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Results of a wind tunnel study on the reduction of airfoil self-noise by the application of serrated blade trailing edges

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ABSTRACT
Wind tunnel measurements on the self-noise of a series of airfoils and flat plates were performed to explore the previously reported noise reducing potential of serrated trailing edges in case of more realistic flows and geometries. For this purpose, different types of airfoils, and flat plates with varying planforms and orientations of the teeth at the trailing edge were used.
All serrated airfoils yield reduced trailing-edge noise levels, the reductions ranging from 3 dB up to 8 dB. Spectral shape and dependency on the flow speed and angle-of-attack appeared to be different for every airfoil type.
The serrated flat plates were found to give reductions up to 10 dB (1 kHz - 6 kHz). Inclination of the complete flat plate by 10 degrees or a swept trailing edge affected this reduction to a very limited extend only (<2 dB). The same holds for a 10 degrees misalignment of the teeth with respect to the flow direction but in the chord plane. However, misalignment of the teeth by 15 degrees with respect to the chord plane caused an increase of the radiated noise. Keywords: Noise; Environmental Aspects; Wind Tunnels; Innovative Aspects.

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RESULTS OF A WIND TUNNEL STUDY ON THE REDUCTION OF AIRFOIL SELF-NOISE BY THE APPLICATION OF SERRATED BLADE TRAILING EDGES

by

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Paper presented at the 1996 European Union Wind Energy Conference and Exhibition, Gothenburg, 20-24 mei 1996.

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NOMENCLATURE

C = model chord (m)
c_0 = speed of sound (m/s)
U_0 = tunnel flow velocity (m/s)
v' = rms-value of velocity fluctuations (m/s)

M = Mach number (U_0/c_0)
Re = Reynolds number (U_0C/υ)

α = model angle of attack (degrees)
β = teeth chord plane misalignment angle (degrees)
ξ = model edge inclination angle (degrees)
υ = fluid kinematic viscosity (m^2/s)
ϕ = teeth flow misalignment angle (degrees)

1. INTRODUCTION

The reduction of turbulent boundary layer trailing-edge noise by the application of trailing-edge serrations ('teeth') was theoretically described by Howe in 1991 [1]. Whether serrations do indeed have these predicted noise reducing capabilities was investigated in the framework of the Dutch Wind Energy TWIN programme in 1993, measuring several two-dimensional blade sections (airfoils) with serrations at the trailing edges in an anechoic wind tunnel of NLR [2].
In all cases significant reductions were found (up to 6 dB) which increased for 'sharper' (long and thin) teeth. The poor comparison with predictions was ascribed to the fact that the experiments did not fully comply with Howe's assumptions on the character of the boundary layer and flow two-dimensionality.

Therefore, measurements on flat plates besides measurements on real airfoils and the mounting of these models between end-plates to obtain a more two-dimensional flow were recommended.

The experiments on the self-noise of a series of serrated airfoils and flat plates of varying geometry and teeth orientation as described in this paper, were carried out as an intermediate step towards the full-scale application of serrated trailing edges. Here, emphasis was laid on the fast and global assessment of a range of more realistic flow conditions and geometries still allowing for noise reduction by the application of serrated trailing edges.

It has to be noted that the optimisation of serrated trailing edges for full-scale application was not an objective of these investigations. For this, a more comprehensive study on the three-dimensional boundary-layer flow including the influence of centrifugal forces on the boundary layer is regarded as essential. These aspects are shortly discussed in the last section of this paper.

A series of closely related measurements carried out on the noise due to inflow turbulence, generated by various airfoils when placed in a disturbed tunnel flow, is not discussed here but is described in separate papers ([3,4]).

2. EXPERIMENTS

2.1 Modification of the set-up

All experiments were carried out in the Small Anechoic Wind Tunnel of NLR, in a way principally similar to the measurements previously reported in [2]. Therefore, only some modifications carried out to improve the quality of the measurements will be discussed. The reader interested in more details is referred to [2].

The major modification consisted of the positioning of the models between end-plates which were mounted to the upper and lower lips of the tunnel exhaust nozzle. For this, the 500 mm diameter circular exhaust nozzle had to be replaced by a 510×380 mm^2 rectangular nozzle. This semi-open test section was regarded as necessary to avoid shear-layer interaction noise which had been shown to limit the quality of the acoustic measurements. Hot-wire measurements showed that the boundary layer thickness along the end-plates at the position of the leading edge of the models is approximately 6 mm and that the turbulence intensity (v'/U_0) of the core flow is approximately 1%. Fig. 1. shows the modified wind tunnel set-up.

