IMPACT OF TURBULENCE MODELS ON RANS-INFORMED PREDICTION OF FAN BROADBAND INTERACTION NOISE

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ABSTRACT
In the present study turbulence characteristics from Reynolds Averaged Navier-Stokes simulations are used as input for the analytical prediction of fan broadband noise due to the interaction of the fan rotor wake turbulence with the outlet guide vanes. The aerodynamic excitation is modeled with a von Kármán spectrum and the blade response with the Sears function extended with a term considering the non-compactness of the source. The influence of different turbulence models, from state-of-the-art two-equation models to a Reynolds-stress transport model, on the simulated turbulence characteristics and consequently on the broadband noise prediction is investigated. Furthermore the impact of the two-equation model extensions for the effects of rotation, transition and the stagnation point is analyzed and discussed. The predicted noise spectra are compared to the experimental test data of the NASA Source Diagnostic Test fan rig. It has been found that different turbulence models and extensions can lead to a variation of predicted broadband interaction noise of up to 2 dB.

KEYWORDS
BROADBAND INTERACTION NOISE, RANS-INFORMED FAN NOISE PREDICTION

NOMENCLATURE
Latin Symbols
\(c\) chord length
\(f\) frequency
\(k\) turbulent kinetic energy,
\(K\) aerodynamic wavenumber
\(p\) pressure
\(r\) radius
\(u'\) root-mean-square of the turbulent velocity fluctuations
\(V\) vane count
\(W\) flow velocity

Greek Symbols
\(\epsilon\) dissipation rate
\(\rho\) density
\(\lambda\) integral length scale
\(\nu\) kinematic viscosity
\(\omega\) specific dissipation rate,
\(\Omega\) angular frequency

Subscripts
\(x\) axial direction
\(r\) radial direction
\(n\) normal direction

Superscripts
\(\cdot\) rotating reference frame
\(\ast\) variable multiplied with \(c/2\)
INTRODUCTION

Direct numerical simulations of turbulence-induced broadband noise are extremely resource demanding due to the stochastic distribution over a broad range of scales. An affordable and sufficiently accurate approach to consider broadband noise during the design process of a fan stage is needed. In the present study fan broadband interaction noise is predicted analytically based on turbulence characteristics provided from Reynolds averaged Navier-Stokes simulations. The aerodynamic excitation is modeled with a von Kármán spectrum and the blade response with the Sears function extended with a term considering the non-compactness of the source similar to Amiet’s compressible low-frequency single-airfoil approach (Amiet, 1974). Cascade and transmission effects are not considered. Both effects should have only little impact on the noise difference induced by the variation of the turbulence models. The study was carried out with the analytical fan acoustic prediction framework PropNoise (Moreau and Guérin (2010, 2011, 2016)). The approach of using simulated flow data as input for the analytical noise prediction with that tool was introduced by Guérin et al. (2012) and since then continuously improved by (Jaron et al. (2014, 2015)).

For the purpose of validation experimental test data of the NASA Source Diagnostic Test fan rig (SDT) are used, which were provided by Edmane Envia of NASA Glenn Research Center in the frame of the Fan Broadband Workshop at the AIAA Aeroacoustics Conferences 2015. The 1/5-scale model of a high bypass ratio fan was tested in the NASA Glenn 9’ x 15’ wind tunnel (see Fig. 1). The fan has 22 blades, a diameter of 55.9 cm, a midspan chord of 9 cm and a design tip speed of 370,3 m/s. The OGV has 54 vanes. Hot wire measurements were conducted by Podboy et al. (2002) at approach at 7.52 cm and 15 cm downstream of the fan tip trailing edge (shown in Fig. 1), referred hereafter as Pos1 and Pos2. Broadband spectra were measured at approach (7808 rpm), cutback (11074 rpm) and takeoff (12656 rpm) by Podboy et al. (2002) and will be compared with the predicted spectra.

