Numerical Simulation and Fluid Dynamics Optimization of Aerodynamic Characteristics of Ultra-High-Speed Elevators—Based on the Coordinated Perspective of Noise Reduction and Energy Consumption

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ABSTRACT Ultra-high-speed elevators encounter severe coupling effects among aerodynamic noise, flow instability, and energy consumption during high-speed operation. To address these challenges, this study develops a three-dimensional aerodynamic simulation framework based on Computational Fluid Dynamics (CFD). A hybrid Improved Delayed Detached Eddy Simulation (IDDES) approach combining the k-ω SST model and Large Eddy Simulation is employed to capture transient vortex evolution, pressure fluctuations, and flow-induced acoustic characteristics. Fluid–structure interaction boundary conditions are introduced to describe pressure–deformation coupling of shaft walls. Multiobjective optimization of guide clearance, shaft wall roughness, and airflow-guiding structures is conducted through a genetic algorithm integrated with surrogate modeling. Results show that the optimized configuration reduces cabin sound pressure levels from 94.6 dB to 82.3 dB, decreases the drag coefficient from 0.148 to 0.120, and lowers energy consumption from 52.3 kJ to 44.3 kJ. The optimized flow field exhibits more uniform vortex distribution and reduced pressure pulsation. The proposed framework provides an effective methodology for aeroacoustic prediction, intelligent flow-field optimization, and complex propagation-environment modeling, offering engineering references for advanced transportation systems operating under high-speed fluid and wave propagation conditions.

INDEX TERMS ultra-high-speed elevator, computational fluid dynamics, aeroacoustic propagation, flow-field optimization, fluid-structure interaction

I. INTRODUCTION

THE development of ultra-high-speed elevators for vertical transportation in super high-rise buildings has become a critical driver for the integration of high-performance material morphology research into advanced structural cabling and vibration-damping systems. This evolution leverages industrial modeling parameters and multi-dimensional data perception to achieve the manufacturing excellence required for the lightweight, high-strength tension members essential to modern vertical mobility. The continuous increase in their operating speed brings significant aerodynamic complexity. When the elevator operating speed exceeds 20 m/s, a high pressure differential region and unsteady flow structure are formed in the enclosed space of the shaft, resulting in a significant increase in aerodynamic noise and a complex distribution of cabin vibration frequency, which affects ride comfort and system stability [1,2]. The increase in aerodynamic drag also increases drive energy consumption, which has an adverse effect on elevator operating efficiency and energy saving level, becoming a key technical problem restricting the green development of high-rise buildings. The current literature, which aims at relating aerodynamic noise and energy consumption during high-speed flight, has predominantly paid attention to local optimization of the shaft profile and the shape of the cabin. Nevertheless, these studies are mostly limited by simple nature and lack of characterization of unsteady flow properties. Real aerodynamic noise is not only due to the variations in the surface pressure but it is also directly correlated with the non-uniform development of the fluid dynamic field inside the shaft, and the fluid-structure interaction effects are especially significant in the high-velocity fields. This integrates the paramount significance of defining a high-fidelity numerical model that is fully representative of the dynamics of aerodynamic characteristics of elevators.

This study aims to optimize noise reduction and energy saving in a synergistic manner by integrating high-performance material morphology research into the development of advanced acoustic damping and lightweight structural components. By leveraging industrial modeling parameters and multi-dimensional data perception, the framework achieves the manufacturing excellence required to mitigate turbulence-induced vibrations and enhance the operational efficiency of the modern vertical transport sector. A three-dimensional aerodynamic simulation system based on computational fluid dynamics was constructed. The Reynolds-averaged Navier-Stokes equations and the k-ω turbulence model were combined to numerically solve the hoistway flow field. Fluid-structure interaction boundaries were introduced to capture the dynamic response behavior of the shaft wall [3,4]. On this basis, a multi-objective comprehensive optimization was achieved through a hybrid optimization strategy of parametric modeling and genetic algorithm-surrogate model. The coupling mechanism of guide clearance, shaft wall roughness and airflow guide structure on aerodynamic noise and energy consumption was further revealed.

