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Subsonic Jet Noise Prediction in Near and Far Field with Optimized Wave-Packet Approach

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In this study, the parameters of a wave-packet model for subsonic jet noise prediction are systematically optimized by leveraging near- and far-field data obtained from the large-eddy simulation (LES) of a free jet at a Mach number of 0.9 across various radial distances. The utilization of near-field information is justified by the observation that the scattering surfaces are typically situated within a few nozzle diameters from the jet axis in the radial direction, both in the current and in innovative aircraft configurations. The far-field information is used to guarantee the correct subdivision between the wave-packet radiating noise and the hydrodynamic components. The results show a notable agreement between the LES data and the wave-packet solutions, consistent with findings documented in the existing literature. This agreement underscores the validity and applicability of the implemented methodology, offering an effective method for obtaining an equivalent jet noise acoustic source, easily implementable in acoustic scattering codes, and accounting for the directional behavior of jet noise.

Nomenclature

c_∞	=	speed of sound of the unperturbed flow
D	=	nozzle exhaust diameter
f	=	frequency
He_l	=	Helmholtz number with characteristic length l, kl
J	=	objective function
k	=	acoustic wave number, ω/c_∞
M	=	jet Mach number, U_j/c_∞
p	=	pressure
$\boldsymbol{q}$	=	parameters vector
R	=	polar distance from the center point of nozzle exit section
Re_D	=	nozzle exhaust Reynolds number, $\rho UD/\mu$
SPL	=	sound pressure level
St	=	Strouhal number, fD/U
TI	=	turbulence intensity
U_j	=	nozzle exhaust jet velocity
$\boldsymbol{v}$	=	design variables vector
x, r, θ	=	cylindrical coordinates
δ_{BL}	=	nozzle exhaust boundary layer
ω	=	angular frequency in radians, $2\pi f$

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I. Introduction

AVIATION noise has been widely identified as a driver of several negative stress-mediated health effects, from sleep disorders to cardiovascular issues [1,2], whose incidence is increasing in the exposed population. The operation and expansion of airports are nowadays limited by strict regulations aimed at controlling and limiting the exposure of the surrounding community to aircraft noise and the number of people affected by it. Forecasts by the international regulation authorities indicate that this situation is the most likely scenario in the future, with increasing air traffic in at least most regions of the world [3].

The research on noise reduction devices is nowadays very active in all the aircraft areas, involving relatively mature technologies for quieter high lift devices [4], chevrons for jet exhaust [5,6], the evolution of acoustic liners [7–12] for turbofan ducts, and also more innovative treatments with a lower technology readiness level [13]. Projecting the research to the mid- and long-term future, ground-breaking solutions are also being developed, aiming at overcoming the saturation trend in noise reduction that characterizes mature technologies. Innovative configurations such as blended- and hybrid-wing–body (BWB and HWB) aircraft are probably the most promising alternative to the well-known tube-and-wing configuration in terms of aerodynamic efficiency and community noise reduction [14–17]. The most popular interpretation of these innovative configurations involves the upper installation of the propulsion system on top of the large centerbody surface, offering interesting acoustic shielding capability to be exploited for engine-related community noise reduction [13,18,19]. The propulsion-airframe acoustic interaction is an aspect of growing research interest for future aircraft and should be accounted for since the beginning of the design process, with particular attention to jet noise.

Jet noise has always been a dominant noise source for turbojets and turbofans, especially during takeoff operations. Over the past 50 years, subsonic jet noise has garnered significant attention and has remained a focal point in the design of modern and future civil aircraft. This emphasis stems from the importance of addressing and minimizing the noise impact associated with these aircraft.

However, the simulation of the scattering and shielding from large surfaces in the audible range of frequencies can be computationally very expensive, requiring accurate solutions up to an extremely high Helmholtz number $He = kl$ (where k is the wave number for the propagating acoustic disturbance and l is the characteristic length of the scattering object). The resources required for direct simulation with high-fidelity Computational Fluid Dynamics (CFD) or Computational Aeroacoustics (CAA) methods make them unfeasible for extensive usage in the conceptual design phase and design optimization processes. There is hence a strong need for low- and mid-fidelity models and solvers able to catch the fundamental feature of installed jet noise, avoiding the solution of the complete set of equations holding the dynamic of the complex fluid structures involved.

In this framework, since the publication of Lighthill [20], many researchers have investigated jet-induced pressure fluctuations both in the near field and in the far field in an attempt to develop models able to predict as accurately as possible the emitted noise. Nevertheless, despite many published papers, jet noise remains a beautiful puzzle with intricate pieces due to its complex physics.

The discovery of coherent structures in jets changed the perspective of jet noise and provided a basis for introducing the wave-packet approach [21]. As suggested by Huang and Papamoschou [22], the wave packet is an amplitude-modulated traveling pressure wave. Several authors have widely used this approach to predict and model the jet noise source from far-field measurements having parameters such as envelope amplitude, wavelength, position, and convection velocity. The wave-packet model has been widely used as a low-order model for the jet noise source both in subsonic and supersonic regimes [23,24]. In Huang and Papamoschou [22], a virtual cylindrical surface hosting the wave packet is assumed to surround the jet region and radiate the pressure perturbations. The parameters such as the envelope amplitude, wavelength, position, and convection velocity were typically estimated from far-field measurements, optimizing their values and maximizing the agreement with experimental data on a training set [25–27].