Figure 1: SDT installed in the NASA Glenn 9 x 15 ft wind tunnel on the left-hand side. On the right-hand side the annulus and the measurement positions. (NASA Glenn)

Nallasamy and Envia (2005) were the first to use an hybrid approach with analytical noise calculation based on simulated turbulence quantities to predict the SDT broadband noise spectra. Grace et al. (2011) and Maunus et al. (2013) investigated with this approach the influence of different mesh setups and different two-equation turbulence models on the calculated broadband spectra. In the present study we use a slightly different analytical formulation and the impact of the extensions of state-of-the-art two-equation turbulence models concerning the stagnation point, effects of rotation and the transition will be investigated. Furthermore the possible improvement through the more advanced turbulence models Explicit Algebraic Reynolds Stress Model (EARSM) and Reynolds Stress Transport Model (RSTM) is investigated.
TURBULENCE MODELING IN THE CFD SIMULATION

The full-scale geometry of the SDT fan is simulated with the DLR in-house CFD code \textit{TRACE} (Becker et al., 2010). \textit{TRACE} is a parallelized Navier-Stokes flow solver for structured and unstructured grids. The code solves the compressible Navier-Stokes equations in the relative frame of reference by using a multi-block approach. The governing equations are discretized in generalized coordinates about the cell centers by using the finite-volume method. The steady RANS simulation is performed with one passage per rotor and stator with periodic conditions on the azimuthal boundaries and a mixing plane at the interface between the blade rows. The mesh consists of 10 million cells. Near-wall regions are meshed fine enough to apply low-Re boundary conditions ($y^+ < 1$). Following turbulence models are used for the study:

- **Wilcox** $k - \omega$ model (Wilcox, 1988): Two transport equations for the turbulent kinetic energy $k$ and the specific dissipation rate $\omega$ and a linear constitutive relation employing the Boussinesq assumption.

- **Menter Shear-Stress-Transport (SST) model** (Menter et al., 2003): Two transport equations with Boussinesq assumption. Blending of the $k - \omega$ model in near wall areas to the $k - \epsilon$ model in the freestream. Improved prediction of adverse pressure gradients through a stress limiter.

- **Hellsten** EARSM $k - \omega$ model (Hellsten, 2005): the two transport equations are modifications of the Menter Baseline Two-Equation Model (BSL) and the Boussinesq assumption is replaced by a more general constitutive relation for the Reynolds stress anisotropy in terms of the strain- and rotation-rate tensor (Franke et al. (2010)).

- **SSG/LRR-$\omega$ RSTM model** (Eisfeld, 2010): The anisotropic Reynolds stress tensor is directly calculated by seven additional, strongly coupled equations. Details about the implementations in \textit{TRACE} and results are given by Morsbach et al. (2015).

The two-equation models from Wilcox and Menter are using the Boussinesq assumption, which postulates that the Reynolds stress tensor is proportional to the mean strain rate tensor (see Boussinesq (1877)). The Boussinesq assumption is violated in flows with strong curvature or accelerated or decelerated flows, which typically occur in flows of rotating turbomachinery. Therefore some extensions were developed to consider these effects. The effect of streamline curvature and rotation on the dissipation of turbulent kinetic energy is modeled with a destruction term in the $\omega$-equation as suggested by Bardina et al. (1985). To remedy the unphysical excessive production of turbulent kinetic energy predicted in the stagnation point by linear models, Kato and Launder (1993) proposed a modification of the production term of the $k$-equation to limit the generation of turbulent kinetic energy. The production term represents the energy transfer from the mean flow to turbulence. Since there is no corresponding compensation included in the energy equation, the approach of Kato and Launder violates the conservation of energy. Durbin (1996) also stated that the approach of Launder and Kato would cause spurious production of turbulent kinetic energy in rotating or swirling flow. Durbin therefore proposed a limiter based on the Cauchy-Schwarz inequality. In \textit{TRACE} the implementation of the Schwarz limiter proposed by Rung (1998) is used. An overestimated generation of turbulent kinetic energy in the stagnation point would affect the complete boundary layer development downstream and therefore lead to broader turbulent wakes. The broader turbulent wakes would lead to an overestimation of the broadband noise. The transition is calculated with the $\gamma - Re_{\theta}$ model developed by Langtry and Menter (2005). Details about the implementations in \textit{TRACE} are given by Marciniak et al. (2010). The impact of these extensions and the transition on the broadband interaction noise prediction is discussed later on.
ANALYTICAL CALCULATION OF BROADBAND INTERACTION NOISE