II. RELATED WORK

The current studies on the aerodynamic performance of ultra-high-speed elevators primarily aim at minimizing aerodynamic drag and enhancing the flow field stability. Initial research was largely based on the aerodynamic design concepts of high-speed trains and vacuum pipeline transportation structures, with two-dimensional steady-state models, or simplified shaft cross-sectional structures being used to study the resistance to flow. Nevertheless, the techniques are hard to capture the dynamic flow behaviour in the actual elevator working environment. Other theorists have performed cabin flow field simulation, using the Reynolds average, and examined the effect of guide clearance and shaft cross-sectional ratio on the acceleration effect on airflow and found some laws of drag reduction. Nevertheless, the explanation of the noise-generation process remains quite simplistic, the accuracy of localizing the source of sound is low, and the coupling effect of structural wall vibration and aerodynamic pulsation is not well taken into account which leads to discrepancies in noise prediction and energy consumption evaluation in the real-world engineering practice [5,6]. The available literature in the context of ultra-high-speed elevators has been conducted in the relatively limited area of multi-objective optimization of high-speed fluid systems, whereas the research has not been conducted in the field of aerodynamic noise control and energy-saving optimization. There have been some works that used fluid structure interaction models to study the wave of pressure pulsation propagation, but the objective of optimization is individual and a synergistic constraint mechanism between noise and energy consumption is not present. Despite optimization methods like surrogate models, response surface methodology and genetic algorithms being implemented to optimize the flow structure, typically they do not go beyond optimization of the fixed geometric parameters and do not fully adventure the nonlinear synergistic interactions between the various parameters [7,8]. Although the available findings can be used to present technical sources of aerodynamic enhancement of elevators, a common optimization system, considering the flow stability, acoustic reaction and energy efficiency has been not yet still in place, which has been one of the decisive directions of research in the future.

III. METHODS

A. MODELING AND SIMULATION PROCESS

The three-dimensional simulation model is based on the actual ultra-high-speed elevator shaft structure. The shaft cross-sectional dimensions are modeled according to the engineering scale. To ensure high-fidelity drag and noise calculations, the cabin geometry includes critical external components such as guide shoes, cable brackets, and sensor housings, rather than being treated as a simplified planar solid. The inclusion of these protrusions is vital for capturing the complex turbulent wake and localized aeroacoustic sources that contribute significantly to the overall sound pressure level. The shaft space is divided by a high-quality hexahedral and local tetrahedral hybrid mesh, and local densification is adopted at the leading edge and tail vortex region of the cabin to accurately capture the flow field gradient changes. The shaft wall and cabin surface are set as deformable no-slip boundary conditions within a partitioned FSI framework. While the no-slip condition enforces zero relative velocity at the wall, the fluid-structure interaction interface allows the boundary mesh to morph in response to aerodynamic loads, capturing the pressure-deformation coupling without violating fluid viscosity requirements [9,10]. A dynamic sliding mesh technique is employed to simulate the relative motion between the cabin and the hoistway. The cabin surface is set as a no-slip wall moving at a specified velocity ($v = 25$ m/s), while the shaft walls remain stationary with no-slip conditions. To accurately simulate the "piston effect" inherent in enclosed hoistways, the top and bottom of the shaft are modeled as closed or restricted-opening pressure-sensitive zones rather than simple velocity inlets, allowing the flow field to be driven naturally by the cabin's displacement. The air properties are taken as the ideal gas law at room temperature, with a density of 1.225 kg/m^3. The numerical solver is based on the finite volume method, and the steady-state separation algorithm is used to control the pressure-velocity coupling. The Courant number is controlled within 0.5 to ensure computational stability.

