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SIMULATION OF AERODYNAMIC SOUND GENERATION ON AIRFOILS IN LOW MACH-NUMBER FLOWS

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ABSTRACT

An improved model for inflow-turbulence noise is presented and employed to simulate the interaction of turbulent gusts with the leading and trailing edge of an airfoil. The model is based on the acoustic analogy by HOWE and makes use of the boundary-element method to predict both the mean flow and the scattering and reflection of sound waves at the airfoil surface. Experimental results, which were obtained in an anechoic wind tunnel using an acoustic array technique, indicate that the total noise level is dominated by the leading edge. In the simulations this result can only be confirmed if a Kutta condition is applied at the trailing edge, i.e. the theoretically infinite velocity around the trailing edge is canceled by shedding vorticity from the trailing edge. Further simulations show that the model is capable to accurately predict the difference in noise radiation from the leading edge between different airfoils. A first attempt to design a silent airfoil turned out to be successful.

1 INTRODUCTION

Since LIGHTHILL's pioneering work it has been known that a turbulent flow radiates sound as if quadrupoles were distributed in the field, the strength being equal to the local fluctuating Reynolds stresses[1]. However, in an unconfined flow or in a turbulent boundary layer at low Mach numbers these quadrupoles are inefficient sound radiators, i.e. only a small fraction of the turbulent energy is converted into sound radiation. This situation will change if the turbulence is convected over an edge, e.g. the leading or trailing edge of an airfoil.

A basic model problem has been analyzed by FFOWCS-WILLIAMS and HALL[2]. They considered the interaction of a quadrupole with a thin, semi-infinite plate and found that the sound radiation is strongly enhanced due to the scattering of the quadrupole's sound field at the edge. Since the sound intensity was found to depend on the 5th power of a typical flow speed in contrast to the well-known 8th power law for free turbulence or the 6th power law for dipole sound from a compact surface, they concluded that for small Mach numbers the sound production will be concentrated at the edges of a plate.

The present paper deals with the sound generation on airfoils in low Mach-number flows, i.e. $M_0 = 0.1$–0.2. The Reynolds number of the flow shall be large enough so that a turbulent boundary layer around the airfoil is present $(Re \geq 10^6)$. Furthermore, the incoming flow shall be turbulent and the acoustic wave length shall be of the same order as the airfoil chord, i.e. the airfoil cannot be considered as acoustically compact. For this situation, only two mechanisms of sound generation will be important, namely trailing-edge noise and inflow-turbulence noise, the first being caused by the boundary-layer turbulence interacting with the trailing edge, the second by the turbulence in the incoming flow interacting with the airfoil.

The investigations presented in this paper are part of a European research project which aims at an improved prediction of trailing-edge noise and inflow-turbulence noise on wind turbines[3]. At present it is believed that trailing-edge noise dominates the spectrum of a wind turbine. However, inflow-turbulence noise may be important if trailing-edge noise is reduced.

In fact, a *separate* study of inflow-turbulence and trailing-edge noise has lead to different means for reducing the noise. Inflow-turbulence noise as radiated from the *leading edge* can be diminished by changing the airfoil shape[4,5]. The reduction of trailing-edge noise can be achieved by giving the trailing edge a serrated shape. This concept has been proposed theoretically by HOWE[6] and proved experimentally by DASSEN ET AL.[7]. Therefore, the question which mechanism dominates under which circumstances has a practical dimension as it determines the changes required in the airfoil or blade design.

The present paper will focus on inflow-turbulence noise. As stated above, the noise radiation from the leading edge can be reduced by changing the airfoil shape. However, this modification would be useless if the turbulence in the incoming flow produced more noise at the trailing edge than at the leading edge. In the latter case, the sound radiation in a highly turbulent flow would always be dominated by the trailing edge.