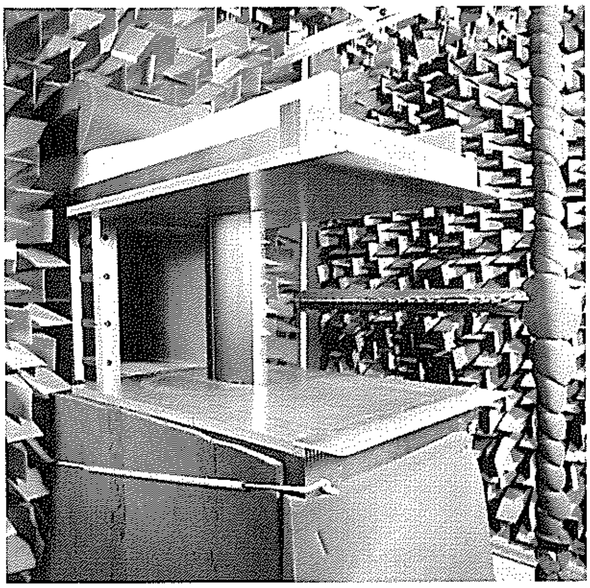

Figure 1: Modified wind tunnel set-up

2.2 Calibration of the acoustic antenna

To allow for the absolute determination of the sound pressure caused by the airfoil, the acoustic antenna was calibrated using a well-defined (monopole) sound source. It was shown that from one single antenna measurement, the (monopole) source sound pressure level can be determined with an accuracy of approximately 3 dB. Differences in sound pressure levels generated by various models can be determined from a series of repeat measurements with an accuracy of approximately 1 dB.

The major uncertainty resulting from the application of an acoustic far-field antenna is caused by the assumed monopole source directivity when determining sound power levels from the measured sound pressure levels. In case the actual directivity is dipole-like, systematic errors of the sound power level of approximately 3 dB may result. Therefore, care has to be taken when drawing conclusions on the influence of model geometry on the total radiated power when using measured changes in sound pressure level. Changes smaller than approximately 3 dB may be due to a change of directivity as well as due to a difference in radiated acoustic power.

2.3 Test models

In total, a series of six flat plates and a series of eight airfoils were manufactured and tested. All plates and airfoils, except the unserrated reference models, had 50 mm long serrations, spaced 5 mm (see Fig. 2). This configuration was predicted [1] and confirmed [2] to give the largest reductions. All reference and serrated models had an effective chord length of 250 mm.

The series of flat plates consisted of one rectangular reference plate and five different serrated plates. The planforms and orientations of the teeth are given in Fig. 3 showing that besides the 'normal' serrated trailing edge, the series comprises flat plates with 'misaligned' trailing edges (15° with respect to the chord plane and 10° with respect to the flow but in the chord plane), and flat plates with aligned teeth but with swept leading and trailing edges (30° swept trailing edge and 10° swept leading and trailing edge).

The series of airfoils consisted of eight models, one reference airfoil and one serrated airfoil of the types NACA_0012, NACA_63018, NACA_63618 and NACA_4418. This series was chosen as representative for a reasonable range of laminar and turbulent, and uncambered and cambered airfoils.

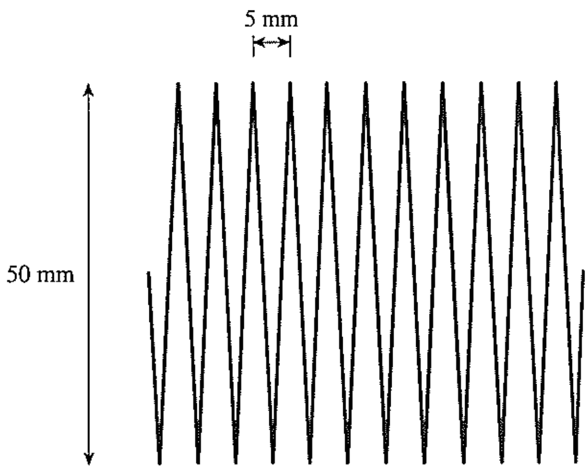

Figure 2: Dimensions of serrated trailing edges

2.4 Acoustic measurements

Acoustic antenna measurements were performed for three different wind speeds (M=0.12, 0.18 and 0.22) yielding Reynolds numbers (Re_C, based on the chord) of approximately 7.10^5, 1.10^6 and $1.4.10^6$). The measurements on the flat plates were performed for zero angle of attack (α) only, except on the flat plate with the teeth 15° misaligned with respect to the chord plane (FP2_15) which was also measured for α=-15° in which case the teeth are in fact aligned with the (undisturbed) flow direction. The measurements on the airfoils were carried out for three angles of attack, theoretically giving lift coefficients (c_L) of 0.0, 0.5 and 1.0.