The spectral density of modal pressure is calculated under the assumption of isolated and uncorrelated blades for broadband interaction noise within PropNoise as follows (see Moreau, 2017):

\[ |p_{m}(\omega)|^2 = V \int |g_{m}(\omega)|^2 (k_{n}c)^2 |\mathcal{L}(k_{l}^*, \tilde{K}^*)|^2 (\pi \rho_0 W_0)^2 \Phi_{ww}(\tilde{f}) l_{r}(\tilde{f}) \, dr, \]  

where \( V \) is the vane count, \( g_{m} \) denotes the Green’s function representing the shape of the modes and their propagation in the duct and \( k_{l} \) (resp. \( k_{n} \)) is the acoustic wavenumber parallel (resp. normal) to the chord. The aeroacoustic transfer function \( \mathcal{L} \) is modeled as follows:

\[ \mathcal{L}(k_{l}^*, \tilde{K}^*) = \Psi(k_{l}^*) S(\tilde{K}^*), \]  

where \( S \) is the low-frequency approximation of the Sears function for incompressible flows (see Sears, 1941) and \( \Psi \) is the chordwise Fourier transform of the non-dimensional distribution of loading \( h_{L} \). \( \Psi \) was introduced by Hanson (1980) and represents the effect of non-compactness of the source along the blade chord and is calculated with \( k_{l} \) in the non-rotating frame of reference as follows:

\[ \Psi(k_{l}^*) = \frac{1}{c} \int_{l=0}^{c} h_{L}(l) e^{ik_{l}l} \, dl = [J_{0}(k_{l}^*) + iJ_{1}(k_{l}^*)] e^{ik_{l}l} \]  

Under the assumption of a non-rotating \( (\tilde{K} = K) \), non-staggered \( (M_{r} = M_{0}) \) single airfoil with an observer located sideline in the far field, which leads to \( k_{l} = \frac{KM_{r}}{2\beta} \) with \( \beta = \sqrt{1 - M_{0}^2} \), the magnitude of Eq. (2) is equal to the magnitude calculated with Amiet’s compressible low-frequency formulation (see Amiet (1974)). With those assumptions Eq. (2) is compared in Fig. 2 against the incompressible low-frequency transfer function provided by Sears (1941) and the compressible high-frequency transfer function from Paterson and Amiet (1976). The asymptotic value of the magnitude of Eq. (2) for \( K \to 0 \) is \(|\mathcal{L}| \to 1 \) which is in line with the Sears function. For high frequencies the magnitude of \( \mathcal{L} \) has the correct asymptotic behavior of \( K^{-1} \), but with a small offset compared to the high-frequency solution. Usually two iterations of the Schwarzschild’s technique are used for calculating the high-frequency solution, which leads to a correct prediction at moderate and high frequencies, but overestimates the response of compact sources at low frequencies (see e.g. Paterson and Amiet (1976), Roger et al. (2006) and Reboul (2010)). Recently Santana et al. (2016) extended Amiet’s high-frequency theory with additional iterations of the Schwarzschild’s technique in order to improve the solutions for low frequencies. The aeroacoustic transfer function given in Eq. (2) seems to be accurate enough and respects the physical behavior both at low and high frequencies to be used in this study to investigate the impact of the turbulence models on the predicted broadband interaction noise.

The 1-D power spectral density of the velocity fluctuations \( \Phi_{ww} \) and the correlation length \( l_{r} \) are described by the von Kármán model as proposed by Amiet (1975):

\[ \Phi_{ww}(\tilde{f}) = \overline{\bar{u}^2}, \quad 2 \lambda \frac{\lambda}{W_{0}} \cdot \frac{1 + (8/3)z^2}{(1 + z^2)^{11/6}}, \]  

\[ l_{r}(\tilde{f}) = \frac{8 \lambda}{3} \left[ \frac{\Gamma(1/3)}{\Gamma(5/6)} \right]^2 \cdot \frac{z^2}{\sqrt{1 + 2z^2(3 + 8z^2)}}, \]  

with the reduced frequency \( z = St/St_{0} \), the Strouhal number \( St = \frac{2\pi\tilde{f} \lambda}{W_{0}} \) and the reference Strouhal number \( St_{0} = \sqrt{\frac{\pi}{15}} \frac{\Gamma(5/6)}{\Gamma(1/3)} \).
The integral in Eq. (1) is discretized with 99 stripes in spanwise direction. At each radial position the necessary parameters are extracted from the RANS simulation, which are the mean flow velocity at the leading edge $W_0$, the turbulence integral length scale $\lambda$ and the root-mean-square of the turbulent velocity fluctuations $u'$. Assuming the turbulence to be isotropic $u'^2$ is equally to $\frac{2}{3}k$. Furthermore the vane geometry is modeled in PropNoise as staggered thin flat plates at each radial position. The calculated 2-D unsteady pressure field at each radial position is coupled to a 3-D duct acoustic field.

