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Data-Driven Multiobjective Optimization of Wave-Packets for Near-Field Subsonic Jet Noise

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Aeroacoustics of innovative aircraft cannot disregard the development of low-order models for the jet noise source, which are essential to assess the propulsion–airframe interactions from the conceptual design stage. The main scope of this work is to provide a noise source model that can be coupled with relatively low computational cost methods for aeroacoustic scattering. To this end, this paper presents for the first time a multiobjective optimization of the zeroth-mode wave-packet in the jet near field. The importance of calibrating the model with near-field pressure data stems from the fact that in new aircraft, the engine nacelles are typically positioned at a few diameters from the wing or fuselage. In this work, the near field of a high subsonic jet at a Mach number of 0.9 is represented as a cylindrical surface radiating the pressure disturbances of a wave-packet source, which is optimized using large-eddy simulation data from three lines at different radial distances. The optimized model has been tested at Strouhal numbers between 0.25 and one, and the optimized solutions have been chosen using a Pareto-ranking criterion considering the wave-packet prediction over an extra line. A good agreement is achieved between the reference data and model predictions for multiple near-field radial distances.

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
Re_D	=	nozzle-exhaust Reynolds number; $\rho U D/\mu$
St_D	=	Strouhal number; fD/U
U_j	=	nozzle-exhaust jet velocity
$\boldsymbol{v}$	=	design variable vector
x, r, θ	=	cylindrical coordinates
δ_{BL}	=	nozzle-exhaust boundary layer
ω	=	angular frequency; $2\pi f$, rad

I. Introduction

SINCE the beginning of aeroacoustics, jet noise has been considered a hot topic in aviation noise because of its dominant role in community exposure. The incoming of increasingly strict noise regulations makes the development of modern strategies essential to reduce the noise emitted by jets and aircraft engines. The design of a modern commercial aircraft must consider the acoustic emissions from the early conceptual phase; hence, reliable and fast prediction methods are of fundamental importance. Tremendous efforts have been and are being deployed in the development of more effective acoustic treatments and devices for quieter aviation, such as quieter high lift devices [1], chevrons for jet exhaust [2,3], acoustic liners, and/or innovative treatments [4–9] for turbofan ducts. Innovative configurations are being studied to avoid technological saturation in the race for aviation noise abatement. The blended wing body (BWB) aircraft is probably the most promising alternative to the currently dominating tube-and-wing configuration: in terms of both efficiency and community noise reduction [10–13]. The main characteristic of a BWB is the non-net distinction between the fuselage occupying the centerbody and wings, with the former being wider and shaped like an airfoil to provide a nonnegligible contribution to the overall lift, resulting in a sensible efficiency increase. The large centerbody surface offers the possibility of the upper installation of the propulsion system, which can be exploited for the acoustic shielding of the engine noise [14–16]. The simulation of the shielding effect in the audible frequency range involves the solution of the scattering problem of the whole aircraft up to an extremely high Helmholtz number of $He_l = kl$, with k as the wave number and l as a characteristic length of the aircraft (e.g., the centerbody length), which makes it computationally very expensive: in particular when introduced in an optimization process. Hence, there is a strong need for fast models for predicting the effects of the propulsion system installation on the acoustic emissions at the aircraft level, enabling its assessment from the first design stages and for disruptive

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configurations. Adaptive metamodeling techniques have been recently applied to this class of problems [17,18] to reduce the computational effort required in determining the optimal position of the propulsion system that minimizes the noise directed toward the ground and community. Boundary elements method (BEM) simulations involving the monopole as a noise source are often used to feed the model creation. However, such a simple source has been demonstrated to not be able to satisfactorily model the jet noise [19]. In some low-order models, the noise sources of a single circular jet were represented by a set of uncorrelated quadrupoles [20]. However, it was shown that the directivity at shallow angles was not well reproduced [21].

In this framework, the discovery of coherent structures in jets changed the perspective of jet noise and provided a basis for introducing the wave-packet approach [22]. As suggested by Papamoschou [23], 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 (see, e.g., Refs. [24,25]). For example, Cavalieri et al. [26] used azimuthally decomposed far-field measurements to determine envelope parameters for higher-order azimuthal modes. However, for the mentioned BWB architecture, the jet is typically in a very closely coupled configuration with the centerbody scattering surface. A large body of literature demonstrated that the low-frequency amplification of the jet noise in the classical jet-wing architecture can be ascribed to the scattering of the jet hydrodynamic field [27–29]. Hence, the prediction of the acoustic shielding needs source models able to capture the near-field characteristics of the emitted noise in order to accurately address the effects of the aircraft scattering. Applications of the wave-packet procedure using near-field measurements have been carried out in various research works. Mollo-Christensen [30,31] provided the first observations of the wave-packet features from the point of view of hydrodynamic instability and aeroacoustics, whereas Crighton and Huerre [32] suggested various simple models to predict near-field structures. Following the literature, the near-acoustic field is characterized by acoustic fluctuations that are small enough to permit linearization but close to the jet so that they could be contaminated by the irrotational hydrodynamic pressure field. In this region, most of the kinetic energy of fluctuations is related to azimuthally coherent structures that lead to nonlinear effects on the wave-packet evolution. Thus, for the complexity mentioned earlier in this paper, the high subsonic jet noise source prediction is still a challenging task, which is crucial because it represents the operative condition of modern turbofan engines. In this framework, the principal focus of the present work is to find out an optimized amplitude-modulated wave-packet able to model the jet near-field noise that can be integrated in the future into the BEM formulation to obtain a reliable prediction of the jet–surface aeroacoustic scattering that is also for innovative aircraft configurations. To tune the present model, we used a numerical database obtained from the large-eddy simulation (LES) of an isothermal round freejet at a Mach number of $M = 0.9$ and a diameter-based Reynolds number of $Re_D = 10^5$ with the nozzle-exhaust turbulence level fixed at a turbulence intensity (TI) of 9%. The database contains pressure data at different axial and radial locations, which we considered in a subset ranging from $x/D = 0$ up to $x/D = 20$ in the axial direction and from $r/D = 0.5$ up to $r/D = 3$ in the radial direction, allowing us to optimize the wave-packet jet near-field domain. The near-field domain depicted in this database is representative of all the jet zones that could be influenced by solid boundaries in reality (i.e., wing or fuselage); see Refs. [27,28,33].