2.5 Hot-wire and balance measurements

Hot-wire measurements of the boundary layer were performed to verify the assumption that the ratio of teeth length and boundary layer thickness is large (> 5) for all models, wind speeds and angles of attack.

Measurements of the lift and drag forces and moments using an external balance were performed to see the influence of serrations on the performance of the airfoils and to enable proper scaling of acoustic results.

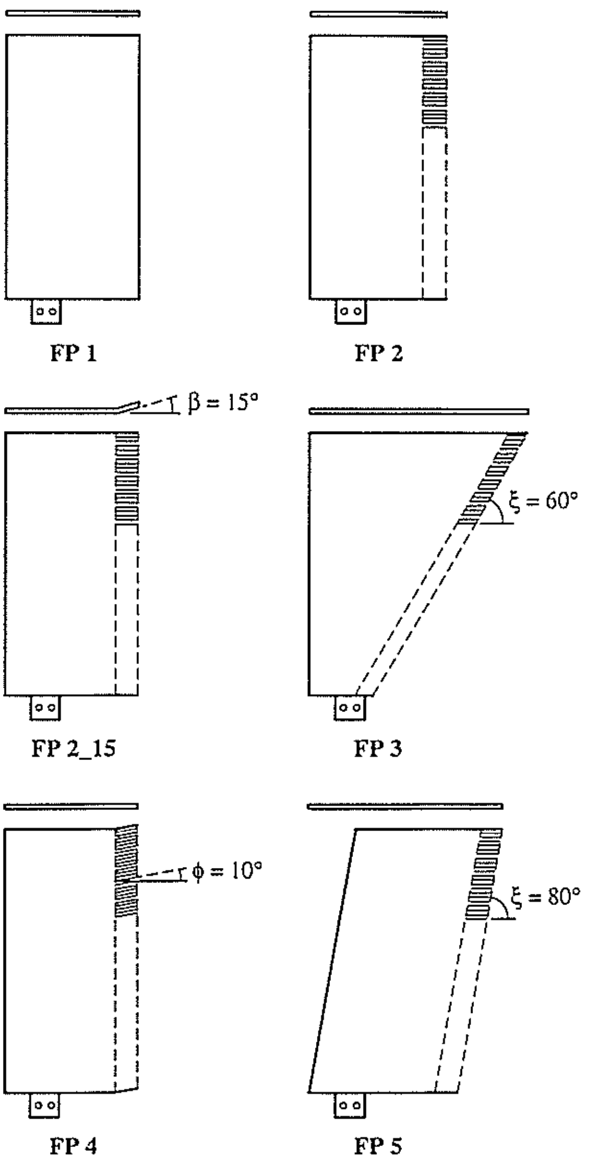

Figure 3: Survey of flat plates

3. RESULTS

The results of the acoustic measurements are summarised in Table 1a (flat plates) and Table 1b (airfoils) as differences in octave band sound pressure levels between a serrated model and its respective reference model. These differences were obtained after the spectra were corrected for whistling tones, which were sometimes found to occur even after a roughness strip was attached to the model. In Table 1a, predicted values for the rectangular, serrated flat plate (FP2) are given as well.

The serrated flat plates exhibit significant reductions in radiated noise levels (in general >5 dB). However, the measured reductions are (again) significantly smaller than the predicted ones. These reductions are not affected by inclination of the trailing edge (FP3) or of both the trailing and the leading edge (FP5) and are reduced only slightly in case the teeth are misaligned with respect to the flow direction by 10° but in the plane of the chord. However, these reductions do not occur in case the teeth are misaligned with respect to the flow and the chord plane. Misalignment of the teeth in this way gave rise to an increase (1-5 dB) of the levels of radiated sound. This increase is even more severe (≈10 dB) in case the flat plate is given an angle of attack of -15°, but may most probably caused by separation of the flow at the leading edge.

The serrated airfoils gave significantly reduced noise levels (5 dB typically). In the case of the NACA_0012 and the NACA_63618 airfoils these reductions appeared to depend on the value of c_L (not shown in the table). Typically, 3-4 dB less reduction for c_L=0 and 3-4 dB more reduction for c_L=1.0. The reductions determined for the NACA_63018 and NACA_4418 were found to be rather insensitive to c_L. Surprisingly, the reductions were found to decrease (slightly) at higher frequencies except for the NACA_0012 airfoil which was found to yield the highest reduction at f=4 kHz. On average, the reductions were rather independent of flow velocity.