2 DESCRIPTION OF THE MODEL

2.1 BASIC APPROACH

A new model for inflow-turbulence noise has been proposed by GUIDATI ET AL.[5]. The model is based on the acoustic analogy by HOWE with the specific stagnation enthalpy B being the acoustic variable[8]. HOWE's equation is simplified by linearizing with respect to B and by assuming a steady, inviscid, irrotational, and isentropic base flow $\mathbf{U}$. The Mach number of the flow shall be small ($M_0^2 << 1$) so that it can be considered as incompressible with a potential Φ, i.e. $\mathbf{U} = U_0 \nabla \Phi$, with U_0 being the free-stream velocity. Neglecting all terms which include squares of the Mach number yields the convected wave equation in the frequency domain[9]

$$\left\{-k_0^2 - 2ik_0 M_0 \nabla\Phi \cdot \nabla - \nabla^2\right\}\hat{B} = \nabla \cdot (\hat{\omega} \times \mathbf{U}). \tag{1}$$

Here the $\exp(-i\omega t)$ convention is used and $\hat{\omega}$ denotes the vorticity. The remaining wave operator is simplified by transforming the acoustic variable according to TAYLOR[10]

$$\mathcal{B} = \hat{B} \cdot e^{iM_0 k_0 \Phi}. \tag{2}$$

Throughout the text, $\mathcal{B}$ will be referred to as the working variable. Introducing Eq. (2) into Eq. (1) and neglecting again terms which are small for low Mach numbers yields the Helmholtz equation for a fluid at rest, which forms the basis for the simulations described in this paper:

$$k_0^2 \mathcal{B} + \nabla^2 \mathcal{B} = -\hat{\sigma}(\mathbf{x}, \omega) e^{iM_0 k_0 \Phi}. \tag{3}$$

Green's third identity allows to express the working variable $\mathcal{B}$ at any field point $\mathbf{x}$ as a volume integral over that part of space where the right-hand side of Eq. (3) is not zero, and as a surface integral of a continuous dipole and source (monopole) distribution, the respective strengths being equal to the local boundary value of the working variable $\mathcal{B}$ and its normal derivative $\mathcal{B}^n$. The resulting integral equation is solved by the boundary-element method.

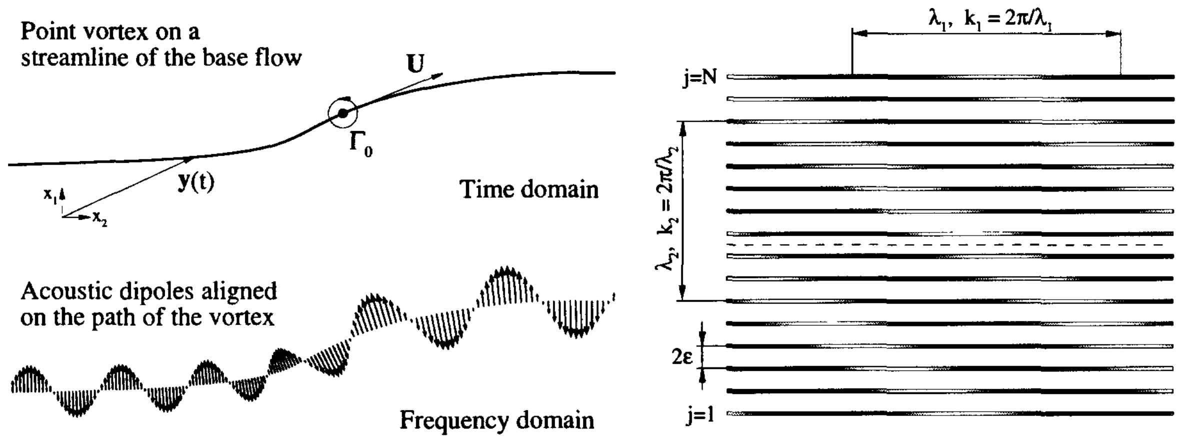

Figure 1: Illustration of the basic approach: spectral decomposition of moving point vortex (left), *N* vorticity waves with harmonically varying vorticity (right).