In Ref. [34], a preliminary study on the optimization of the wave-packet was presented. In this paper, an extensive analysis is performed at multiple Strouhal numbers, namely, $St_D = fD/U_j = 0.25$, 0.5, 0.75, and 1, where f and U_j are the frequency and the nozzle-exhaust jet velocity, respectively; and for the zeroth azimuthal mode, which has a relevant intermittency around the frequencies associated with the lower Strouhal numbers [35,36]. This intermittent behavior has been confirmed by Cavalieri et al. [26], who found a superdirective wave-packet to be consistent with the polar structure of the sound field for azimuthal Fourier modes of $m = 0$, 1, and 2 and $0.2 < St_D < 0.8$ [37]. As suggested by Rodriguez et al. [38], at low and moderate Strouhal numbers, the zeroth mode is the most relevant one for the noise radiated by single jets. This is due to the more elongated structure of the corresponding wave-packet, the higher peak amplitudes, and slower radial decay. For this reason, this mode can be considered representative of the whole signal in the analyzed domain; for this optimization of the wave-packet using near–field data, we take into account only the axisymmetric mode $m = 0$. The optimization has been performed using a multiobjective particle swarm optimization algorithm [39], originally introduced by Kennedy and Eberhart [40], which is based on the social-behavior metaphor of a flock of birds or a swarm of bees searching for food; it belongs to the class of heuristic algorithms for evolutionary derivative-free global optimization.

The paper is structured as follows. Key information about the numerical simulation used to generate the database is presented in Sec. II. In Sec. III, details about the wave-packet model and the optimization algorithm are reported. Results are shown in Sec. IV. Some concluding remarks are proposed in Sec. V.

II. Numerical Setup

The near field of the isothermal round freejet at the 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 $\delta_{bl} = 0.15r_0$ and the nozzle exit turbulence intensity at 9% (see Ref. [41] 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 a previous work [42]. 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 Ref. [43] for a description of the available data. In addition, the near-pressure field of this jet has been also investigated in Ref. [44]. It has been propagated to the far field in Refs. [41,45]. Because the present study is limited to the near-field domain, we consider arrays of virtual microphones parallel to the nozzle exhaust, which are positioned at $r/D = 1, 2, 2.5$, and 3. Each array contains 1024 probes that cover a domain that spans between $x = 0$ up to $x/D = 20$. The data have been stored at a sampling frequency corresponding to $St_D = 12.8$, with a total of 3221 time snapshots. A representative one is shown in Fig. 1. The LES dataset selected for the present work is over-resolved for the purpose; and less resolved simulations or (also) experimental data might be, in principle, used successfully. Nevertheless, we preferred a very well-assessed simulation with a very high spatial resolution for this first study on optimizing a wave-packet with near-field data. The original pressure signals are represented in terms of their azimuthal components through the azimuthal decomposition [46]. The Fourier coefficients are stored for the first four azimuthal modes that dominate the sound field for low polar angles. As mentioned earlier in this paper, 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 one [26].

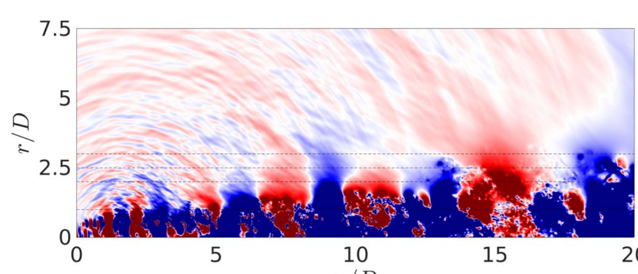


Fig. 1 Snapshot in the (x, r) plane of the pressure signals. The black dashed lines represent the probe arrays.

III. Wave-Packet Model

The noise source model used (i.e., the wave-packet model for the jet noise) was introduced by Papamoschou in Refs. [19,23,24] and by Huang and Papamoschou in Ref. [47], who in turn developed it from the works by Morris [48,49] and the previous ones by Tam and Burton [50], Crighton and Huerre [32], and Avital et al. [51]. The fundamental assumption at the basis of the model is that the peak noise radiation from the jet in the aft region is related to the large-scale coherent structures in the jet flow, which can be modeled as instability waves at its boundary, growing and then decaying along the axial distance [19]. In the model, the jet is substituted with a cylindrical surface (surrounding the original jet), radiating the pressure perturbation imposed on it. Applying the wave-packet ansatz, the pressure on the cylindrical surface at r_0 surrounding the jet is prescribed as

