Radiation of noise in turbulent non-premixed flames

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Abstract

A model for the prediction of combustion-generated noise in non-premixed flames has been developed. This model is based on Lighthill’s acoustic analogy and employs the flamelet/progress variable model to express the excess density as function of mixture fraction and reaction progress variable. In this model, three major sources of sound have been identified, and their individual contribution to the acoustic spectra and overall sound pressure level are analyzed for a nitrogen-diluted methane–hydrogen/air flame. The hybrid approach, combining a large-eddy simulation and a computational aeroacoustic method, introduces spurious noise which can pollute the acoustic results. All relevant sources of spurious noise are analyzed, and a physics-based low-pass filter is proposed which eliminates spurious noise due to the convection of acoustic sources. The numerical predictions for both statistical flow field quantities and acoustic results have been validated with experimental data. The good agreement between experiments and simulation highlights the potential of the method for applications to more complex flow configurations and to provide further understanding of combustion noise mechanisms.

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1. Introduction

Recent studies project an increase in the world energy consumption by more than 60 percent over the next 30 years [1]. Over this period, combustion of fossil fuels are predicted to remain a major technology for the energy supply in all end-user sectors. However, accompanied with combustion are unwanted effects such as the emission of pollutants and noise. Particularly the reduction of the noise footprint of aircraft is currently of great interest in order to meet future stringent noise regulations.

Numerical simulation techniques promise to be a viable tool to gain a better understanding of the underlying noise-generating mechanisms and to assist in developing quieter combustion systems. The generation of aerodynamic sound, however, is a rather inefficient process, since only a minute fraction of the thermochemical and kinetic energy of the turbulent reactive flow is radiated as sound. For the prediction of the emitted noise spectra, it is therefore essential to use accurate numerical methods and computational schemes characterized by low dispersion and dissipation. Furthermore, the accurate modeling of coherent structures and other acoustic sources in a turbulent reacting flow...
is essential, since these structures are the main contributors to the radiated noise.

The large-eddy simulation (LES) technique has the potential to provide further insight into the noise-generating mechanisms of turbulent reacting flows. In LES, the larger energy-containing scales are time-accurately resolved and only the effect of the smaller and more homogeneous scales requires modeling. The success of LES in the prediction of non-premixed turbulent flames is attributed to the improved description of scalar mixing and the lower complexity of models for the chemical source terms and other unclosed terms. However, the computational cost and the disparity between the characteristic turbulence and acoustic length scales in low-Mach number flows restricts the LES application to the near field domain, and acoustic analogies are frequently employed to propagate the acoustic perturbations to the far-field.

Lighthill [2] derived an acoustic analogy for the acoustic pressure perturbation, $p'$, by rearranging the Navier–Stokes equations to obtain a linear wave operator for a homogeneous, stationary medium on the left hand side, and regarding the right hand side as an equivalent acoustic source term distribution.

A model for the prediction of noise from non-premixed flames was developed by Klein & Kok [3]. In this model, infinitely fast chemistry is used and the input parameters for the characterization of the turbulence spectrum are obtained from a steady RANS calculation. A similar model was recently employed for the prediction of noise emissions from premixed swirling flames [4], and good agreement between simulation results and experimental data was obtained. In this respect, it is interesting to point out that acoustic spectra are rather insensitive to changes in geometry and operating conditions for non-premixed and premixed flames [5,6]. However, the spectral characteristics, total sound power, and scaling rules exhibit considerable differences for both combustion modes, and are dependent on the variations in equivalence ratio, fuel composition, and inlet velocity spectrum.

Flemming et al. [7] recently combined LES with Lighthill’s analogy to predict direct combustion-noise in an open hydrogen flame. In order to partially account for acoustic effects due to the variation of the sound speed, $a$, inside the flame, they replaced the constant speed of sound in the original formulation by the local sound speed and ignored effects due to the additional term $\nabla \cdot \frac{\rho'}{\rho}$, which appears in the inhomogeneous stationary wave equation. The acoustic source term is modeled by the density variation $\rho'$, which was obtained from LES and interpolated from the LES grid to the CAA grid.

A different approach is followed by Bui et al. [8,9], in which an acoustic perturbation equation for reacting flows (APE-RF) is used. This formulation accounts for inhomogeneous acoustic media and identifies the unsteady heat release rate as major sound source. Computational results obtained for different jet flame configurations are in good agreement with experimental data.