**INTEGRAL LENGTH SCALE AND TURBULENT KINETIC ENERGY FROM RANS SIMULATIONS**

In steady RANS simulations the flow field is circumferentially averaged at the interface between blade rows. For the noise calculation the actual distribution of the turbulence kinetic energy and the integral length scale at the leading edge of the stator is needed. Therefore the actual distribution of both quantities is reconstructed in front of the stator with an extrapolation model.

**Calculation of the Integral Length Scale**

The integral length scale can be calculated with the turbulent kinetic energy and the specific dissipation rate using phenomenological arguments:

$$\lambda = C_\lambda \frac{\sqrt{k}}{\omega \cdot 0.09}$$

The factor of proportionality $C_\lambda$ is calculated as proposed by Grace et al. (2011). Donzis et al. (2005) summarized, that the mean dissipation rate dependency on the fluid viscosity is limited to small Reynolds numbers. For high Reynolds numbers the mean dissipation rate becomes independent of the fluid viscosity. The functional form describing this phenomena was provided by Doering and Foias (2002):

$$C_\lambda = f(Re_\lambda) = A(1 + \sqrt{1 + (B/Re_\lambda)^2}),$$

where $Re_\lambda = \sqrt{(20/3) \cdot k^2 / (\epsilon \cdot \nu)}$ is the Reynolds number based on the Taylor microscale. The constants $A = 0.2$ and $B = 92$, given by Donzis et al. (2005), yield an asymptotic value of 0.4 for high $Re_\lambda$, which agrees with the data given by Pope (2000) and Gamard and George.
Donzis et al. (2005) point out that while the asymptotic behavior is universal for all turbulent flows, the coefficients depend on the type of flow.

Figure 3: Simulated specific dissipation rate and calculated integral length scale in the vicinity of the SDT rotor blade at midspan at approach.

Figure 3 shows the specific dissipation rate and the integral length scale calculated with Eq. (6) in the vicinity of the rotor blades at mid span of the SDT fan. The stagnation point anomaly fix raises the dissipation rate in order to limit the production of the turbulent kinetic energy. The fix does not only effect the stagnation point, the dissipation rate is also increased slightly upstream and far downstream of the blades. As the calculation of the integral length scale depends on the dissipation rate, the result from the Menter SST model with stagnation point fix differ significantly from the result of the fully anisotropic SSG/LRR model, where no stagnation point fix is needed. Especially in the region in between the wakes the length scale differs due to the increased dissipation rate in the Menter SST simulation.

As input for the analytical noise calculation the circumferentially averaged integral length scale is needed. One possible averaging method is to use the separately averaged turbulent kinetic energy and dissipation rate (see Nallasamy and Envia (2005)):

$$\lambda = C_\lambda \frac{\sqrt{k}}{\omega_i \cdot 0.09}.$$ (8)

In Fig. 4 the circumferentially averaged turbulent velocity fluctuations ($u' = \sqrt{(2/3)k}$) and the circumferentially averaged dissipation rates are shown.

The simulated turbulent kinetic energy agrees well with the measurements. The Hellsten and SSG/LRR models have a slightly smaller level in the region of 20%-80% blade height. The dissipation rate is expectedly smaller with the turbulence models without stagnation point fix. The averaged integral length scale calculated with Eq. (8) is shown in Fig. 5 on the left-hand side. A second averaging method is investigated, which weights the local integral length scale with the
local turbulent kinetic energy in order to filter the regions in between the wakes where comparably little turbulent energy is transported and as previously mentioned the values of the integral length scale are wrong due to the stagnation point fix (see Fig. 3):

$$\bar{\lambda} = \frac{\sum_{i=1}^{n} \lambda_i \cdot k_i}{\sum_{i=1}^{n} k_i}.$$  

(9)

Figure 4: Circumferentially averaged root-mean-square of the turbulent velocity fluctuations and specific dissipation rate of the SDT fan at approach at Pos 1. The Menter SST and Wilcox results are simulated without transition, with Schwarz limiter and consideration of rotational effects.