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

where m is the azimuthal mode number, x denotes the axial coordinate, θ is the azimuthal angle, and $\omega = 2\pi f$ is the pulsation. In the present study, the reference surface is taken at $r_0 = D$ and the wave-packet axial shape $p_0(x)$ is given in the form [19]

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

The coordinate x_0 is used to locate the relative position between the origin of the wave-packet function and the nozzle exit. The signal growth is controlled by the parameters b_1 and p_1, whereas b_2 and p_2 define its decaying rate. Following Morris [49] and Papamoschou [19], the solution in the linear regime (i.e., solution for the three-dimensional (3-D) wave equation in cylindrical polar coordinates) for an arbitrary radial distance $r \geq r_0$ can be evaluated as

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

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. The model adopted is derived from the 3-D wave equation in cylindrical coordinates, for which the solution is radially decaying as a combination of a Bessel of the first and second kinds (i.e., a Hankel function of the first kind [49]). The pressure field generated by the wave-packet can be easily separated in its radiative and decaying components looking at the supersonic ($|\omega/k| \geq c_\infty$) and subsonic ($|\omega/k| < c_\infty$) values of the phase speed, respectively.

In the work of Papamoschou [19], the parameters of the deterministic wave-packet were obtained through a numerical optimization aimed at matching the experimentally measured far-field directivity of the jet, hence involving only the radiative part of the wave-packet. The tuned wave-packet was then employed as an equivalent noise source for the jet in BEM scattering calculations to predict the shielding effect from a thin plate. However, the interactions between the pressure perturbation generated by the wave-packet and the obstacle typically happen in the jet near field. The wave-packet axial location was adjusted to match the near-field peak emission obtained from phased-array measurements to include some information on the acoustic near field.

In this work, the same deterministic wave-packet model is used, but its parameters are defined from near-field data on coaxial lines at several radial distances from the jet axis, namely, $r/D = 1, 2$, and 2.5. A multiobjective optimization procedure aims at matching the complete pressure fluctuation envelope from the model with the one from the numerical simulations for each of the considered lines. A generic unconstrained optimization problem consists of the research of the set of variables $\boldsymbol{v}$ that yields to a minimum of the N_J objective functions $J_n(\boldsymbol{v}, \boldsymbol{q})$

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

where $\boldsymbol{q}$ is the vector of the 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 $\boldsymbol{v} = [p_1, b_1, p_2, b_2, \omega/(\alpha U_j), x_0]$ and $N_J = 3$ defines the three objective functions to be minimized, with one for each r_n considered:

$$J_n(\boldsymbol{x}, \boldsymbol{y}) = \sqrt{\iint \left(\frac{|p_n(r_n) - p_{\mathrm{LES}}(r_n)|}{\max(|p_{\mathrm{LES}}(r_n)|)}\right)^2 \mathrm{d}x} \tag{5}$$

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 LES over the axial extension of the considered lines, divided by the peak value from the reference curve for each radial distance to normalize the objective function values. Multiple Strouhal numbers have been considered, optimizing the wave-packet source model separately for each value in the set $St_D = 0.25, 0.5, 0.75$, and 1, and using pressure data from the numerical database for the dominant axisymmetric azimuthal mode. With the values of the three objective functions tending to zero simultaneously, the wave-packet model would perfectly trace the simulations for the considered radial distances. A solution reaching this goal would occupy the so-called utopia point in the codomain that, as its name suggests, is not reachable for nontrivial multiobjective problems in which the involved functions are even just partially conflicting. In these cases, including the one considered in this paper, the optimization process identifies a set of compromise solutions that identify an (approximated) Pareto front in the codomain. The defining property of solutions lying on a Pareto frontier is that, when moving from one to the other, none of the objective functions can be improved in value without degrading some of the others. Hence, the Pareto front identifies all the possibly infinite, nondominated solutions of the multiobjective optimization problem, which is considered optimal in a Paretian sense and equally good. Any choice of the preferred solution within this set is subjective and is to be made by depending on the problem under analysis with a specific grade of arbitrariness [52,53].

IV. Results

Because the interest is primarily on matching the shape of the modeled pressure at several radial distances and the relative amplitudes among them rather than the absolute ones, the data from the simulations have been normalized with respect to the maximum value at r_0. For each St_D, a multiobjective particle swarm optimization algorithm is employed to find the solutions minimizing all the objective functions together. This heuristic optimization algorithm introduced originally by Kennedy and Eberhart [40] was extended to handle multiple objective functions by Sierra and Coello [39] and Coello et al. [54]. The optimization has been performed with a MATLAB implementation using a fixed budget of 500 iterations, with a swarm composed of 140 individuals, for which the initial positions were randomly defined in the domain with uniform distribution. The total computation time on a workstation with an Intel Xeon® E5-2620 v4 CPU at 2.10 GHz took about 200 s per optimization on a single core. The subroutines might be better optimized to further reduce the computation time. At the present moment, the method allows us to find the optimum wave-packet by modeling only one azimuthal mode; when more than one is expected to give a significant contribution, the total noise source can be obtained with a linear combination. A possible future extension of the method might simultaneously optimize more than one wave-packet: each one with a different azimuthal mode. The drawback of this approach is that a good solution is expected to be more difficult to find as the dimension of the domain increases; this problem is typically referred to as "the curse of dimensionality."