Both approaches employ a multi-linear interpolation to transfer the localized acoustic source term distribution from the fluid domain to the acoustic region. Since the source distribution is localized in a narrow region surrounding the stoichiometric mixture and both computational meshes are typically not aligned in the overlapping region, this procedure introduces errors in the acoustic solution. Additional errors due to the residual scale models and limitations on the numerical resolution of the LES are introduced, and the identification and quantification of these errors is essential for the accurate prediction of the acoustic far-field.

Such an error quantification for combustion-noise applications has so far not been presented and the objective of this work is to identify major sources of spurious noise which may result in a miss-prediction of the acoustic far-field spectra. In order to accomplish this, a numerical method for the prediction of combustion-noise is first presented. In this method, a flamelet-based combustion model is employed to extend Lighthill’s acoustic analogy to account for effects due to the unsteady reaction rate and density variations on the radiated noise. This homogeneous-media wave equation is solved in Fourier-space for arbitrary far-field locations using an integral formulation.

The remainder of this article is organized as follows. The combustion model and the aeroacoustic model are summarized in the next section, and the experimental configuration and numerical setup are presented in Section 3. Statistical flow-field results are discussed in Section 4. Sources of spurious noise and computational results for the acoustic pressure signal, source term intensity, and sound pressure levels are analyzed in Section 5. The paper finishes with conclusions.

2. Mathematical formulation

In the present work, Lighthill’s acoustic analogy is employed to predict the radiated sound field emitted from a non-premixed turbulent flame. In this analogy, the noise-generating sources in a limited flow domain $\Omega_{\infty}$ are represented by an acoustically equivalent source term distribution, embedded in a homogeneous stagnant fluid region $\Omega_{\infty}$, having constant reference properties.

For the simulation of the turbulent reactive flow-field, a low-Mach number variable density
LES formulation is used. This is motivated by the observation that for a turbulent reactive jet, the exit Mach number, \( M = U_{\text{ref}}/u_{\text{ref}} \), based on the jet bulk exit velocity and sound speed in air at ambient temperature, is typically very low to ensure flame stability.

### 2.1. Governing equations and combustion model

In low-Mach number variable density LES, the instantaneous Favre-filtered conservation equations for mass and momentum are solved in the fluid domain \( \Omega_f \). The filter operator introduces a residual stress tensor in the governing equations, which is modeled by a dynamic procedure \([10,11]\). In addition, the filtered density and all filtered molecular properties are also unclosed quantities, and a state equation is required to close the set of equations.

In the following, this state equation is obtained from the flamelet/progress variable (FPV) combustion model, which relates all thermochemical quantities to two scalars, namely the mixture fraction \( Z \) and the reaction progress variable \( C \) \([12,13]\). This reactive scalar corresponds to a linear combination of major product mass fractions, and is here defined as
\[
Z = Y_{CO_2} + Y_{CO} + Y_{H_2O} + Y_{H_2}.
\]
In this model, all chemical states of a burning flame are obtained from the solution of the steady flamelet equations, and the FPV state relation, in which all thermochemical quantities are parameterized by \( Z \) and \( C \), can then be written as
\[
\psi = \mathcal{F}(Z, C),
\]
and \( \mathcal{F} \) is the residual mixture fraction variance. More details on the combustion model are given in Refs. \([12,13]\) and are here omitted.

In addition to the solution of the Navier–Stokes equations, the FPV model requires then the solution of the following transport equations for \( Z \) and \( C \):

\[
\begin{align*}
\overline{p_Z} Z &= \frac{1}{\text{ReSc}} \nabla_y \cdot (\overline{p_Z} \nabla_y Z) + \nabla_y \cdot r_{Z}, \\
\overline{p_C} C &= \frac{1}{\text{ReSc}} \nabla_y \cdot (\overline{p_C} \nabla_y C) + \nabla_y \cdot r_{C} + \text{Da} \overline{\partial_C \rho}.
\end{align*}
\]

and a dynamic procedure is used to model the residual scalar fluxes \( r_{Z} \) and \( r_{C} \) \([12]\). The residual mixture fraction variance, appearing in Eq. (1) is computed from an algebraic closure model \([14]\). In the above equations, \( \mathcal{F} = \partial_y + \overline{u} \cdot \nabla_y \) denotes the Favre-filtered substantial derivative, and the time-space coordinate \((\tau, y)\) refers to a location in \( \Omega_f \). Note, that in this paper all quantities are non-dimensionalized with reference flow-field quantities and are written in non-dimensional form \([15]\). The Reynolds number is denoted by \( Re \), \( Sc \) is the Schmidt number, and \( Da \) is the Damköhler number \([15]\).