2.2 DEFINITION OF SOURCE TERM

In this approach, the spectral decomposition of a point vortex of strength Γ_0, which is passively convected along a streamline of the mean flow, resulted in harmonic vorticity waves which are taken as basic source patterns for the simulation of inflow-turbulence noise[5]. The field of such a vorticity wave is found to be

$$\mathcal{B}(\mathbf{x},\omega) = \int_{-\infty}^{+\infty} \left[\Gamma_0 U e^{iM_0 k_0 \Phi(\mathbf{y})} e^{i\omega t} (\nabla G \cdot \mathbf{n})\right] \mathrm{d}t . \tag{4}$$

Eq. (4) describes a field of acoustic dipoles which are continuously distributed on the path of the vortex. The dipole axis is perpendicular to the path. The strength varies harmonically with the time-like co-ordinate *t* and is furthermore modulated by the local velocity *U* and the term which is due to the TAYLOR transform (see Figure 1).

For a uniform flow it was shown that the velocity field which is induced by two vorticity waves close above and below a flat plate airfoil is identical to the harmonic gusts in thin airfoil theory, which forms the basis for the model by AMIET[11]. An extension to arbitrary airfoils could be found by making the vorticity waves follow streamlines around the airfoil.

Although this approach turned out to be successful in predicting the differences in inflow-turbulence noise at the leading edge of different airfoils, it is difficult to justify that two discrete vortex sheets should be a valid representation of a turbulent flow field. Therefore, a general uniform, incompressible gust field is defined, which is convected with the uniform flow $\mathbf{U} = (U_0 \quad 0)^t$ with $U_0 = \omega / k_1$

$$\mathbf{u}(\mathbf{x},t) = A' \begin{pmatrix} -k_2/k_1 \\ 1 \end{pmatrix} e^{i(k_1 x_1 + k_2 x_2 - \omega t)} . \tag{5}$$

The amplitude of the vertical fluctuations is labeled A'. Note that the velocity field is incompressible. The corresponding vorticity field is given by

$$\omega_3(\mathbf{x},t) = i k_1 A' \left(1 + \frac{k_2^2}{k_1^2} \right) e^{i(k_1 x_1 + k_2 x_2 - \omega t)} . \tag{6}$$

This shows that the vorticity is spread throughout the whole field. Now consider the vorticity wave which results from the motion of a vortex in a uniform flow $\mathbf{U} = (U_0 \quad 0)^t$ directed in the x_1 direction at $x_2 = y_2$. Application of Eq. (4) yields for $c_0 \to \infty$ the incompressible velocity field which is induced by this vorticity wave

$$\mathbf{u}(\mathbf{x},t) = \frac{A''}{2U_0} e^{i(k_1 x_1 - \omega t)} e^{-|k_1(x_2 - y_2)|} \begin{pmatrix} -\mathrm{sign}(x_2 - y_2) \\ -i \end{pmatrix}. \tag{7}$$

The amplitude A'' is defined below. Here use has been made of the momentum equation $\mathbf{u} = -i/\omega \nabla B$. Now consider a large number of N waves with a spacing of 2ε in x_2 direction which are centered around $x_2 = 0$ (see Figure 1). The phase of the waves varies in the x_2 direction such as $\exp(ik_2 x_2)$. The vertical velocity u_2 at the centerline $x_2 = 0$ is given by

$$u_2(x_1,0,t) = -\frac{iA''}{2U_0} e^{i(k_1 x_1 - \omega' t)} \sum_{j=1}^{N/2} \left(e^{-(k_1 - ik_2)(2j-1)\varepsilon} + e^{-(k_1 + ik_2)(2j-1)\varepsilon} \right) = -\frac{iA''}{2U_0} e^{i(k_1 x_1 - \omega t)} F_2(\varepsilon, N) \tag{8}$$

with

$$F_2 = \frac{1}{2} \left(\frac{1 - e^{-(k_1 - ik_2)N\varepsilon}}{\sinh\{(k_1 - ik_2)\varepsilon\}} + \frac{1 - e^{-(k_1 + ik_2)N\varepsilon}}{\sinh\{(k_1 + ik_2)\varepsilon\}} \right). \tag{9}$$