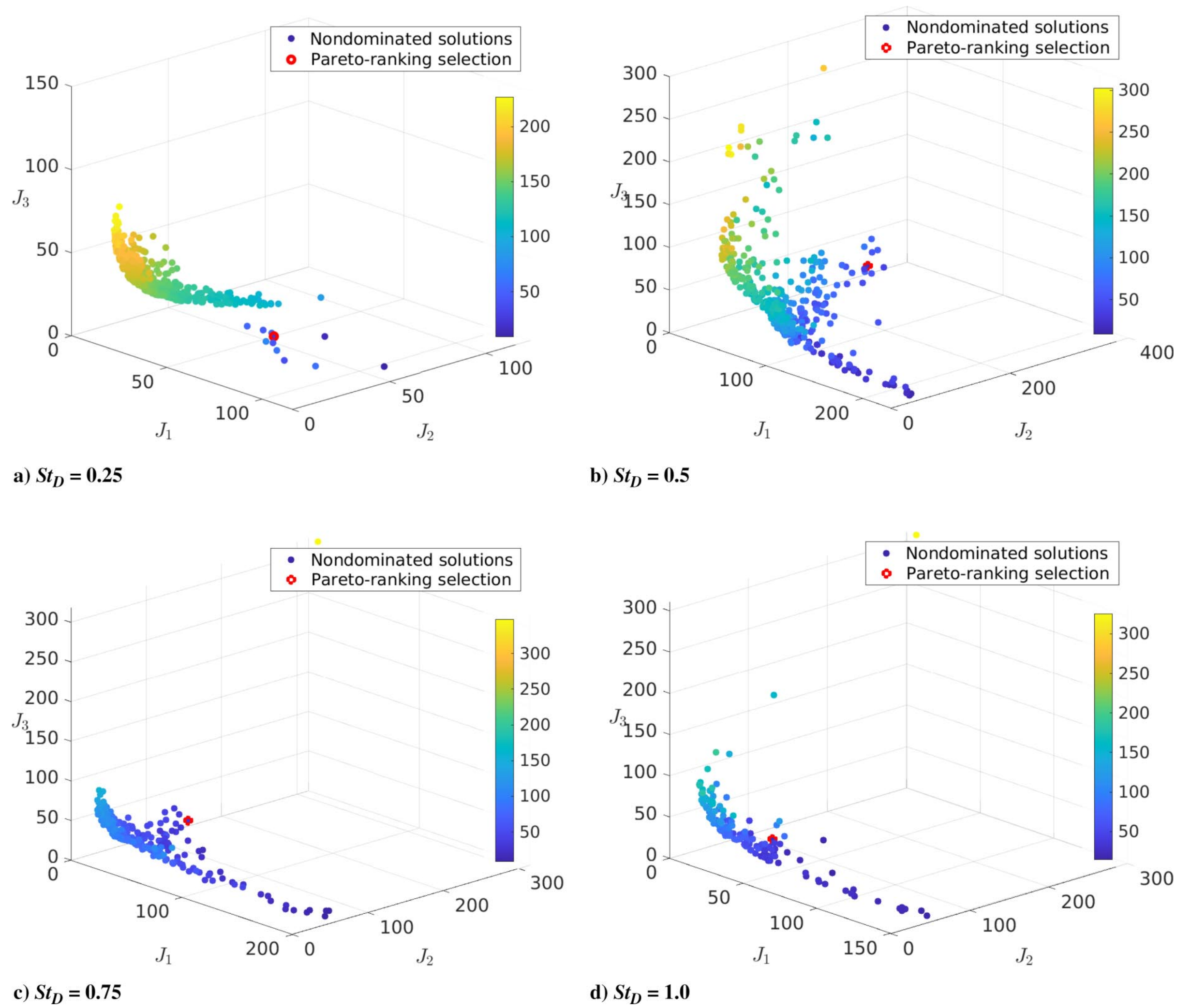


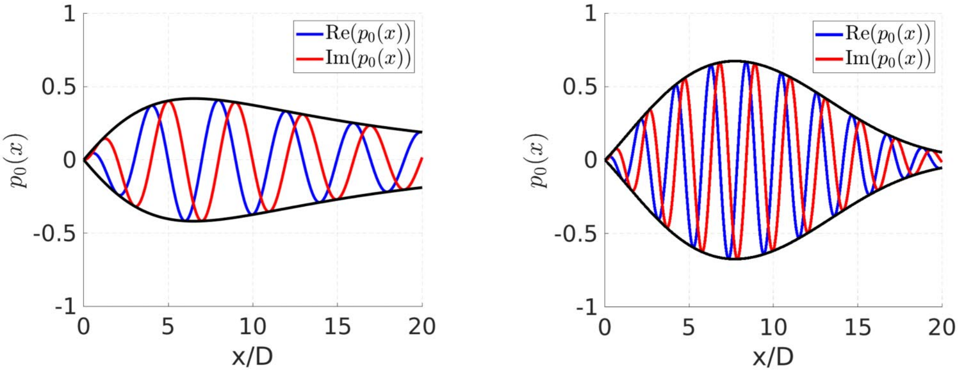
Fig. 2 Codomains of the optimization problems. Nondominated solutions of the multiobjective optimization for the analyzed Strouhal numbers.