### 2.2. Acoustic model

In a turbulent flame, sound is generated by both the turbulent flow field and the combustion in \( \Omega_f \). The sound propagates as acoustic waves to the point of perception \((\tau, x)\) in \( \Omega_f \). Lighthill \([2]\) derived the following inhomogeneous wave equation for the pressure disturbance \( p' = p - p_{\text{ref}} \):

\[
M^2 \partial_x^2 p' - \Delta \rho = \nabla_y \cdot \nabla_y \cdot (\overline{p' \overline{u} \overline{u}}) - \partial_x^2 \rho_e - \nabla_y \cdot \left( \frac{1}{\text{ReSc}} \partial_x \right) \rho_e, \quad (3)
\]

where \( \overline{p} \) and \( \rho_e \) are the viscous and residual stress tensors, respectively, and \( \rho_e = \rho' - M^2 p' \) is the excess density \([16]\). By employing the FPV state relation, Eq. (1), together with Eq. (2), the excess density can be reformulated. Then, after neglecting contributions due to viscous stresses and all residual scale contributions, Eq. (3) can be written as

\[
M^2 \partial_x^2 p' - \Delta \rho = \nabla_y \cdot \nabla_y \cdot \left( \overline{p' \overline{u} \overline{u}} \right) - \partial_x^2 \rho_e - \nabla_y \cdot \left( \frac{1}{\text{ReSc}} \partial_x \right) \rho_e. \quad (4)
\]

The term \( \mathcal{T}_R \) represents a quadrupole source due to unsteady Reynolds stresses, and \( \mathcal{F}_M \) is a fluctuating mass flux of dipole nature. The term \( \mathcal{Q}_R \) denotes a monopole due to the chemical reaction rate of the progress variable, and is precomputed and stored in the flamelet library. Note that Eq. (4) is a homogeneous-media wave equation and does not account for refraction effects due to sound speed variations in the source.
region. Potential implications of this model assumption are discussed in Section 5. An integral formulation for the far-field pressure signal as function of frequency \( \omega \) can be obtained by applying a free-space Green’s function and a Fourier transformation to Eq. (4), viz.

\[
\hat{p}(\omega, x) = \frac{1}{4\pi} \int \int \int_{\Omega} \left[ M^2 \hat{g}(\omega^2) \hat{\Omega}_R \right. \\
+ M \hat{\lambda}(\omega^2) \cdot \hat{\Omega}_M - D \hat{\mu}(\omega) \hat{\Omega}_R \bigg] dy, \tag{5}
\]

and \( \kappa, \lambda, \) and \( \mu \) are directional cosine factors as result of the partial integration. By employing a free-space Green’s function, it is assumed that all acoustic sources radiate undisturbed to the far-field, and effects due to diffraction at the nozzle or other obstacles are negligible. Diffraction effects are typically only relevant for high frequencies [17], and its significance is dependent on the directivity angle. As such, they have usually insignificant effect on radiation in forward direction, but become increasingly important with increasing angle to the jet axis. Nevertheless, in the experiment that will be used here for model validation, such effects were minimized by covering the orifice and tubing with sound-absorbing material [18,19]. The dependence of the three source terms on Mach- and Damköhler numbers is separately indicated in the prefactors of these terms, and the asymptotic dependence of the three coefficients on \( \omega \) for large distances between source and observer locations is shown in parentheses. More details on the derivation of Eq. (5) can be found in Ref. [15].

3. Experimental configuration and numerical setup

The N\(_2\)-diluted CH\(_4\)-H\(_2\)/air flame was experimentally studied by Bergmann et al. [20], Meier et al. [21], and Schneider et al. [22]. The burner configuration for the non-premixed flame consists of a central fuel nozzle of diameter \( D_{\text{ref}} = 8 \) mm, which is surrounded by a co-flow nozzle of square shape. The fuel bulk velocity is \( U_{\text{ref}} = 42.2 \) m/s. Co-flow air is supplied at an axial velocity of \( 7.11 \times 10^{-3} U_{\text{ref}} \). The jet fluid consists of a mixture of 22.1 % methane, 33.2 % hydrogen, and 44.7 % nitrogen by volume with a stoichiometric mixture fraction of \( Z_{\text{st}} = 0.167 \). Spectral noise emissions and sound pressure levels of this flame have been quantified by Singh et al. [18,19].