Figure 5: Integral length scale of the SDT fan at approach at Pos 1 calculated with Eq. (8) on the left-hand side and Eq. (9) on the right-hand side.

The results with the weighted averaging are shown on the right-hand side of Fig. 5. The length scales from the measurements is computed through the integration of the autocorrelation coefficient (see Podboy et al. (2002)). The averaging with Eq. (8) leads to a good agreement of the length scales of the two-equation models and the SSG/LRR model with the measurements. With the Hellsten model the length scale is too large nearly over the whole span. The weighted averaging with Eq. (9) leads to smaller length scales for the Menter SST and Wilcox models. For the Hellsten model the length scale is similar to the two-equations models. The SSG/LRR model has the highest deviation from the measurements. For the results shown hereafter Eq. (8) is used for the averaging. However it should be noted, that the selection of the averaging method influences the predicted spectra.
Extrapolation of the Turbulent Kinetic Energy and the Integral Length Scale

Ganz et al. (1998) and Gliebe et al. (2000) found empirically by investigating the development of turbulent wakes, that the decay rate for the turbulent kinetic energy is proportional to $1/x$ and that the integral length scale increases proportional to $\sqrt{x}$. Using this empirical development correlations the turbulent kinetic energy and the integral lengths scale are extrapolated to Pos2. In Fig. 6 the extrapolated results are compared with measurements.

![Figure 6: Measured and extrapolated data at Pos2 of the SDT fan at approach. Circumferentially averaged root-mean-square of the turbulent velocity fluctuations (left) and circumferentially averaged integral length scale (right).](image)

The extrapolation gives satisfactory results. The higher difference of $u'$ compared to Pos1 (Fig. 4) is due to the overestimated dissipation rate in all turbulence models, but especially the dissipation rate within the wakes of the SSG/LRR model is higher than in the other turbulence models. The extrapolated length scale is also in a good agreement with the measurements.

RESULTS AND DISCUSSION

In this section the analytically calculated broadband interaction noise spectra are compared with the measured spectra. The impact of the stagger angle of the modeled OGV as well as the impact of different turbulence models on the predicted spectra is investigated.

Impact of the Stagger Angle on the Predicted Broadband Noise

As previously mentioned PropNoise is modeling the OGV as staggered thin flat plates. In Fig. 7 the modification of the spectra in dependency of the stagger angle of the modeled OGV is shown. The leading edge angle and the trailing edge angle of the original OGV are used for the comparison.

Using the leading edge angle the radiated sound power is increased by 3.6 dB upstream of the fan compared to the results with the trailing edge angle. Downstream of the fan the difference is only 1 dB. The transmission of the stator noise through the rotor is not considered in the current state of the model. Rotor shielding should lead to a partial reflection and consequently to a reduction of the noise upstream and an increase downstream. For both radiation directions the impact of the stagger angle is higher in the high frequency range. Grace et al. (2011) found a steeper slope in the high frequency range of the spectrum with increased stagger angle, whereas the slope in Fig. 7 is constant due to the use of the von Kármán spectrum. Furthermore using the leading edge angle is more coherent with the analytical formulation of the aerodynamic excitations pressure term $\zeta$ where the distribution of the unsteady pressure on the blade surface given by the Sears function is concentrated at the leading edge. Therefore the leading edge angle is used for the results shown hereafter.
Figure 7: Spectra calculated with modeled OGV staggered with the leading edge angle and with the trailing edge angle of the original OGV of the SDT fan at approach with Menter SST. The difference of the integrated PWL to the measurements is given in the legend.

Impact of Two-Equation Model Extensions and Transition Model on the Predicted Broadband Noise

The impact of the extensions for the turbulence models using the Boussinesq assumption concerning the effects of rotation and the stagnation point and the consideration of transition on the predicted broadband interaction noise is shown in Tab. 1.

Table 1: Impact of turbulence model extensions on the predicted total broadband interaction noise given as difference to the measured PWL of the SDT fan at approach.