Recently, Palma et al. [28] followed the approach introduced by Papamoschou [22,25–27], calibrating the model parameters on near-field large-eddy simulation (LES) data of a high-speed subsonic isothermal jet. The mentioned paper presents a multi-Strouhal-number (multi-*St*) analysis optimizing the wave-packet source model separately for each value in the set $St = 0.25, 0.5, 0.75$, and 1 and using pressure data from the numerical database for the dominant axisymmetric zeroth azimuthal mode. It has been shown that optimizing the model parameters with pressure data at multiple distances in the near field provides a noise source that also preserves agreement with the reference data for radial positions outside the training set, improving the reliability of its prediction. However, even though the so-obtained wave packet is reliable in near-field pressure prediction, this method cannot be useful to accurately predict the acoustic far field probably due to the limitation of the training domain, which included only near-field data, sometimes partially immersed in the jet flow.

To bypass the mentioned issue, this paper extends the findings put forth by Palma et al. [28], improving the model capabilities by integrating data from both near and far fields in the derivation of the wave-packet parameters via a multi-objective optimization.

The training data are derived from the same high-fidelity LES as in the work of Palma et al. [28]. However, this study enhances the predictive accuracy of the wave-packet model by introducing an additional objective function in the minimization process to refine the model's performance in the far field. Moreover, a tailored decision procedure to extract the optimal solution from the set resulting from the multi-objective optimization problem is proposed, leveraging the presence of the additional objective function. The problem is computed for various Strouhal numbers St, specifically focusing in this paper on the zeroth azimuthal mode, which is highly representative of the energy content of the subsonic jet noise at the considered frequencies. The obtained wave packets demonstrate utility in accurately predicting both near-field and far-field behaviors. Due to the accurate prediction both in the entire domain and its fast evaluation, this wave-packet formulation is particularly well suited to be coupled with a wide range of aeroacoustic solvers, especially low- and mid-fidelity methods.

The paper is organized as follows: The numerical setup that provided the data used in this work is briefly introduced in Sec. II. The wave-packet model and its optimization are described in Secs. III and III.B, respectively. The results from the optimization are reported in Sec. IV. Final remarks can be found in Sec. V.

II. Numerical Setup

The near field of the isothermal round free jet at a Reynolds number of $Re_D = 10^5$ used for this paper has been computed by LES. The nozzle exhaust jet Mach number has been fixed at $M = 0.9$, with the nozzle-exhaust boundary-layer thickness set at $\delta_{bl} = 0.15 r_0$ and the nozzle exit turbulence intensity at 9% (see [29,30] for details). The LES has been carried out using an in-house solver of the three-dimensional filtered compressible Navier–Stokes equations in cylindrical coordinates (r, θ, x) based on low-dissipation and low-dispersion explicit schemes. The quality of the grid for the present jet LES has been assessed in previous work [31]. Specifically, the grid contains approximately one billion points. Pressure has been recorded at several locations spanning a large near-field domain and gaining time-resolved signals; see reference [32] for a description of the available data. In addition, the near-pressure field of this jet has also been investigated in [33]. It has been propagated to the far field in [30,34] using an in-house OpenMP-based solver of the isentropic linearized Euler equations in cylindrical coordinates based on the same numerical methods as the LES.

Concerning the near-field domain, we consider arrays of virtual microphones parallel to the nozzle exhaust, containing 1024 probes covering a domain that spans between $x = 0$ and $x/D = 20$. The data have been stored at a sampling frequency corresponding to $St = 12.8$, with a total of 3221 time snapshots. A representative one is shown in Fig. 1. In the far field, we consider a polar arc of virtual microphones centered at the nozzle exit, positioned at $R = 75D$, from 15 to 165 deg relative to the jet direction, with a spacing of one degree.

The original pressure signals are represented in terms of their azimuthal components through the azimuthal decomposition [35]. The Fourier coefficients are stored for the first four azimuthal modes that dominate the sound field for low polar angles. As aforementioned, the wave-packet model presented in this paper has been carried out for the zeroth azimuthal mode, which is dominant for the noise generation at Strouhal numbers lower than 1 [21].

III. Wave-Packet Approach

A. Wave-Packet Model

A wave-packet model is used as a source for reproducing the noise produced by a subsonic jet. It has been introduced by Morris [36,37], Tam and Burton [38], Crighton and Huerre [39], and Avital et al. [40]. The formulation adopted in this paper was derived by Papamoschou and coworkers [22,25–27]. The model is based on the fundamental assumption that the peak noise radiation from the jet in the aft region

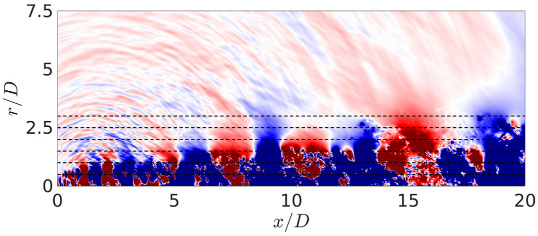


Fig. 1 Snapshot in the (x,r) plane of the pressure fluctuations. The black dashed lines represent the probe arrays in the near field.

is related to the large-scale coherent structures in the jet flow, which can be modeled as instability waves at their boundaries, growing and then decaying along the axial distance [25].