The Reynolds number, based on the nozzle diameter, pipe bulk exit velocity, and kinematic viscosity of the fuel mixture, is \( Re = 14,740 \). The Schmidt number is \( Sc = 0.486 \), the Mach number is \( M = 0.123 \), and the Damköhler number is \( Da = 0.644 \).

The Favre-filtered conservation equations for mass, momentum, mixture fraction, and progress variable are solved in a cylindrical coordinate system in \( \Omega_x \) with \( y = (r, \phi, y)^T \).

The computational domain is \( 40 \times 2\pi \times 120 \) in radial, circumferential, and axial directions, respectively. The radial direction is discretized by 160 unevenly spaced grid points concentrated in the fuel nozzle. For the discretization of the jet radius, 30 grid points are used. The circumferential direction is equally spaced and uses 64 points. The grid in axial direction uses 320 points and is, beginning at the nozzle exit, stretched in stream-wise direction. The total number of grid points used for the simulation is approximately 3.28 million.

The turbulent inlet velocity profile is generated by separately performing a periodic pipe flow simulation by enforcing a constant mass flux. Convective outflow conditions are used at the outlet and slip-free boundary conditions are employed at the radial boundaries.

Flow-field statistics are collected over five flow-through-times after a statistically steady flow-field was obtained. For the computation of acoustic results, 4,096 samples separated by a sample width of \( \Delta t = 0.04 \) were used. This data set was subdivided into 15 overlapping intervals to increase statistical sampling, which is common practice in signal processing. The Strouhal number is defined as \( St = f D_{\text{ref}}/U_{\text{ref}} \) with \( f \) denoting the frequency.

The computed mean and resolved variance are obtained by averaging in temporal and azimuthal directions, and are denoted by \( \langle \psi \rangle (r, y) \) and \( \langle \psi^2 \rangle (r, y) \), respectively, for a scalar quantity \( \psi \).

4. Flow-field results

Statistical results for axial velocity and mixture fraction along the centerline of the jet are shown in Fig. 1. Symbols denote experimental data and lines correspond to the computational results.
Apart from the slight over-prediction of the decay rate for $10 \leq y \leq 30$, the prediction of the mean axial velocity, shown in Fig. 1a, is in good agreement with experimental data in the self-similar region of the jet flame. The predicted velocity fluctuations, shown by the dashed line, are also in good agreement with experimental data.

The accurate prediction of the mixture fraction field is crucial for the description of scalar and temperature distributions in the flame. The evolution of the mean and root-mean-square (rms) mixture fraction along the jet centerline is shown in Fig. 1b. The numerical results for the mean mixture fraction in the rich part of the flame, i.e., for $y \leq 65$, are in good agreement with the measurements. The slight over-prediction of $\langle Z \rangle$ further downstream results in an over-prediction of the temperature by approximately 100 K (not shown) due to the strong temperature sensitivity in the fuel-lean part of the flame. The resolved mixture fraction variance can considered to be in excellent agreement with the experimental data.

Radial profiles of the mean mixture fraction and resolved mixture fraction variance are presented in Fig. 2 for three axial locations in the jet flame. Apart from the slight over-prediction of the peak rms mixture fraction in the shear layer for $y = 10$, the computational results can considered to be in excellent agreement with measurements.

Profiles of the normalized temperature, $\Theta$, are compared with experimental data in Fig. 3. It can be seen that the heat release close to the nozzle occurs in a narrow region. The width of this zone increases with increasing downstream distance. The rms temperature profiles at the first two measurement stations exhibit two pronounced peaks which are separated by a local minimum. The reason for this can be attributed to the temperature sensitivity with respect to the mixture fraction around the stoichiometric condition, and has been discussed in Ref. [23].

5. Acoustic results

In the following, acoustic results are discussed that are obtained by evaluating Eq. (5). In this equation, the volume integral extends over the entire LES domain up to 120 diameter in the downstream direction. In a sensitivity study it was found that this integral converges for $y \geq 80$, which confirms that all major acoustic sources are contained in the LES domain.