The horizontal velocity fluctuation is given by

$$u_1(x_1,0,t) = -\frac{A''}{2U_0} e^{i(k_1 x_1 - \omega t)} F_1(\varepsilon, N) \tag{10}$$

with

$$F_1 = \frac{1}{2} \left(\frac{1 - e^{-(k_1 - ik_2)N\varepsilon}}{\sinh\{(k_1 - ik_2)\varepsilon\}} - \frac{1 - e^{-(k_1 + ik_2)N\varepsilon}}{\sinh\{(k_1 + ik_2)\varepsilon\}} \right). \tag{11}$$

In order to match the vertical gust velocity A' in Eq. (5), the amplitude A'' must be equal to

$$A'' = \frac{2iU_0 A'}{F_2(\varepsilon, N)}. \tag{12}$$

By introducing Eq. (12) into Eq. (8) and considering the limit of $N\varepsilon k_1 \to \infty$ and $\varepsilon k_1 \to 0$ it follows that the vorticity field and consequently the velocity field of the N vorticity waves approach Eqs. (6) and (5), respectively. Especially the ratio between vertical and horizontal velocity fluctuations tends towards the one defined in Eq. (5). An extension to arbitrary airfoil shapes is again achieved by making the N vorticity waves follow the streamlines of the base flow around the airfoil. Results of simulations are presented in Section 4.

2.3 Implementation of a Kutta condition

It is well known that the theory of inviscid, incompressible, and irrotational flows (potential theory) is not able to predict the lift produced by an airfoil if the so-called Kutta condition is not specified at the trailing edge. Without a Kutta condition, the velocity at a sharp trailing edge would become infinite which is physically unrealistic. In the steady case, a Kutta condition is implemented by introducing a wake panel with constant dipole strength through which the flow potential exhibits a jump. This jump is chosen in such a way that it matches the jump in potential between the panels on the upper and lower side at the trailing edge. As a consequence the flow leaves the trailing edge tangentially.

In the case of a harmonic disturbance caused by a vorticity wave, the condition of finite velocity at the trailing edge is violated as well. Therefore, it is assumed that a harmonic vorticity wave is also shed from the trailing edge. In analogy to the steady case, the strength is chosen in such a way that the fluctuating flow leaves the trailing edge always tangentially.

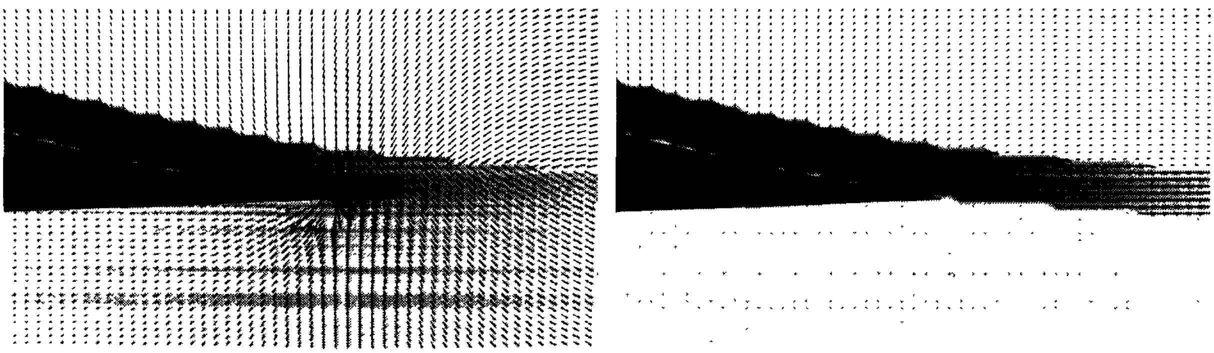

Figure 2: Instantaneous field of stagnation enthalpy and velocity; without Kutta condition (left), with Kutta condition (right).

While in the first case the trailing edge can sustain a jump in pressure between the upper and the lower side, this jump will be greatly reduced if a Kutta condition is applied. Figure 2 shows the stagnation enthalpy and the vectors of the acoustic velocity. Apparently, there is a flow around the trailing edge which is removed if a Kutta condition is enforced.