The present formulation introduces a cylindrical virtual surface at a radial distance r_0 from the jet axis. The surface radiates the pressure perturbation imposed on it, representing and substituting the jet from the acoustic point of view. Applying the wave-packet ansatz, the pressure on the cylindrical surface surrounding the jet is prescribed as

$$p_w(m, r_0, x, \theta, t) = p_0(x) e^{-i\omega t + im\phi} \quad (1)$$

where m is the azimuthal mode number, x denotes the axial coordinate, ϕ is the azimuthal angle, and $\omega = 2\pi f$ is the pulsation. The wave-packet axial shape $p_0(x)$ is given in the form [25]

$$p_0(x) = \tanh\left(\frac{(x - x_0)^{p_1}}{b_1^{p_1}}\right)\left[1 - \tanh\left(\frac{(x - x_0)^{p_2}}{b_2^{p_2}}\right)\right] e^{i\alpha(x - x_0)} \quad (2)$$

The radial distance of the virtual surface is taken as $r_0 = D/2$. The coordinate x_0 is used to locate the relative position between the origin of the wave-packet function and the nozzle exit. The two are considered to be coincident in this work, i.e., $x_0 = 0$. The signal growth is controlled by the parameters b_1 and p_1, while b_2 and p_2 define its decaying rate. Following Morris [37] and Papamoschou [25], the solution in the linear regime (i.e., solution for the 3D wave equation in cylindrical polar coordinates) for an arbitrary radial distance $r \geq r_0$ can be evaluated as

$$p_w(m, r, x, \theta, t) = \frac{1}{2\pi} e^{-i\omega t + im\phi} \int_{-\infty}^{\infty} \hat{p}_0(k) \frac{H_m^{(1)}(\lambda r)}{H_m^{(1)}(\lambda r_0)} e^{ikx}\, \mathrm{d}k$$
$$\text{with } \lambda = \left[\left(\frac{\omega}{c_\infty}\right)^2 - k^2\right]^{1/2}, \quad -\frac{\pi}{2} < \arg(\lambda) < \frac{\pi}{2} \quad (3)$$

where $\hat{p}_0(k)$ is the Fourier transform of $p_0(x)$, c_∞ is the speed of sound of the unperturbed flow, and $H_m^{(1)}$ is the Hankel function of the first kind and order m. In the radiation process, particular care must be taken to the spatial length of the wave packet from the numerical point of view. A premature truncation of the waveform introduces noise and errors in the signal propagated to higher r. The phase speed can be used to distinguish among the radiative and nonradiative components of the pressure field generated by the wave packet, characterized respectively by supersonic ($|\omega/k| \geq c_\infty$) and subsonic ($|\omega/k| < c_\infty$) values.

B. Wave-Packet Optimization

In this work, the method described by Palma et al. [28] is followed and further extended. The wave-packet noise source introduces some parameters whose values can be adjusted to match the pressure fluctuations from the reference jet using LES. A wave packet describing the pressure fluctuations for a free jet is obtained by optimizing its parameters with near-field data on co-axial lines at two radial distances from the jet axis, namely, $r/D = 2$ and 2.5, and on a far-field polar arc, $R = 75D$. The radial distance of the near-field probes has been chosen considering that the wave-packet model is valid for lines that are outside of the jet stream and, at the same time, sufficiently close to the jet to sense and provide information about the hydrodynamic component of the pressure fluctuation. The near-field reference data are obtained through LES simulation [30,41] and the acoustic perturbations have been propagated to the far field using a solver of the isentropic linearized Euler equations in cylindrical coordinates [30,34] based on the same numerical methods as the LES, as described in Sec. II. In the following, the data at the mentioned lines and arc are referred to as a *training* set, meaning that the model is informed by these data, while a *test* set is composed of the pressure field at other monitoring points.

The training of the model is performed using a multi-objective optimization procedure. The unconstrained optimization problem consists of the research of the set of variables $\boldsymbol{v}$ that yield a minimum of the N_J objective functions $J_n(\boldsymbol{v}, \boldsymbol{q})$

Table 1 Lower and upper bounds of optimization variables

Parameter	p_1	b_1	p_2	b_2	$\omega/(\alpha U_j)$
Min	0.2	0.022	1.2	0.022	0.43
Max	40	0.44	40	0.44	0.75

$$\text{minimize}\,[J_n(\boldsymbol{v}, \boldsymbol{q})], \quad n = 1, \ldots, N_J \text{ and } \boldsymbol{v} \in \mathcal{D}_{\boldsymbol{v}}$$
$$\text{with bounds } v_s^L \leq v_s \leq v_s^U, \quad s = 1, \ldots, N_v \quad (4)$$

where $\boldsymbol{q}$ is the vector of the fixed parameters, and $\boldsymbol{v}$ is the vector of the N_v design variables bounded by v_n^L and v_n^U in the design space $\mathcal{D}_{\boldsymbol{v}}$. In the present application, $\boldsymbol{v}$ represents the vector collecting the wave-packet parameters $\boldsymbol{v} = [p_1, b_1, p_2, b_2, \omega/(\alpha U_j)]$, while the vector $\boldsymbol{q}$ contains, among others, the azimuthal order $m = 0$, the St number, the speed of sound of the unperturbed flow c_∞, etc. Suitable boundaries are selected for the components of $\boldsymbol{v}$, as reported in Table 1. The number of objective functions to be minimized at the same time is $N_j = 3$, and the objective functions are described by

$$J_n(\boldsymbol{x}, \boldsymbol{y}) = \sqrt{\int_{\mathcal{L}_n} \left(\frac{|p_n - \hat{p}_{\mathrm{REF}_n}|}{\max(|\hat{p}_{\mathrm{REF}_n}|)}\right)^2 \mathrm{d}s} \quad (5)$$