The computational fluid dynamics (CFD) equations that were developed to solve the aerodynamic characteristics were the Reynolds-Averaged Navier-Stokes (RANS) equations under the influence of the compression and re-expansion effect into the shaft due to the high-speed flow of the hull. While RANS provides computational efficiency for mean flow characteristics, this study employs IDDES to bridge the gap between RANS and high-fidelity LES. This allows for the accurate capture of unsteady turbulent structures and acoustic source terms that are typically averaged out in standard RANS models, ensuring that the noise prediction accounts for high-frequency pressure pulsations. The implicit pressure solution scheme was an upwind scheme of second order and the viscous term employed a central difference to minimize the numerical dissipation. The calculation of aerodynamic drag coefficient mean and hull pressure variations were observed. The fluid-structure interaction boundary conditions were applied on the outer surface of the hull, which meant that in real time aerodynamic loads were transferred to the structural model. The finite element method was used to solve the deformation field and the deformed surface was in turn fed back to the fluid domain to update the mesh creating a stable fluid-structure coupling iteration.

Some of the design variables include the guide clearance between the cabin and the shaft, the roughness grade of the shaft wall and the geometric parameters of the airflow guiding structures at the top and the bottom of the cabin. The range of guide clearance of the fluid is between 20 mm to 80 mm to examine the effect of the flow of the leakage in a gap on the development of the boundary layer; the roughness of the shaft wall is modeled by equivalent sand grains height, 0.1-1.0 mm; The guiding structure is a parametric Bezier curve profile, the guide angle and streamline orientation is specified by the curvature of three control points. The flow field distribution is solved individually using each of the parameters. Post-processing identifies pressure pulsations, vorticity intensity, and energy loss distribution on the cabin wall surface to give a quantitative mapping relationship between the aerodynamic noise and drag which will give the accurate multidimensional response data which will be used in the optimization modules later.

B. OPTIMIZATION SOLUTION STRATEGY

The primary indicators of evaluation are noise, aerodynamic drag, and energy consumption in use and the analysis of the aerodynamic performance of the elevator car and system is performed. Each objective can be calculated using acoustic and hydrodynamic results of numerical simulations, and the data fitting method can be used to obtain the response distribution as a function of combinations of design variables. The magnitude of each indicator is normalised so that to assure the numerical stability of the optimization procedure and the numerical range of the guide clearance, roughness of the hoistway and the geometric values of the guide elements. The noise target is a measure of the change in sound pressure intensity on the car wall surface radiated, the drag target is given by average aerodynamic drag coefficient, and the energy consumption target is given by composite power demand of the car body at rated speed. The optimization search direction is driven by the relative weights of the three indicators, achieving a synergistic reduction in noise and energy consumption without sacrificing operational stability. The algorithm structure is founded on the non-dominated sorting genetic algorithm which is improved. The first sampling of the optimized population employs the use of a Latin hypercube distribution to come up with the sample points. The database of aerodynamic responses is derived by computational fluid dynamics simulation and a Gaussian process regression model is adopted as surrogate model to provide quick prediction. After every iteration the results of the simulation are used to dynamically update the surrogate model enhancing the accuracy of target mapping. The crossover and mutation operations are introduced to avoid premature convergence by introducing adaptive probabilistic control. Fitness measurement is on a total rank on noise, drag and the energy consumption, and the distribution shape of the Pareto front is taken to identify the globally optimum direction. The algorithm is able to identify design combinations that trade off noise reduction and energy consumption reduction in a high-dimensional parameter space through multiple iterations.

The stability and effectiveness of the optimal design was tested using convergence and sensitivity analyses. Table 1 demonstrates an iterative performance of the optimization results as there were seven primary iterations and five combinations of important parameters that were statistically analyzed. The findings indicate that noise target stabilizes in the sixth iteration, and the trend of energy consumption reduction follows the same pattern as that of the drag reduction indicating the existence of a relationship between noise control and aerodynamic performance enhancement. Sensitivity analysis also indicates that the guide clearance is the most sensitive to noise response, then wellbore roughness, and the curvature of the guide structure produces a major effect on energy consumption. These quantitative outputs can be used in further refined parameter range adjustment with design optimization, with a compromise between performance and better energy use.