It must be clearly stated that the question whether an unsteady Kutta condition should be applied and how this condition should look like cannot be answered by this investigation. Here, only two limiting cases are considered, i.e. no Kutta condition ⇒ infinite velocity, and a strict Kutta condition ⇒ flow leaves trailing edge tangentially. In reality the trailing edge is not infinitely thin, and it may be possible that the stagnation point moves up and down.

3 RESULTS OF WIND TUNNEL TESTS

Measurements were carried out in the Small Anechoic Wind Tunnel (KAT) at the National Aerospace Laboratory NLR in the Netherlands. A variety of measurement techniques was employed on a total number of 9 models. Important for the topic discussed in this paper are only the sound measurements which were performed using an acoustic antenna.

This acoustic array technique allows to separate the noise coming from the trailing and leading edge of the model. The application of a standard beam-forming algorithm results in a so-called acoustic image, which shows the location of the main sound sources. Previous work proved that it is possible to determine a sound pressure level from the height of the peak which is found in the acoustic image[12].

Measurements were performed on four models with different airfoils, namely a NACA-63612, a NACA-63618, an FX-79-151A, and a new airfoil which was designed to minimize inflow-turbulence noise. The chord length was 0.25 m and 0.2 m for the FX-79-151A.

The models were installed at incidence angles giving lift coefficients of $c_l = 0.0, 0.25, 0.5, 0.75$. The turbulence level in the flow was greatly increased by mounting a grid on the tunnel exhaust nozzle. The flow speed was set to $M_0 = 0.10, 0.15, 0.18$. Hot-wire measurements revealed that the turbulence was nearly isotropic and that the intensity decreased by approximately 4 dB from the leading-edge position of the airfoils to the trailing-edge position.

Figure 3 shows the acoustic image together with the background noise which was measured without model. It can be seen that there is a pronounced peak at the leading edge of the airfoil ($x = -0.2$), which is clearly dominating the sound radiation. For some frequencies a second peak is visible further downstream. However, it is difficult to judge whether this second peak is an inevitable side band of the first peak or if it indicates a sound radiation from the trailing edge ($x = 0$). It should be noted that the acoustic images are almost independent of the incidence angle. The general shape is independent of the Mach number.