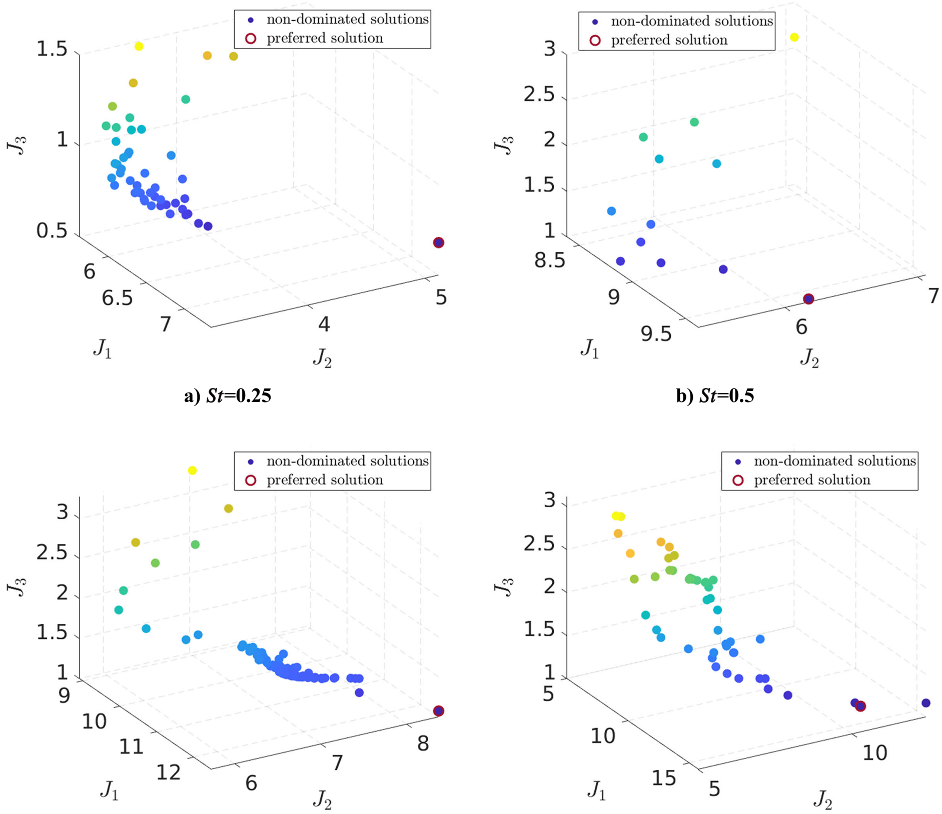
where $\hat{p}_{\mathrm{REF}_n} = p_{\mathrm{REF}_n}/\hat{p}$ is the value of the reference pressure field on the nth line, numerically evaluated by LES or LEE simulations, normalized with $\hat{p}$, the maximum value at the line $r/D = 0.5$. The objective functions represent the L2-norm of the difference between the pressure predicted by the wave-packet source model and the reference pressure from the numerical simulations, namely, LES in the near field for $n = 1, 2$ and LEE for the far-field arc for $n = 3$. The integral in Eq. (5) is defined over the axial extension from 0 up to $x/D = 20$ for the lines in the near field ($r_n = 2D, 2.5D$), defining J_1 and J_2. For the definition of J_3, the integral extends over a polar arc, ranging from 15 to 165 deg, centered on the jet axis at the nozzle exit with radius $R = 75D$. According to Eq. (5), each objective function is normalized by the peak value from the reference pressure field on the respective line $\mathcal{L}_n$. Both the hydrodynamic and the acoustic parts of the pressure fluctuations are included in the p_{REF}; hence, the resulting wave packet is expected to reproduce the complete fluctuation envelope, with the limitation given by the hypothesis that the wave packet is not immersed in the jet flow. The optimizations are performed using a multi-objective particle swarm optimization algorithm [42,43], using a fixed budget of 70 particles per variable (a total of 420) and 500 iterations.

IV. Results

When the objectives to be minimized are, at least partially, conflicting, the solutions to the optimization problems are such that it is not possible to find other points in the domain improving the score of one objective function without worsening the performance of at least one of the remaining ones. The solutions of a nontrivial multi-objective optimization are, hence, optimal in a Paretian sense [44], leading to the definition of nondominated solutions, which form the approximated Pareto front of the optimization problem.

Figure 2 shows the nondominated solutions obtained for the four considered St numbers at the end of the optimization procedures. The wave-packet parameters of the selected solutions are reported in Table 2. It is important to notice that all the solutions on the Pareto fronts have the same dignity, and the preferred one can be chosen at will by the designer for the problem at hand [45]. A ranking criterion can be identified to help the decision process, which can be arbitrarily defined: simple subjective preferences to more complex analyses of the results are in principle all valid methods to pick only one of the Pareto optimal solutions [46–48].