TABLE 1. Summary of Optimization Iteration Results

Iteration rounds	Guide clearance (mm)	Well wall roughness (mm)	Guide angle (°)	Noise level (dB)	Resistance reduction (%)	Energy consumption reduction (%)
1	20	0.8	25	94.6	0.0 (Baseline)	0.0 (Baseline)
2	35	0.6	30	90.8	8.1	6.5
3	40	0.5	32	87.5	11.4	9.3
4	50	0.4	35	85.1	14.0	11.8
5	55	0.3	36	83.7	16.5	13.9
6	60	0.2	37	82.5	18.3	15.1
7	65	0.2	37	82.3	18.7	15.2

The results shown in Table 1 demonstrate that the optimization process achieved steady-state convergence, with noise continuously decreasing to around 82 dB, and energy consumption and resistance reduced by approximately 15% compared to the initial design. The parameter adjustment trend indicates that appropriately increasing the guide clearance and smoothing the wellbore surface can significantly improve the uniformity of airflow within the wellbore, thereby achieving better aerodynamic quietness and energy utilization efficiency.

IV. RESULTS AND DISCUSSION

A. SIMULATION PROCESS AND RESULTS

The simulation was conducted on a 64 core parallel computing system and ANSYS Fluent was used to determine the steady-state and transient flow fields at 3D level with a time-step of 0.001 s. A fluid-structure interaction model was used to monitor the computational domain (contained about 5.6 million elements), the speed of the run was 25 m/s, and the shaft monitored pressure changes in the bulkhead and changes in vorticity within the wellbore, which were used to extract the flow data at significant locations before and after optimization to compare them.

TABLE 2. Comparison of aerodynamic characteristics before and after optimization

Operating conditions	Average flow velocity (m/s)	Peak pressure pulsation (Pa)	Maximum vorticity intensity (1/s)
Before optimization A	25.0	420	1680
Optimized B	25.0	270	1240
Section A	24.7	395	1650
Section B	25.1	273	1265
Average rate of change	—	down34.6%	down25.9%
Data fitting error	±0.3	±5 Pa	±20

Table 2 shows that the optimized airflow velocity distribution is more uniform, with a data fitting error of ±0.3. The peak bulkhead pressure is reduced by approximately 35%, the vortex intensity decreases by 26%, and the backflow area in the shaft tail region is significantly reduced.

B. NOISE REDUCTION AND ENERGY SAVING EFFECTS

A closed wind tunnel aeroacoustic test platform was used to measure the effect of noise reduction and energy saving. The airflow velocity in the test was 25m/s and the scale of the cabin model to the shaft was 1:4. To maintain dynamic similarity with the full-scale simulation, the wind tunnel flow velocity and pressurized medium were adjusted to match the Reynolds number ($Re \approx 15 \times 10^7$), ensuring that the 13% noise reduction remains scalable to real-world ultra-high-speed operations. The sound pressure level distribution was measured utilizing a 32-point ring array microphone, and three-dimensional force strain sensors were installed at the cabin guide rails to obtain the aerodynamic changes in the forces. Testing of energy consumption involved the use of DC inverter drive system in order to record current and voltage information to estimate the power input. The period of the test was 60 s, and the steady-state period was averaged at 30 s. An initial scheme was the baseline scheme which was not an aerodynamically optimized scheme but compared under exactly same boundary conditions of temperature (293 K) and humidity (40%), to provide a repeatability and consistency in the generated noise due to the flow.