5.1. Spurious noise sources

The conversion of thermal and kinetic energy into acoustic power is typically a rather inefficient process, especially at low-Mach numbers. Because of this inefficiency, only a minute fraction of the total energy in a jet is radiated as sound to the far-field. For the accurate prediction of the far-field sound, it is therefore not only important to employ non-dispersive and non-dissipative numerical methods for the sound propagation, but also provide an accurate characterization of the acoustic source term distribution. These sources are embedded in a turbulent reactive flow-field, whose spatial extend can considerably be larger than the source region of isothermal jets.
at comparable operating conditions. The size of the computational domain in LES can therefore be limited by the required numerical resolution. Furthermore, the different physical models employed in LES can introduce errors which may only have a second order effect on the prediction of statistical flow-field quantities; however, they can pollute the aeroacoustic results. In a simulation of turbulent reactive flows, the following sources of spurious noise can be identified:

1. LES residual model
2. Combustion model
3. Strouhal number limitation of the acoustic samples
4. Strouhal number limitation of the computational grid

The residual scale models in LES can result in unphysical noise at high frequencies, corresponding to the unresolved turbulent scales. In the present work, a dynamic procedure was employed [12]. In order to assess the effect of the residual scale viscosity and diffusivity on the acoustic spectra, a highly resolved LES of a reduced computational domain was performed, for which the energy spectra were evaluated. In this study, it was concluded that the residual scale model is an insignificant contributor to the high-frequency noise.

Another important source of unphysical noise can be the FPV combustion model, which employs a tabulation method for the parameterization of all thermochemical quantities. Pierce & Moin [12] pointed out that the low-Mach number variable density formulation can be affected by spurious heat release which is caused by dispersion errors in the convection terms of the equations for species transport and mass conservation. While the effect of this on the high-frequency noise contribution was not quantified in this work, it was found that the accurate evaluation of the state relation greatly reduces the high frequency error. Examples are shown in Figs. 4 and 5, which compare temporal spectra of two source term contributions obtained with increasing table resolutions at different locations in the jet flame. It can be seen that spurious noise at high frequencies is introduced when a poorly resolved chemistry representation with only 125 grid points in each $Z$ and $C$ directions is used. The spurious noise can further be reduced by employing lookup tables with finer resolutions. Spectra that are shown by solid lines in both figures correspond to results in which a tetrahedral integration method [24] was used. In this method, a computational cell is subdivided into tetrahedrons. The state equation is then integrated for each sub-cell using high-order quadrature rules. Employing this method resulted in better convergence and numerical stability, and was therefore used throughout this work. A detailed analysis of this method, which is not presented here, confirmed that a converged solution is obtained using a table resolution with 1000 grid points in each $Z$ and $C$ directions. Note however that depending on the integration scheme, the computational cost of the simulation can increase considerably.

The acoustic source terms were collected at a constant sampling time of $\Delta t = 0.04$. From this, the Nyquist Strouhal number can be computed as $St_N = (2\Delta t)^{-1} = 12.5$. Note that the flow solver is advanced with a time increment of $\Delta t = 0.02$, corresponding to a Strouhal number of 25. Therefore, the temporal resolution is sufficiently fine to resolve all relevant audible frequencies.

The acoustic sources are generated by a turbulent reactive flow-field, which is advected in
downstream direction. A critical Strouhal number associated with the advection of the acoustic source terms and the mesh spacing can be written as 

\[ St_a(y) = \frac{\langle \bar{u} \rangle (y)}{2\Delta y(y)} \]

Here, it is assumed that the axial velocity component is the dominant advection velocity, which is valid for turbulent jet flows. The decay of the mean axial velocity in the self-similar region of a turbulent round jet is \( \langle \bar{u} \rangle \propto y^{-1} \), and the axial grid stretching in the present LES, is \( \Delta y \propto y \). Thus, the critical Strouhal number can be approximated roughly as 

\[ St_a \propto y^{-2} \]

For application in LES, the critical advection Strouhal number is evaluated from the computed mean axial velocity and the grid spacing, and is shown in Fig. 5 by the vertical dashed lines. It can be seen that \( St_a \) correlates well with the onset of the spurious noise in the high-frequency range of the spectra. Since \( St_a \) represents the limiting frequency for which the acoustic predictions are reliable, a sharp spectral cut-off filter of the form 

\[ H(2\pi St_a(y) - \omega) \]

is introduced, where \( H \) denotes the Heaviside function.

5.2. Instantaneous pressure field

Using Eq. (5), the pressure signals resulting from each of the three source terms are computed as function of \( x \) and \( \omega \). These pressure fields are then transformed into the time domain and are shown in Fig. 6 for a particular time instant. For reference, the corresponding source term distributions are also shown. Note that only the axial components of \( T_R \) and \( F_M \) are shown. It is interesting to point out that all three source terms have a different spatial distribution. The source term \( Q_R \) is mainly aligned with the location of the stoichiometric mixture and extends up to 50 nozzle diameters in downstream direction. Similarly, \( F_M \) extends to the stoichiometric flame length. The source term \( T_R \) is constrained to the shear layer region in the jet flame, and extends to about 15 diameters in the streamwise direction. Note, however, that for subsonic flows only a small portion of the source term components are radiating. An interpretation of the noise radiation and the role of source convection in wavenumber-frequency space has been given by Crighton [25].