In this study, one of the already evaluated objective functions is used as the ranking criterion: the solutions are ordered by their J_3 result, and the one minimizing the reproduction error on the far-field line is taken as the preferred solution. The mentioned choice is



a) *St*=0.25 b) *St*=0.5

c) *St*=0.75 d) *St*=1.0

Fig. 2 Solutions of the optimization problems for the considered *St* numbers. Points are colored with the value of the ranking criterion, from blue to yellow.

Table 2 Wave-packet parameters of the selected optimal solutions

St	p_1	b_1	p_2	b_2	$\omega/(\alpha U_j)$
0.25	3.988	0.1224	8.366	0.2029	0.725
0.50	14.221	0.1093	14.559	0.1636	0.531
0.75	20	0.0914	12.929	0.1283	0.570
1.0	37.704	0.0995	26.041	0.1450	0.550

justified by the fact that the integration lines $\mathcal{L}_n$ ($n \in [1, 2]$) in the near-field objective functions are partially immersed in the jet flow. In Fig. 3, a rough estimation of the portions of the lines immersed in the jet stream is obtained, assuming a spreading angle for the jet of 7° [49]. Reference data are noted to have high-frequency oscillations at axial positions that are estimated to be in-flow.

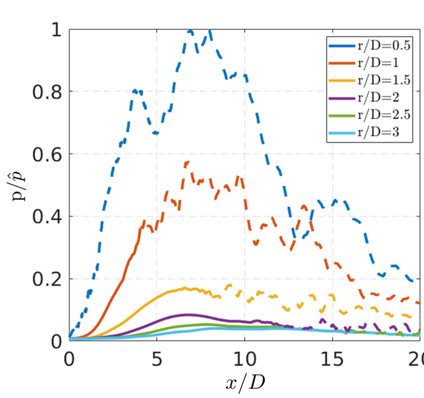


Fig. 3 Reference field from LES on near-field axial lines at several r/D. Dashed lines refer to the portion of data that are estimated to be immersed in the jet, assuming a 7° opening angle.

As stated in Sec. III, the model assumes the monitoring points to be outside the jet stream. Hence, the solutions that try to tightly follow the p_{REF} of the near-field lines may be driven away from the "correct" wave-packet shape by the influence of the jet flow in the reference pressure field. Therefore, it is reasonable to assume that the evaluation of J_1 and J_2 is affected by some error when calculating the difference between the predicted and simulated pressure for large axial positions, even for the "correct" wave packet. It is important to stress that the use of multi-objective optimization with near- and far-field data and the subsequent selection of the preferred solution by means of the presented ranking criterion are absolutely not equivalent to the optimization of the wave packet using only far-field data. In fact, any solution to the multi-objective problem has been obtained simultaneously, minimizing the objective functions related to both the near-field and the far-field predictions. It can be said that the preferred solution is the best far-field solution that at the same time optimizes the near-field response.

To get noise prediction for a wide range of frequencies, a dedicated optimization is performed for each of the considered St numbers, namely, 0.25, 0.5, 0.75, and 1.

Figures 4–7 show the comparison between the reference pressure field and the one predicted by the optimal wave packets at six near-field radial distances and the far-field polar arc, for the four mentioned St numbers. It is important to stress that, among the near-field axial lines on which the results are presented, only data from radial distances $r/D = 2$ and 2.5 were used in the optimization as a "training set." The other distances can be interpreted as a "test set" for the wave packets. As evidenced by comparing the aforementioned figures, for higher St, the optimization struggles a bit more in finding a wave packet whose solution well reproduces the near field. It is interesting to note that the selected solutions closely reproduce the shape of the reference data on the near-field lines only up to roughly the axial position where the lines start to be inside the jet flow for all the considered St (being the $r/D = 0.5$ line completely immersed, the wave-packet prediction over that line is typically off compared with the reference pressure). The test lines confirm that the