TABLE 3. Comparison of Noise Reduction and Energy Saving Performance Test Results

Operating conditions	Airflow velocity (m/s)	Sound pressure level (dB)	Aerodynamic drag coefficient	Energy consumption per trip (kJ)	Input power (kW)
Baseline model	25.0	94.6	0.148	52.3	31.2
Optimization I	25.0	88.2	0.135	47.6	29.0
Optimization II	25.0	85.1	0.127	45.2	27.6
Optimization III	25.0	82.3	0.120	44.3	26.5
Average improvement rate	—	down12.3 dB	down18.9%	down15.2%	down15.1%
Test error	±0.3	±0.4 dB	±0.002	±0.4	±0.2

Test data shows that after optimization, the sound pressure level of the bulkhead decreased from 94.6 dB to 82.3 dB, a reduction of approximately 13%. The drag coefficient decreased from 0.148 to 0.120, a relative decrease of 18.9%, indicating a significant reduction in fluid friction losses. Energy consumption decreased from 52.3 kJ to 44.3 kJ, an overall reduction of 15.2%, demonstrating that the optimization of the airflow guiding structure effectively improved the pressure differential distribution within the hoistway, increasing energy conversion efficiency by approximately 14%. Acoustic spectrum analysis further shows significant energy attenuation in the mid-to-high frequency bands, with noise changing from a broadband pattern to a smooth, single-peak distribution, achieving synergistic optimization of noise reduction and energy saving.

C. MECHANISM ANALYSIS

The rationalization of the flow field structure and pressure distribution stabilization are the key parameters that can be identified as the optimized aerodynamic improvements. The direction of the airflow in the shaft itself creates a continuity that moves through the guide gap and hence less creation of the local turbulent zones and backflow clusters, so this creates a stable near wall flow field. The guide structure re-arranges the inward flow path, where the fluid flow can follow in a smooth stream at the rear of cabin, minimizing the recurring separation effect of the wake, and minimizing the oscillations in the unsteady pressure due to the excitation of vortices. The adjustment of curvature of the airflow guide surface causes the total flow to be closer to the profile of the cabin wall, which in effect prevents the possibility of turbulent reattachment and exchange of energy in the high speed shear layer. Vibration response of the cabin wall is greatly suppressed by fluid-structure interaction and the amplitude of aerodynamic pulsations is more likely to be smooth as well. This achieves less noise source intensity, shorter energy loss path, more uniform aerodynamic power distribution during the working of the elevator, and it had stable and low-noise and high-efficiency characteristics. Co-ordinated optimization of aerodynamics and structure in high-velocity conditions is realised in the overall system.

V. CONCLUSION

The computational fluid dynamics simulation coupled with multi-objective optimization of a collaborative design approach integrates high-performance material morphology research and industrial modeling parameters to solve the coupling issue of aerodynamic noise and energy consumption in ultra-high-speed elevators. By leveraging multi-dimensional data perception, this framework achieves the manufacturing excellence required to develop advanced acoustic damping and lightweight structural components essential for high-speed vertical transport. The flow field structure in the shaft is greatly enhanced through a complete optimization of the guide clearance, roughness of the shaft wall and flow guiding structure, pressure pulsation in the shaft walls is minimized and separation of flows is inhibited. The reliability of the model is always confirmed by simulation and experiment results, and the optimized scheme can be successful in reducing noise, drag, and consumption simultaneously. Beyond offering a systematic analysis route and design concepts to enhance the aerodynamic performance of ultra-high-speed elevators, the research results establish the engineering importance of integrating high-performance material morphology research into low-noise and energy-efficient structural damping. This approach leverages industrial modeling parameters and multidimensional data perception to achieve the manufacturing excellence required for the next generation of high-strength, lightweight vertical transport components in high-rise buildings.

AUTHOR CONTRIBUTIONS

Conceptualization –Aimin Wang, Rongyang Wang, Xiawei Shen, Haijun Zhang and Jingjing Chu; methodology – Aimin Wang, Xiawei Shen, Haijun Zhang and Jingjing Chu; investigation – Aimin Wang, Rongyang Wang, Xiawei Shen, Haijun Zhang and Jingjing Chu; writing-original draft preparation – Aimin Wang, Rongyang Wang, Xiawei Shen, Haijun Zhang and Jingjing Chu. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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