As anticipated in the previous section, when the objectives conflict, the solutions resulting from the minimization are optimal in a Paretian sense. The set of Pareto-optimal solutions lying on the Pareto front, plotted in Fig. 2, has equal dignity in terms of minimization of the objective functions. Because it represents the set of the nondominated solutions, moving along the front is not possible to improve one of the objective values without worsening at least one of the others. One of the techniques that may be employed to identify the preferred solution among the optima is to identify a ranking criterion [16,52,55–57] (also called the decision-maker algorithm), to be used as an added objective, evaluating the solution's performance on it and then selecting the solution resulting as the most suitable. Any selection criterion is valid in principle and may be used reasonably: from simple subjective preferences to more complex analyses of the results. In this study, a Pareto-ranking criterion is formulated by combining the analysis of the performance of the optimized source model when predicting the pressure fluctuations over the $n + 1$ line at $r_{n+1}/D = 3$ (a farther radial distance from the ones used during the optimization) and the distance of the solutions from the utopia point in the codomain of the problem. In particular, solutions are ordered on the basis of their J_{n+1} value, and all the solutions with a relative difference in their value under 100% with respect to the best one are included in a subset of optimal solutions; the one closest to the utopia point is taken as the preferred one. The only exception is the $St_D = 0.5$ case, in which the solution minimizing the error on the closest line of $r/D = 1$ is selected. This kind of decision-maker (DM) algorithm can be classified in the class of the a posteriori *articulation of preferences* [55], implying that the DM's involvement starts posterior to the explicit revelation of "interesting" solutions.

In Fig. 2, the optimal solutions are highlighted by red circles on their respective three-dimensional Pareto fronts. Each dot representing a solution is colored on the basis of its fitness over the $n + 1$ line. It can be seen that the Pareto-ranking criterion tends to prefer solutions that privilege the results on J_1 and J_3 more than the performance on the second radial distance J_2.

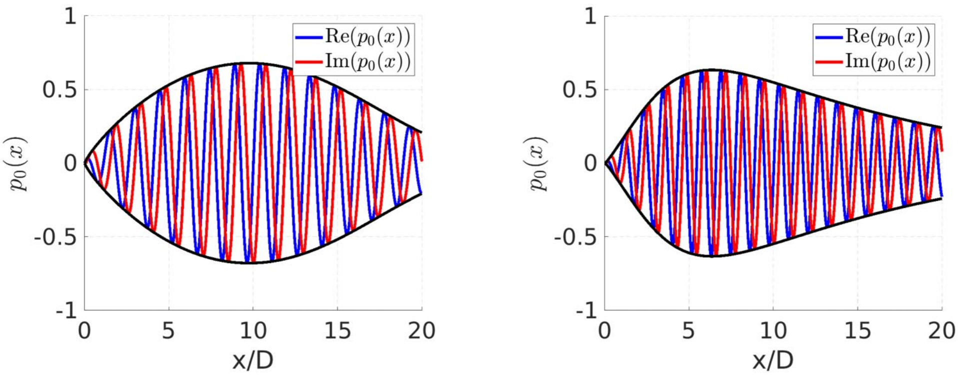
Figure 3 shows the shapes of the optimal wave-packets identified by the Pareto-ranking criterion. The envelope of the complex pressure is represented in black, with the real and imaginary parts plotted with blue and red lines, respectively. The sound emission of a wave-packet source depends on both the spatial envelope and temporal growth and decay [32,58]. As expected, the wave-packet shapes strongly depend on the Strouhal number, which affects (in particular) the peak amplitude location. It can be seen that the number of spatial oscillations inside the envelope increases with the Strouhal number because the spatial and temporal frequencies are linearly connected by the sound speed.

Figures 4–7 show the sound pressure levels (SPLs) predicted by the LESs and by the optimized wave-packets at the four St_D and radial distances considered. The optimized wave-packets selected with the Pareto-ranking criterion give satisfactory agreement with the LES SPL on the lines located at $r/D = 1, 2$, and 2.5 used in the optimization for all the Strouhal numbers analyzed in Figs. 4a–4c, 5a–5c, 6a–6c, and 7a–7c. A good prediction of the pressure perturbation by the wave-packet model is also observed at $r/D = 3$ in Figs. 4d–7d. It should be noted that the propagation of the pressure perturbation considered by



a) St_D **= 0.25-**
$\mathbf{v_{opt}}$ **= [1.0558, 0.1327, 0.7017, 0.3699, 1.0112, 0.0001]**

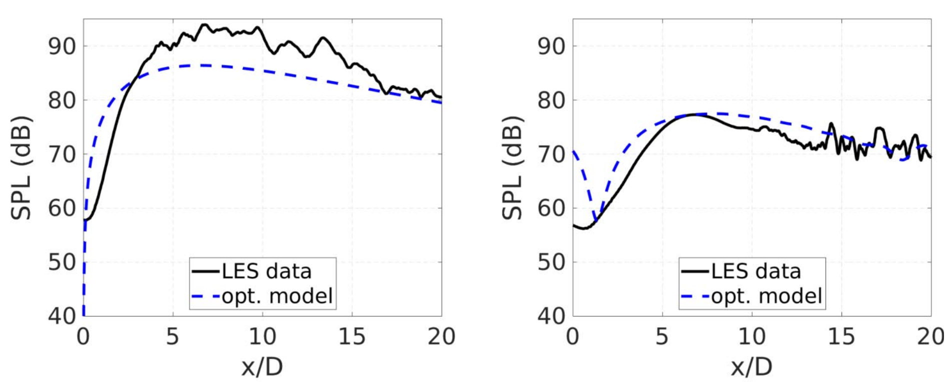
b) St_D **= 0.5-**
$\mathbf{v_{opt}}$ **= [1.0664, 0.1502, 2.4476, 0.3459, 1.0625, 0.0018]**



c) St_D **= 0.75-**
$\mathbf{v_{opt}}$ **= [0.8120, 0.2031, 2.9113, 0.4321, 1.1268, 0.0122]**