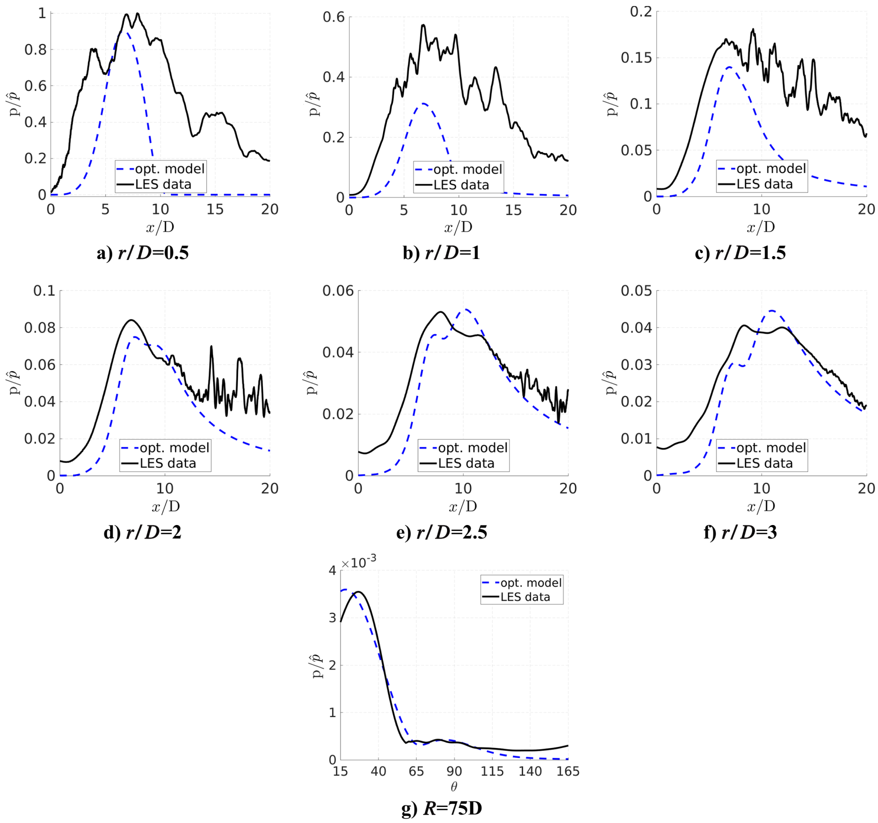


Fig. 4 Comparison between reference and optimized wave-packet normalized pressure. Near-field predictions in figures from (a) to (f) and far-field prediction in (g), $St = 0.25$.

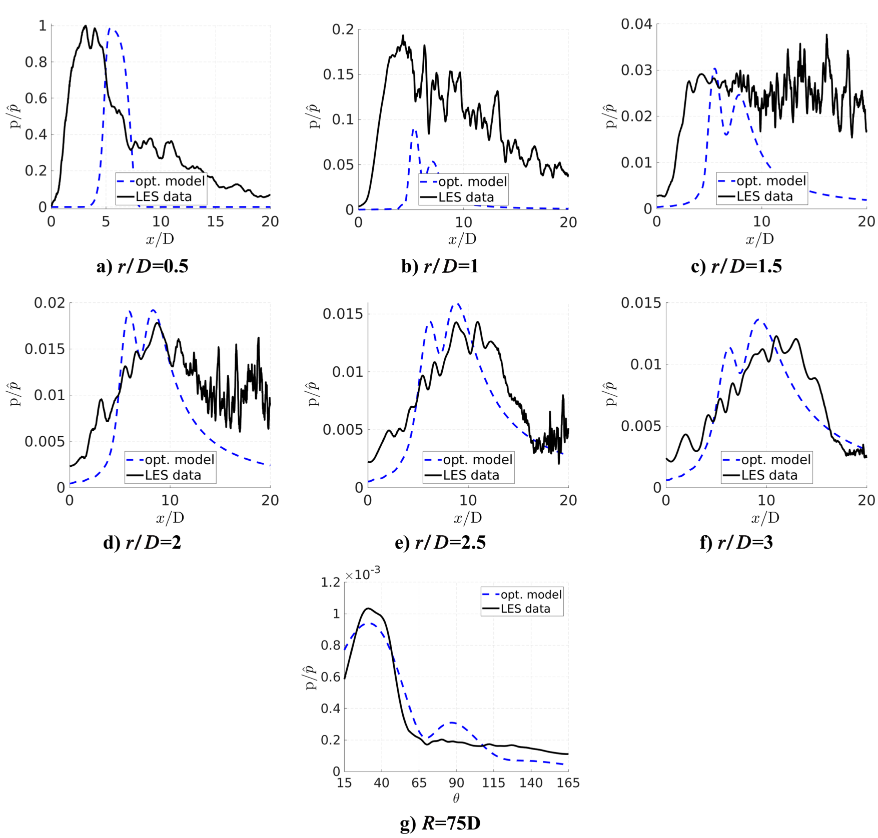


Fig. 5 Comparison between reference and optimized wave-packet normalized pressure. Near-field predictions in figures from (a) to (f) and far-field prediction in (g), $St = 0.5$.

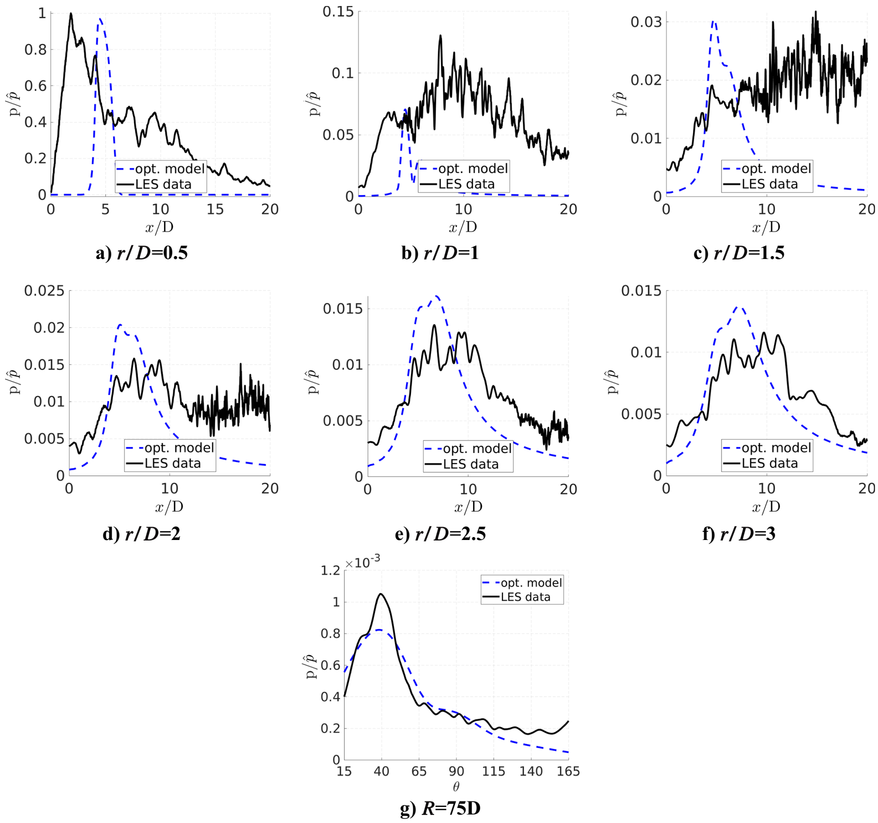


Fig. 6 Comparison between reference and optimized wave-packet normalized pressure. Near-field predictions in figures from (a) to (f) and far-field prediction in (g), $St = 0.75$.