<table>
<thead>
<tr>
<th>Menter SST</th>
<th>rotation</th>
<th>transition</th>
<th>stagnation point fix</th>
<th>Δ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>on</td>
<td>off</td>
<td>Schwarz limiter</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>on</td>
<td>off</td>
<td>Kato &amp; Launder</td>
<td>+0.1</td>
<td></td>
</tr>
<tr>
<td>on</td>
<td>on</td>
<td>Schwarz limiter</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>off</td>
<td>off</td>
<td>Schwarz limiter</td>
<td>-2.3</td>
<td></td>
</tr>
<tr>
<td>off</td>
<td>on</td>
<td>Schwarz limiter</td>
<td>-2.8</td>
<td></td>
</tr>
<tr>
<td>off</td>
<td>on</td>
<td>Kato &amp; Launder</td>
<td>-2.5</td>
<td></td>
</tr>
</tbody>
</table>

The two different stagnation point fixes lead to a difference of ~0.2 dB in the predicted PWL. As previously shown the integral length scale is very similar for the two-equation models with stagnation point fix and the SSG/LRR model without stagnation point fix. Furthermore in view of the results shown in Tab. 1 the stagnation point fix seems to have no negative impact on the broadband interaction noise prediction at least for this configuration. The consideration of transition leads to a reduction of PWL by about 0.5 dB due to a thinner boundary layer. The consideration of rotational effects has the highest impact on the noise prediction (~2.4 dB) as this extension enhances the production of turbulent kinetic energy.

Impact Of Higher Order Turbulence Models on the Predicted Broadband Noise

Figure 8 shows the predicted broadband interaction noise calculated with simulations with the four different turbulence models. The Menter SST and Wilcox results are simulated with rotational effects, without transition and stagnation point fix as proposed by Rung (1998).

The variation between the models in PWL is about 2 dB. However, it should be considered that there are some uncertainties. For example the stagger angle could be weighted between the
Figure 8: Measured and calculated spectra based on RANS simulations with various turbulence models of the SDT fan at approach. The difference of the integrated PWL to the measurements is given in the legend.

leading edge and trailing edge angle, as it was proposed by Nallasamy and Envia (2005) and the calculation and averaging of the integral length scale also has an impact on the results.

**Impact of fan Operating Point on the Predicted Broadband Noise**

The impact of higher fan speed on the acoustic power is shown in Fig. 9. The predicted spectra were calculated based on simulations with the Menter SST model, rotational effects, without transition and stagnation point fix as proposed by Rung. The measured spectra contain beside the interaction noise also rotor self noise and jet noise, which explains the increase of the spectra at lower frequencies and the higher levels compared to the predicted spectra (see Nallasamy and Envia (2005)). The trends at high frequencies are quite well reproduced in terms of amplitude and frequency shift.

Figure 9: Measured spectra containing interaction noise, rotor self noise and jet noise (left). Predicted total interaction noise with Menter SST (right).
CONCLUSIONS

Fan broadband interaction noise has been calculated analytically based on turbulence information from steady RANS simulations. The impact on the noise prediction of different turbulence models from state-of-the-art two equation models with Boussinesq assumption up to anisotropic models directly calculating the Reynolds stress tensor was investigated. Furthermore the impact of the extensions of the two equation models concerning effects of rotation and the stagnation point and the consideration of transition was investigated. Accounting for transition leads to a reduction of PWL by about 0.5 dB due to a thinner boundary layer on the rotor blade surface. The consideration of rotational effects has the highest impact on the noise prediction (~2.4 dB) as this extension enhances the production of turbulent kinetic energy. It was found, that with different turbulence models the broadband interaction noise was predicted with a discrepancy of 2 dB on the integrated PWL value. No improvement was found by using anisotropic turbulence models with the present approach. More sophisticated analytical models may take an advantage from anisotropic turbulence data.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the German Federal Ministry for Economic Affairs and Energy through the research project LiST (Das leise installierte Triebwerk 20T1307B). The authors would like to acknowledge Edmane Envia of NASA Glenn Research Center for organizing the fan broadband workshop on the AIAA Aeroacoustics Conferences since 2014 and providing the community with experimental test data from the SDT used for validation of the presented models, Gary G. Podboy for the SDT hot wire data and Richard P. Woodward for the SDT sideline acoustics data, both from NASA Glenn Research Center.

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