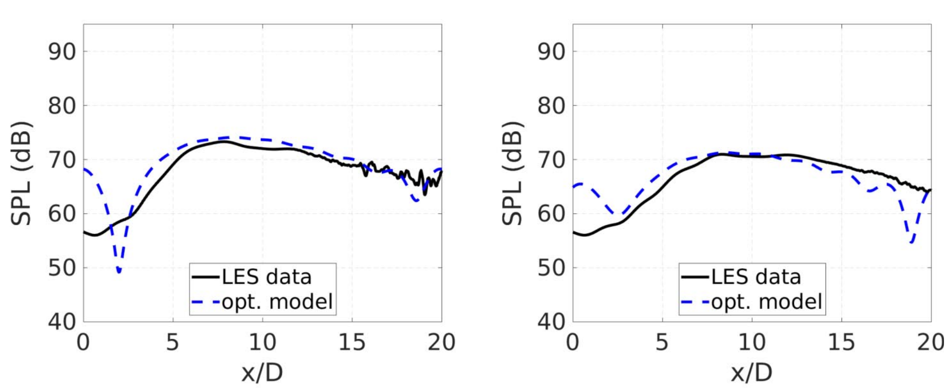
d) St_D **= 1.0-**
$\mathbf{v_{opt}}$ **= [1.1596, 0.1047, 1.0663, 0.4420, 1.1350, 0.0169]**

Fig. 3 Shapes of the optimized wave-packets and their parameters.