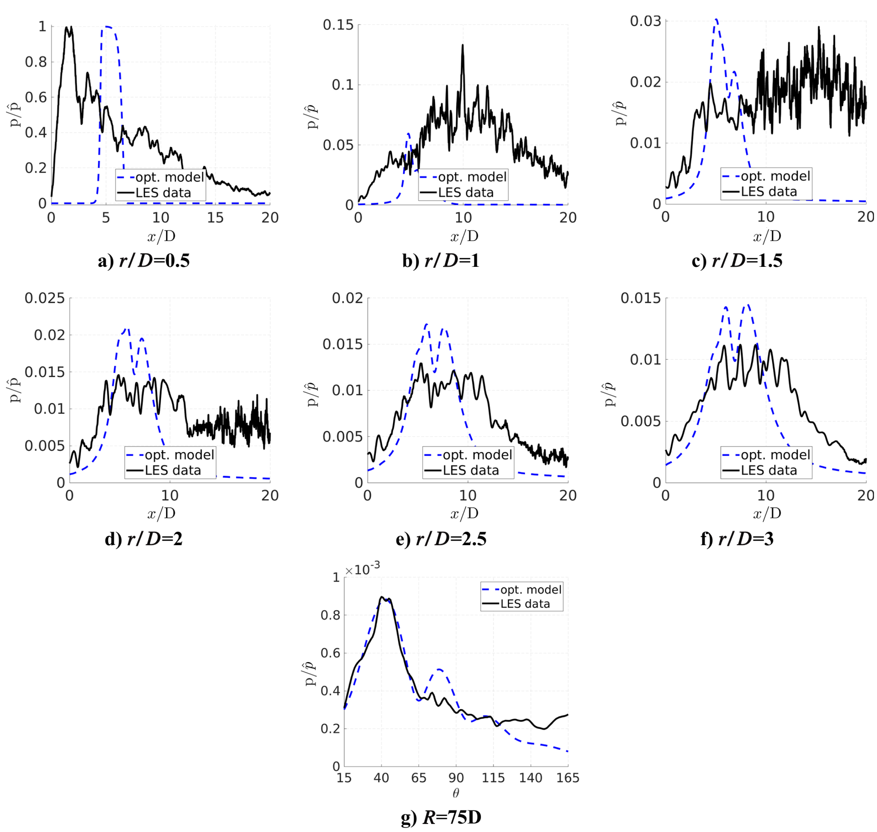


Fig. 7 Comparison between reference and optimized wave-packet normalized pressure. Near-field predictions in figures from (a) to (f) and far-field prediction in (g), $St = 1.0$.

optimized wave packets catch the characteristics of the jet noise source, correctly capturing the radial decay of the pressure fluctuations derived from the relative importance of the hydrodynamic and acoustic parts of the wave-packet source. The effect of the St on the reproduction on the far field is limited by the ranking criterion used to select the preferred solution.

The optimized solutions show an excellent capability of capturing the emission peak from the jet for all the studied St (see Figs. 4–7g), while appearing to lack energy for polar angles larger than 100°. This is reflected also in Fig. 8, where the comparison between the frequency spectrum of the reference signal in the far field and the one obtained with the optimized wave packets is shown around the maximum directivity angle, $\theta = 40°$, in a direction normal to the jet axis and aligned with the nozzle exit, $\theta = 90°$, and for a large polar angle pointing rearward, $\theta = 130°$. This can be ascribed to the characteristics of the wave-packet source, which is able to model the sound emission by large-scale turbulent structures in the jet, that dominate in the downstream direction (see Refs. [21,37,50]). However, the wave-packet source has limited emission at large polar angles, where the radiated noise mainly comes from fine-scale turbulent motions. This results in an underprediction of upstream traveling waves. To improve prediction accuracy at higher polar angles, given the limitations of the wave-packet approach, a potential future step involves combining the presented model with a localized omnidirectional noise source near the nozzle exit [25]. This source can be generated considering an acoustic monopole or higher-order modes, such as the helical mode ($m = 1$) and the double-helical mode ($m = 2$) [18], since these modes play a more significant role in the sideline direction [51].

Wave packets with very different shapes and parameters can be found in the Pareto front of each optimization, obtaining a similar result on the ranking criterion, i.e., on the far-field prediction. However, their performance on the near field is completely different. This confirms the ill-posedness of the inverse acoustic problem when the wave packet is retrieved from far-field measures only, highlighting the importance of including both near and far-field lines in the optimization procedure.