The different source term characteristics which were also discussed in Section 2.2 result in different pressure fields. The instantaneous pressure field that is produced by \( T_R \) is shown in Fig. 6a. This source is mainly radiating in the 45° forward direction. Compared to the other two pressure fields shown in Fig. 6b and c, the characteristic wave length is considerably smaller. Furthermore, the magnitude of the pressure wave emitted by the source \( T_R \) is compared to that generated by \( F_M \) and \( Q_R \) smaller by one and two orders of magnitude, respectively. Compared to the quadrupole source, the directivity of the pressure signal generated by \( F_M \) (Fig. 6b) is less pronounced. Interestingly, the radiation pattern of the chemical source (Fig. 6c) shows a pressure perturbation of rather large wave length. A detailed analysis of the temporal evolution of the pressure and the source term spectrum suggests that the acoustic source responsible for this low-frequency emission is mostly confined to the spatial location around \( y = 30 \) diameter.

5.3. Pressure spectra

The computed sound pressure level (SPL) at two far-field locations and the individual source term contributions are presented in Fig. 7. Experimental data, measured by Singh et al. [18,19], are shown by symbols and computational results are shown by lines.

This figure shows that the quadrupole source term \( T_R \) is the least efficient contributor to the total sound pressure level. The reason for this

Fig. 6. Instantaneous pressure distribution in the acoustic domain.
can be deduced from Eq. (5), which shows that this term scales quadratically with the Mach number.

The fluctuating mass flux contribution is about 10–15 dB lower than the total SPL in the low- and mid-frequency range, which can be attributed to its linear dependence on the Mach number.

The dominant source term contribution to the total SPL is the chemical source term. This suggests that for the prediction of the SPL at low and mid frequencies, the source terms \( T_R \) and \( F_M \) can essentially be neglected, and the total SPL radiated from an open non-premixed flame can be sufficiently characterized by the chemical source term alone.

It is interesting to point out that some phase cancelation can be observed in the side line direction around \( St \approx 0.1 \). This cancelation is a result of the phase shift between the three different source term contributions, and results in a total SPL which is approximately 1–2 dB lower than the SPL generated by the chemical source term alone.

The prediction shows that the SPL is approximately constant for \( St \lesssim 0.3 \), which is in agreement with the experimental data, and also with the theoretical analysis by Strahle [26].

The numerical simulation over-predicts the SPL for \( St \approx 1 \) in the 45° forward direction. A careful analysis of the experimental data and further theoretical analysis provides some evidence that this is caused by high-frequency refraction effects which are only insufficiently captured with Lighthill’s acoustic analogy and the assumption of constant sound speed [27,28]. In Ref. [27] it was shown that acoustic refraction due to temperature-dependent variations in the sound speed are mostly relevant in the jet forward direction. High-frequency acoustic waves that propagate in the downstream direction interact with sound speed gradients, and are refracted away from the jet axis. This leads to the formation of a so-called “zone of silence,” which increases with increasing frequency.

6. Conclusions

A model for the prediction of combustion-generated noise in non-premixed turbulent flames has been presented. This model is based on Lighthill’s acoustic analogy and employs the FPV assumption in order to express the excess density in terms of mixture fraction and progress variable. The resulting wave equation is converted into an integral formulation and solved in Fourier-space. The following conclusions can be drawn:

- Mainly three acoustic sources have been identified as contributors to the far-field pressure, and the computed SPL confirms that the chemical source term is the main contributor to the far-field noise for low-Mach number flows.
- The hybrid LES/CAA formulation introduces spurious noise into the prediction of the acoustic pressure. All relevant sources have been analyzed, and it was found that the limitation of the numerical grid resolution and the chemistry representation are the major sources of spurious noise.
- A physics-based low-pass filter has been proposed, which eliminates spurious noise introduced due to the convection of acoustic sources.
- The SPL is in good agreement with experimental data; some discrepancies in the SPL in the jet forward direction at high frequencies are apparent and are attributed to refraction effects which are not fully captured with the present model formulation.

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