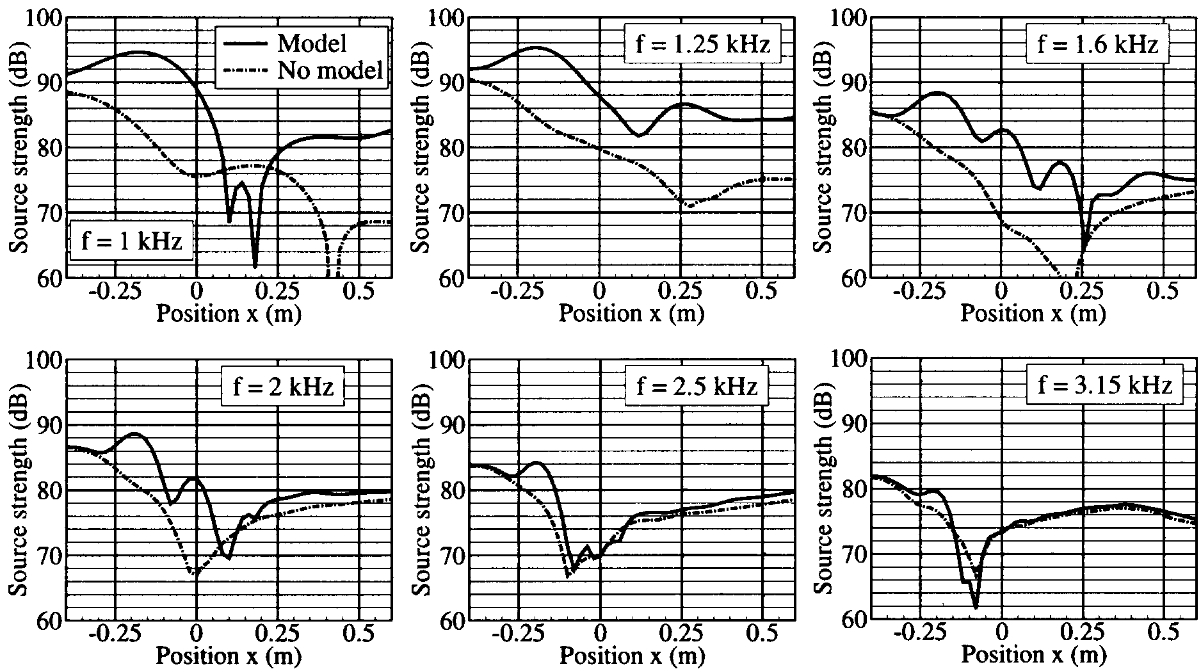

Figure 3: Acoustic image for different frequencies; FX-79-151A; $M_0 = 0.18$.

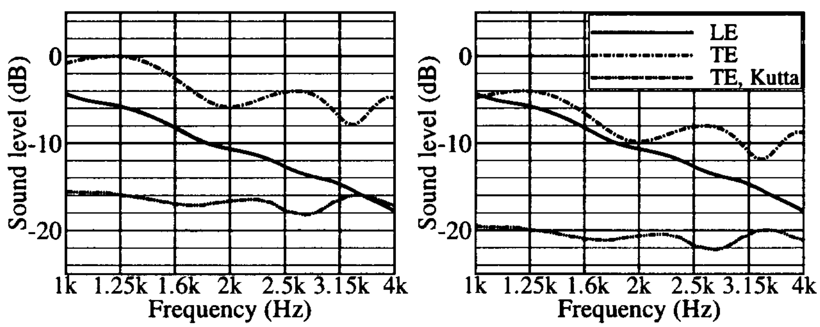

Figure 4: Predicted sound level from leading and trailing edge; FX-79-151A; $M_0 = 0.18$.

4 RESULTS OF SIMULATIONS

Since the grid turbulence was found to be nearly isotropic, the wave numbers in Eq. (5) were set to $k_2 = \pm k_1$. The resulting skewed gusts which belong to the different signs are assumed to be uncorrelated, and the resulting powers are summed up. For the simulations presented in the next section, the sound radiation was quantified by determining the sound power level as an integral on a circle around the airfoil. For the simulations discussed in Section 4.2 a beam forming algorithm was modeled analogously to the measurements.

4.1 Radiation from leading and trailing edge

Simulations were carried out for the FX-79-151A airfoil at $M_0 = 0.18$ and an incidence angle of $\alpha = 4$ deg. In order to separate the effects of the noise production at the leading edge and at the trailing edge, the simulation was carried out in three steps. First the interaction of a gust with the leading edge was modeled. Then the interaction with the trailing edge was modeled without forcing a Kutta condition. Finally, the second step was repeated with a Kutta condition. The resulting sound power levels are shown in Figure 4.