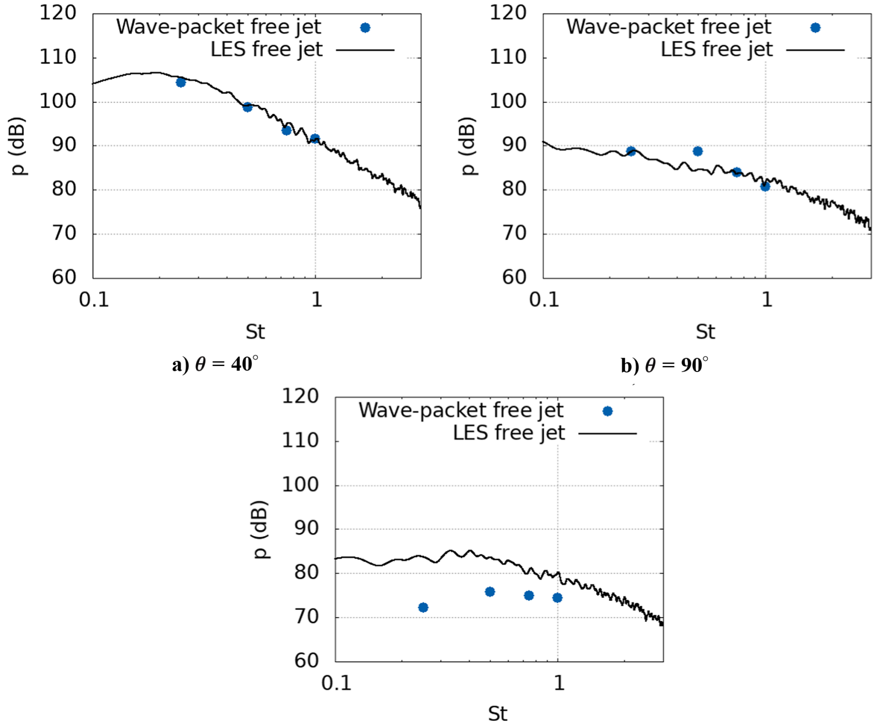
The analysis and optimization have been conducted here using data from a jet stream at $M = 0.9$. The calibration obtained can be reused for different Mach numbers; according to the literature [50], the shapes of the spectra should not change in the subsonic regime by reducing the jet Mach number. Energy spectra can, thus, be scaled by using empirical models available in the literature [52], and so can the prediction from the wave packets.

The methodology has been here applied to an axisymmetric jet, using only the $m = 0$ azimuthal mode extracted from the LES data to optimize the wave packet. According to the literature [53,54], for a nozzle with chevrons, the acoustic far field is still associated mainly with the $m = 0$ azimuthal mode, which remains the most efficient acoustically radiating mode for low polar angles. In other words, the acoustic field can still be accurately described by the zeroth azimuthal mode because the higher-order ones, whose order is related to the number of chevrons, are less acoustically efficient and do not significantly contribute to the emitted noise. The chevrons may be able to reduce the growth rate of the instabilities and increase the phase speeds of the waves compared to thrust-equivalent round jets. These effects are associated with their ability to reduce the radiation efficiency of large-scale structures and thus noise reductions. Consequently, the wave packet must be calibrated to data from chevron jets to capture this phenomenon.

The proposed method can, in principle, be extended to account for some flight effects, getting closer to realistic configurations of aeronautical interest. The effect on the acoustic propagation of a uniform freestream velocity can be included in the wave-packet model using the Prandtl–Glauert coordinate transformation [55]. In this way, the pressure field predicted by the wave-packet model can be corrected, including the effects of a relative uniform motion between the nozzle/jet and the hosting fluid, under the hypothesis of irrotational perturbations propagating within a uniform mean flow. However, this correction cannot account for the influence of the flight stream on the jet characteristics, like the modification of the jet shape, such as a shear layer or potential core length. To consider these effects related to a more realistic nonuniform flow, dedicated simulations or experiments must be conducted to produce a reliable training set for wave-packet calibration.

V. Conclusions

This study used a multi-objective optimization approach to identify the optimal parameters of a wave-packet model for jet flow noise prediction. A ranking criterion based on the agreement on far-field



a) $\theta = 40°$ b) $\theta = 90°$ c) $\theta = 130°$

Fig. 8 Far-field noise spectra for $\theta = 40,90,130$ deg.

data was proposed to identify a unique solution among the Pareto front obtained from the optimizations. The preferred solution is not merely the best far-field solution resulting from a single objective optimization, as the multi-objective approach simultaneously takes into consideration the near-field result in the error minimization process. The use of combined near- and far-field data has proven to be a robust method for guiding the optimization to solutions able to effectively predict both the hydrodynamic and the acoustic components of the pressure fluctuations in the reference data. The optimized wave packets show a notable capability of reproducing the pressure fluctuations in the whole domain. In particular, in the far field, the directivity peak of the jet noise source is correctly captured, and the noise spectra show a nice agreement up to polar angles of 90°. At higher angles, where the emitted noise is minimum, the modeled spectrum is underpredicted, especially for lower frequencies. The fast evaluation and accuracy of the model in both the near and far field makes it well suited to be coupled with low- and midfidelity aeroacoustic solvers (such as BEM solvers) for jet noise scattering predictions, with the simplifying hypothesis that the acoustic field can be effectively separated into an incident and a scattering part. This means that the jet aerodynamics/shape can be considered not to be strongly influenced by the presence of the scattering surfaces (i.e., the acoustic source is independent of its position), and thus the pressure field produced by the wave-packet model can be used as the incident field in a scattering code.

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