The results of the airfoil boundary-layer measurements yielded values ranging from approximately 5 for the ratio of teeth length and boundary layer thickness on the suction side up to 10 for the ratio of teeth length and boundary layer thickness on the pressure side ($Re_C=1.10^6$, c_L=1.0). These values, when used in the 'flat-plate formulas' of Howe, predict reductions of approximately 7, 12 and 17 dB and 10, 15 and 20 dB respectively at 1, 2 and 4 kHz [1].

From the results of the balance measurements, no influence of the serrations on the performance was established.

4. DISCUSSION AND FUTURE WORK

Acoustic wind tunnel measurements on flat plates and airfoils with serrated trailing edges have shown that their previously observed noise reducing capabilities remain in case of more realistic geometries and flow conditions. However, the measurements on the teeth

Table 1a: Measured differences between sound levels of serrated flat plates and reference flat plates (dB) (predicted values in parenthesis)

	f (kHz)	M=0.12	M=0.18	M=0.22
FP2-FP1	1	-8(-10)	-5(-10)	-5(-10)
	2	-9(-15)	-6(-15)	-6(-15)
	4	-2(-20)	-8(-20)	-7(-20)
FP3-FP1	1	-12	-5	-3
	2	-6	-5	-4
	4	0	-10	-7
FP4-FP1	1	-7	-3	-3
	2	-6	-4	-6
	4	-2	-6	-7
FP5-FP1	1	-8	-7	-5
	2	-5	-2	-6
	4	-2	-8	-9
FP2-FP2_15	1	5	3	1
(α=0°)	2	4	1	2
	4	7	5	5
FP2-FP2_15	1	6	12	12
(α=-15°)	2	7	10	12
	4	8	12	15

Table 1b: Measured differences between sound levels of serrated airfoils and references airfoils (dB) (c_L=0.5)

	f (kHz)	M=0.12	M=0.18	M=0.22
NACA_0012	1	-3	-4	-3
(ser-ref)	2	-7	-2	-2
	4	-10	-6	-8
NACA_63618	1	-5	-10	-6
(ser-ref)	2	0	-5	-3
	4	5	-2	1
NACA_63018	1	-7	-7	-7
(ser-ref)	2	-8	-8	-8
	4	-2	-6	-4
NACA_4418	1	-5	-6	-6
(ser-ref)	2	-2	-6	-5
	4	0	-4	-2

which were misaligned with respect to the chord plane, have shown that faulty application may easily occur and can even lead to increases of the radiated noise.
These findings were confirmed only very recently, by the results of measurements on a two-bladed, one MW wind turbine with one blade equipped with serrations at the trailing edge of the outer part of one blade, carried out in the framework of the Dutch national TWIN programme.

The work described led to the conclusion that it is worthwhile to investigate the optimal application of serrated trailing edges for real turbines in more detail, and has been formulated in the JOULE-III proposal "Investigation of Serrated Trailing-Edge Noise (STENO)" which has meanwhile been awarded under the JOULE-III contract JOR3-CT95-0073.

In STENO the optimal application of serrated trailing edges in the outer region (outer 10-20%) of the blade will be the topic of study. In this region the flow is strongly three-dimensional and the boundary layer flow and turbulence is known to be affected by the centrifugal forces. Optimal application of serrations requires adjustment of the length, position and orientation of the teeth to the direction of the flow and the turbulent length scales. Therefore wind tunnel experiments simulating the three-dimensional flow around twisted blade tip models will be carried out allowing for the measurements of the tip flow, boundary layer turbulence and unsteady pressures at the surface caused by the convection of boundary layer turbulence past the trailing edge. Based on the outcome of the wind tunnel experiments, a series of serrations will be defined and mounted to the tip of a blade of the UNIWEX turbine and their noise reduction potential will be measured.

Finally, the results of the work described in this paper have also shown that the noise reductions obtained with the serrated flat plates do not compare with predictions. From an analysis not discussed in this paper, it has been shown that this is at least partially caused by the relatively high levels of tunnel background noise and turbulence. For this reason the tunnel is currently modified to obtain significantly lower tunnel background noise levels (10 dB in the 500 Hz to 2 kHz range) and turbulence levels (a few tenths of percents less). The measurements in the framework of the STENO project will be performed in this modified wind tunnel.

ACKNOWLEDGMENT

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