a) r/D = 1

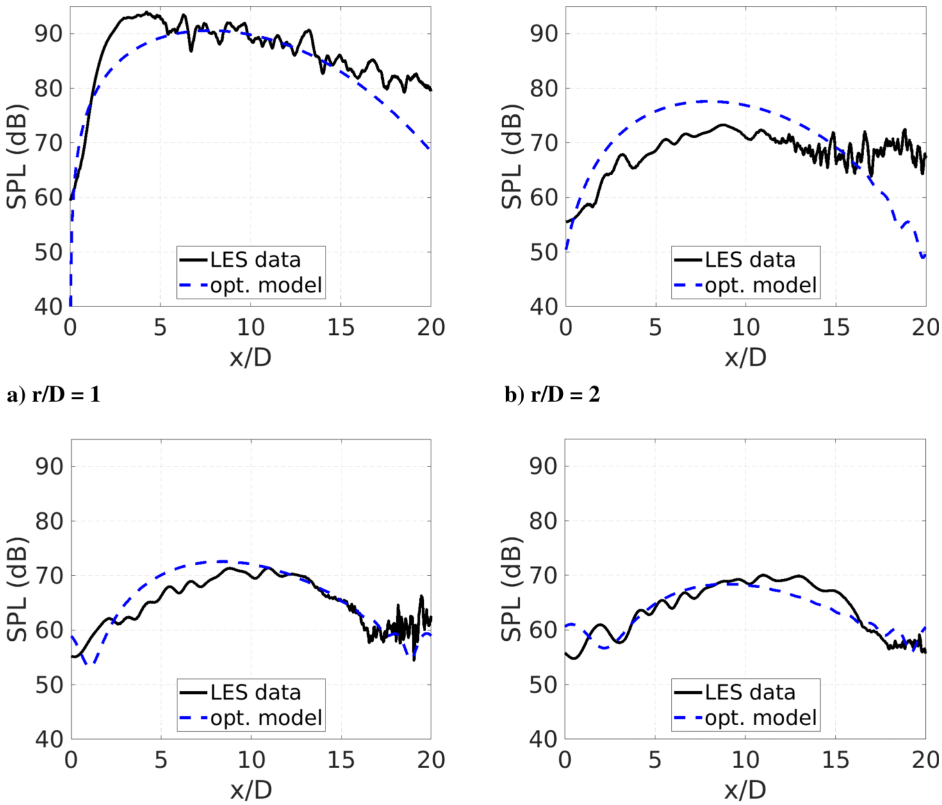
b) r/D = 2



c) r/D = 2.5

d) r/D = 3

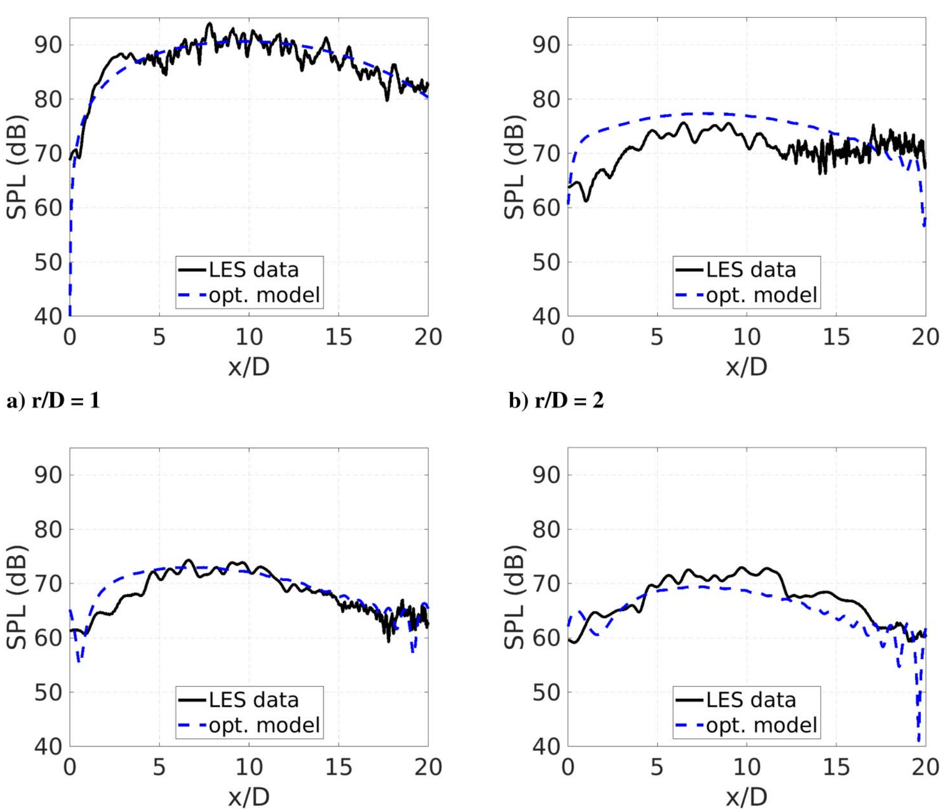
Fig. 4 Solution selected by the Pareto-ranking criterion for $St_D = 0.25$**. Results for the radial distances used in the a–c) optimization (opt.) and for the d) validation line.**



a) r/D = 1 b) r/D = 2

c) r/D = 2.5 d) r/D = 3

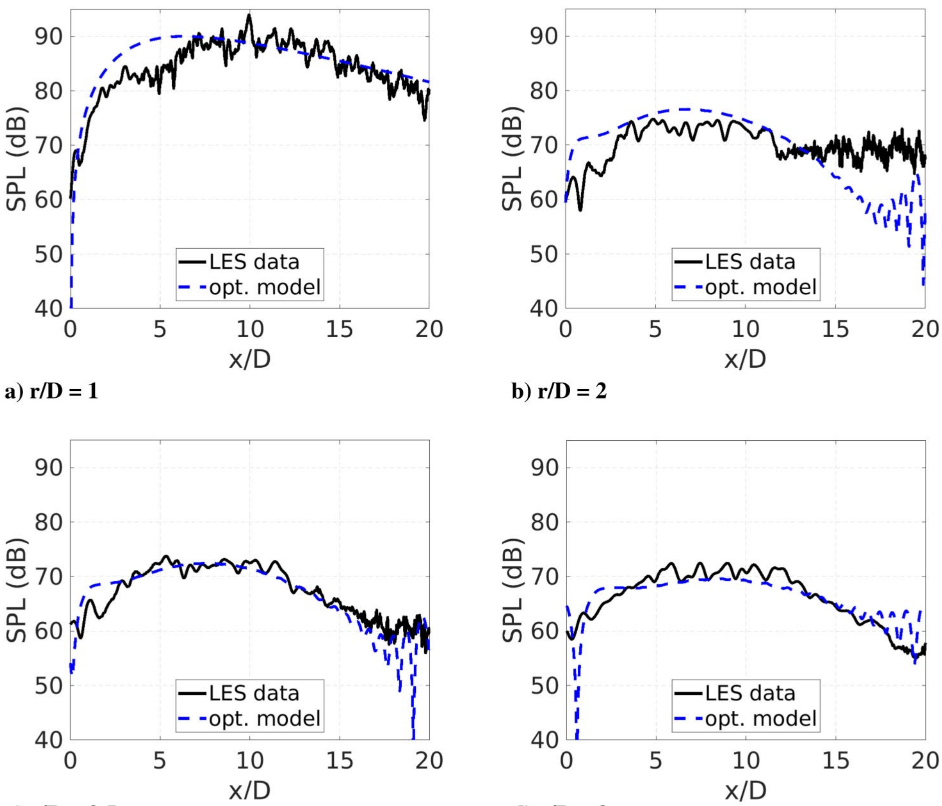
Fig. 5 Solution selected by the Pareto-ranking criterion for $St_D = 0.5$. Results for the radial distances used in the a–c) optimization (opt.) and for the d) validation line.



a) r/D = 1 b) r/D = 2

c) r/D = 2.5 d) r/D = 3

Fig. 6 Solution selected by the Pareto-ranking criterion for $St_D = 0.75$. Results for the radial distances used in the a–c) optimization (opt.) and for the d) validation line.



a) r/D = 1
b) r/D = 2
c) r/D = 2.5
d) r/D = 3

Fig. 7 Solution selected by the Pareto-ranking criterion for $St_D = 1$. Results for the radial distances used in the a–c) optimization (opt.) and for the d) validation line.

the wave-packet model assumes that the radiating surface is outside of the jet plume, whereas the first line at $r/D = 1$ is immersed in the flow for a large part of its axial extension. It is necessary to use this kind of approximation of the model to include the near-field hydrodynamic contribution inside the optimized source, which is important to predict the scattering noise generated by a jet installed close to a solid boundary. Without a good match on the propagated information at $r/D = 3$, the wave-packet prediction capabilities would be comparable to an interpolation model. On the contrary, the agreement on the fourth line confirms that the optimized wave-packets correctly catch some of the jet noise source characteristics and the relative importance of the hydrodynamic and acoustic parts of the pressure perturbation because the wave-packets were not informed of the LES pressure fields for $r/D > 2.5$.