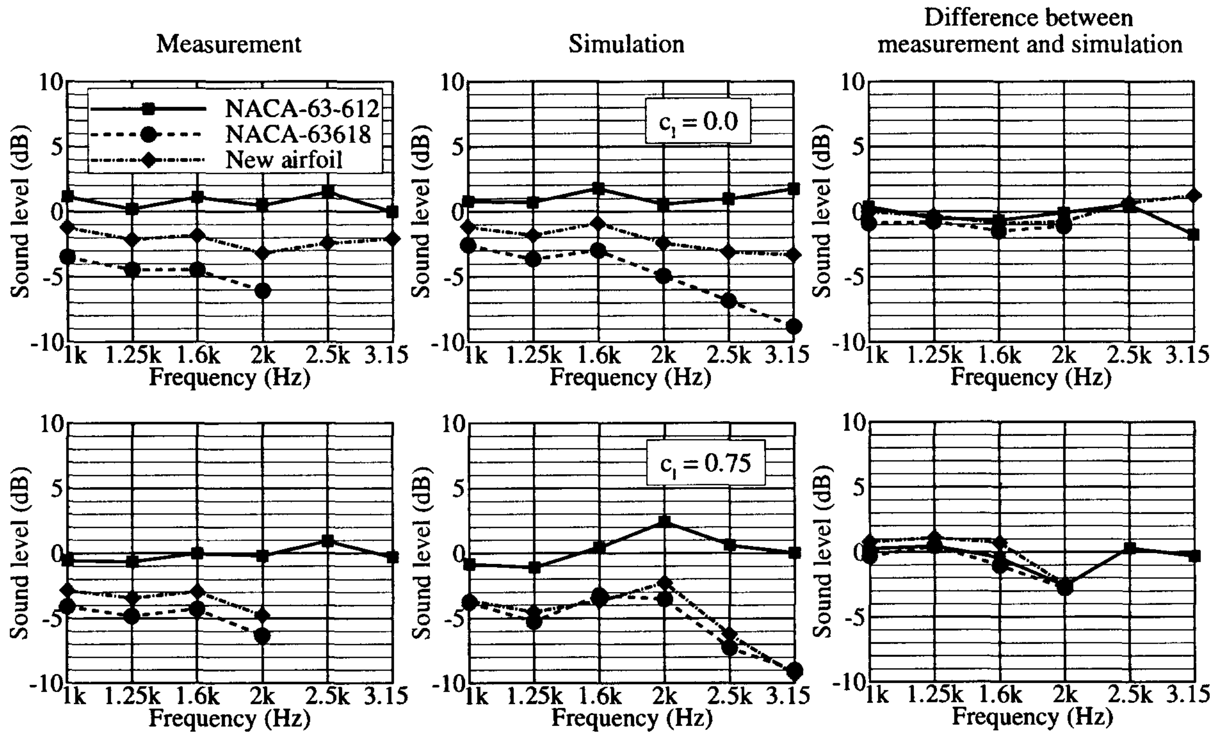

Figure 5: Measured and predicted sound levels for three different airfoils and two lift coefficients; $M_0 = 0.18$.

In order to take the decreased turbulence level into account, the level at the trailing edge is diminished by 4 dB on the right figure. It can be seen that the sound level which is radiated from the trailing edge (TE) is higher than the one from the leading edge (LE) if no Kutta condition is applied. However, with a Kutta condition enforced (TE, Kutta), the leading-edge radiation is clearly dominating.

4.2 INFLUENCE OF AIRFOIL SHAPE ON SOUND FROM LEADING EDGE

Additional simulations focused on the influence of airfoil shape on the sound radiation from the leading edge. Figure 5 shows the results of measurements and simulations for the three 0.25 m chord models. Apparently, the differences in sound radiation from the leading edge, which are due to the airfoil shape, are predicted with a remarkable accuracy. It should be noted that the accuracy of the sound prediction is significantly increased compared to the original approach with only two vorticity waves[13]. Furthermore, the new airfoil, which was designed to minimize the sound radiation from the leading edge, shows a reduction of 3–5 dB.

5 DISCUSSION OF RESULTS AND CONCLUSIONS

The simulations have shown that in a turbulent flow the sound radiation from the trailing edge is higher than the one from the leading edge if no Kutta condition is specified at the trailing edge. This is in contradiction to the experimental results where only a pronounced leading-edge peak could be detected. If a Kutta condition is enforced the sound radiation from the trailing edge diminishes by 10-15 dB and the leading-edge radiation dominates.

This result may indicate that a Kutta condition must be enforced in order to achieve a correct description of the sound which is generated by the interaction of turbulent gusts with an airfoil. However, since the measured acoustic images do not allow to determine the sound level radiated from the trailing edge (since it is masked by the leading-edge peak), it is not possible to judge whether the strict Kutta condition, as it was used here, is correct. Furthermore, the sound radiation from the trailing edge is also influenced by the turbulent boundary layer around the airfoil, which was neglected in this investigation.

An excellent quantitative agreement, however, could be achieved between the measured and predicted differences in leading-edge radiation for different airfoil shapes. Furthermore, it turned out that it is possible to design airfoils which radiate less inflow-turbulence noise from the leading edge. This result may be interesting for the noise reduction on low-pressure fans, high-by-pass-ratio turbo fans, or wind turbines.

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