-art.
The developed wind-farm design tool includes several European regulations for the calculation of sound pressure levels in the surrounding of windturbines. The program allows different possibilities of data input. It is compatible to other standard programs (e.g. WASP). The program is extremely user-friendly and allows siting of the turbines via mouse on a previously digitized map. It is possible to switch between the graphic display and the tables with input parameters and results. Changes that are made in one of the display modes are automatically transferred into the other mode. The display shows the location and characteristics of the sound sources and the immission points and acoustic iso-lines.

# 6 Exploitation plans and anticipated benefits

The prediction models for trailing-edge and inflow-turbulence noise will be used within the follow-up project DATA (Design of Acoustically Optimized Airfoils for Wind Turbines, JOR3-

CT98-0248). In this project the University of Stuttgart will act as a coordinator and will be responsible for the design of silent airfoil sections. This design includes the application of the new prediction models for the important noise mechanisms. In this project the National Aerospace Laboratory NLR and the TNO Institute of Applied Physics will also be involved. Both organizations acted as major subcontractors in DRAW.
Since the noise mechanisms which were treated in DRAW are relevant for a large number of technical applications such as different types of fans, propellers, etc. the prediction models may also be useful for achieving substantial noise reductions in these related fields.

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