The mean difference between the wave-packet and the LES SPL curves is representative of the model's average error. The values for all radial distances and Strouhal numbers are reported in Table 1. They are lower than 3 dB for 75% of the analyzed data. Some grade of conflict of the objective functions is somehow expected. The ideal jet noise source model would simultaneously fit the reference pressure curves at all distances, leading to a unique optimum solution instead of a Pareto front. However, it has to be remembered that the wave-packet model used in this study is a simplified interpretation of the actual noise production and propagation phenomena related to the jet. The line at $r/D = 1$, moreover, is partially immersed in the jet due to the jet expansion angle, whereas the wave-packet model assumes the pressure propagation to higher radial distances to happen in a quiescent fluid, introducing an approximation in the model. Nevertheless, the wave-packet needs to be informed with the pressure perturbations in the very proximity of the jet axis for a more reliable prediction of the hydrodynamic part of the field.

Table 1 Mean error in decibels on each virtual probe line between predicted and LES levels for each Strouhal number

St_D	$r/D = 1$	$r/D = 2$	$r/D = 2.5$	$r/D = 3$
0.25	4.9	2.4	2.1	2.4
0.5	3.6	5.8	2.2	1.8
0.75	1.7	4.2	1.6	2.6
1.0	3.0	4.6	1.9	2.1

Further investigations that involve multimodal analyses including other azimuthal contributions and different turbulence levels are ongoing. The multimodal approach will be needed to extend the presented model toward complex geometries, like chevrons and scarfed nozzles, in which jet flows are no longer characterized by axial symmetry; hence, higher azimuthal order modes need to be involved in the analysis.

V. Conclusions

For the first time, a multiobjective optimization of a wave-packet in the jet near field is presented to predict the behavior of the zeroth azimuthal mode. The results of the optimizations are found to provide a good agreement between the numerical reference data and the model in the tested Strouhal range of $0.25 \leq St_D \leq 1$. The optimizations have been performed for a wide range of Strouhal numbers where the zeroth mode is known to be an essential component in the whole jet pressure field, as well as for radial distances relevant for the jet–surface scattering phenomena in innovative aircraft configurations.

A Pareto front has been obtained as a solution of each optimization due to the objectives being partially conflicting, i.e., the model–simulation agreement at three different radial distances from the jet axis. The preferred solution on the front is then selected using a Pareto-ranking criterion method by considering the wave-packet prediction over an extra line. The optimized noise source model prediction can reproduce the LES data from the freejet with a mean error for each radial distance of the probe arrays within 3 dB for most cases and is suitable to be integrated into the BEM solver to evaluate of jet–surface aeroacoustic scattering. Specifically, the idea (which is currently under development) is to use this optimized noise source to generate the incident field over the scattering body (such as the wing pressure side for standard aircraft or the trailing part of a BWB centerbody section) and then evaluate a solution for the jet installed noise including the scattering and shielding effects from the surfaces. In the present approach (because the wave-packet is related to a freejet), in order to address different engine–airframe arrangements, it is sufficient to adjust the evaluation of the incident field by changing only the relative positioning between the noise source and the scattering surfaces without modifying the wave-packet parameters. The process can be easily included in an optimization loop to find the solution, minimizing (for example) the noise radiated toward the ground. The computational cost related to the acoustic simulation of each configuration can be significant (in particular, for high-frequency acoustic simulations), making the whole optimization process barely affordable or even not affordable. To mitigate the effort required, some metamodeling techniques can be applied. Among other techniques, adaptive radial basis functions (also in their stochastic version) and/or artificial neural networks may be used, which have been recently applied to the metamodeling of similar problems, for both shielding and jet noise prediction [17,18]. Such surrogate models allow for very fast evaluations of the specific metrics they are built for (e.g., insertion loss at some observation points), dramatically reducing the optimization cost. The computational effort is substantially moved to the building of the metamodel, which must be trained with some (possibly costly) acoustic simulations. However, it is expected to be lower than what a direct approach would require.

The optimized wave-packet capability to predict the solution at a higher radial distance shows that it captures at least some of the features of the modeled noise source, such as the relative contributions of the radiating and nonradiating parts of the pressure perturbations. It has been evidenced how the probe line closer to the jet axis is partially immersed in the flow, which is somehow a limit of the model. However, the final aim of the work is to develop a jet noise source model able to predict the scattering effects in closely coupled installed jet configurations, where the flow grazes the scattering surfaces and the hydrodynamic part of the perturbation is relevant.

The method is, in principle, applicable to any noise signal produced by jets in which the contribution from coherent structures is significant. Furthermore, the input for the wave-packet optimization is not restricted to numerical simulations because experimental data are also eligible. In any case, if turbulent jets are considered and if the underlying hypotheses of the wave-packet modeling of jet noise are satisfied, the optimization procedure is expected to be able to find a set of parameters for the wave-packet; this is also true for a Reynolds number typical of flight conditions (i.e., about two orders of magnitude higher than what has been considered in this study). Jet noise scaling relationships have been proposed in the literature for estimating the SPL of a subsonic freejet accounting for modification of the jet exit velocity and nozzle-exhaust diameter. These can be used on top of the results predicted by the wave-packet model to readily include the effects of the mentioned jet parameters without reoptimizing the noise source. It is worth noting that two orders of magnitude of the Reynolds number can involve a variation of the shape of the SPL spectrum, yielding nonperfect effectiveness of the empirical laws at all the Strouhal numbers St.

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