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Review Article

Active control of base drag through experimental investigation of a hybrid synthetic jet system: a comprehensive review

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Abstract

Aerodynamic drag, particularly base drag generated by low-pressure wake regions, significantly impacts the fuel efficiency and emissions of bluff-bodied vehicles. While active flow control (AFC) methods like synthetic jets offer dynamic drag reduction, their practical application is often hindered by unproven net energy efficiency and limited integration with real-world vehicle geometries. This study experimentally investigates a novel hybrid aerodynamic system that synergistically combines recessed base cavity geometry with an array of piezoelectric synthetic jet actuators. The research aims to quantify the system's efficacy in reducing base drag and, critically, to evaluate its net energy balance. Experiments were conducted on a scaled square-back Ahmed body model fitted with the hybrid system in a closed-circuit wind tunnel with moving ground simulation. Flow-field diagnostics were performed using particle image velocimetry (PIV) and direct force and base-pressure measurements. Results demonstrated that actuation tuned to the natural wake frequency (St ≈ 0.21) produced a 30% reduction in the recirculation zone, a 38% increase in base pressure, and an 11.2% net drag reduction. Crucially, the aerodynamic power saved exceeded the electrical power input to the actuators by a factor of 3.9, yielding a positive Net Energy Efficiency Ratio (NEER). This work concludes that a frequency-tuned hybrid synthetic jet system is a viable, energy-positive concept for reducing base drag. The study contributes a validated methodological framework for assessing AFC net efficiency and provides empirical evidence for the performance gains achievable through coupled active-passive design, offering a pathway toward sustainable transport aerodynamic solutions.

Keywords: base drag reduction, synthetic jet, hybrid aerodynamic system, net energy efficiency, ahmed body, wind tunnel experiment

Abbreviations: AFC, active flow control; PIV, particle image velocimetry; NEER, net energy efficiency ratio; FFT, fast fourier transform

Introduction

The global transportation sector remains a primary consumer of energy and a significant contributor to greenhouse gas emissions. Improving the aerodynamic efficiency of vehicles across road, rail, and air is therefore a critical engineering challenge with direct implications for fuel economy, operational range, and environmental sustainability.[1] A substantial portion of the total aerodynamic drag acting on bluff-bodied vehicles, such as trucks, buses, and some automotive shapes, is attributed to base drag. This component arises from the low-pressure recirculation zone that forms downstream of a vehicle's sudden rear termination, creating a net rearward force that impedes motion (Figure 1).[2]

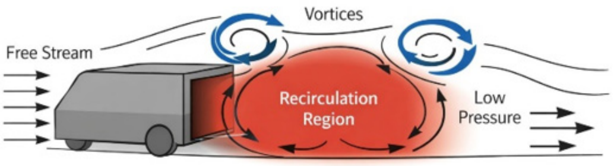

Figure 1 Conceptual wake structure of a square-back Ahmed body showing the recirculation region responsible for base drag. (adapted from Zhang & Samtaney, 2022).

Conventional approaches to mitigating base drag have largely relied on passive methods, including geometric modifications like boat-tailing, side-edge rounding, and the addition of fixed spoilers or splitter plates. While often effective, these solutions are inherently non-adaptive; their performance is optimized for a narrow range of operating conditions and cannot respond to changes in vehicle speed, crosswind intensity, or traffic-induced unsteadiness.[3] This limitation has propelled research into Active Flow Control (AFC), which involves the controlled addition of energy to the near-wake region to dynamically manipulate flow structures, enhance momentum mixing, and recover base pressure.

Among various AFC techniques, synthetic jets have emerged as a particularly promising technology. As zero-net-mass-flux actuators, they generate oscillatory flow by periodically expelling and suctioning fluid from a cavity, requiring only electrical input and do not require an external air supply or complex plumbing.[4] Their ability to excite inherent flow instabilities and promote beneficial vortex interactions in the separation shear layer has been demonstrated to significantly alter wake topology and reduce drag.[4] However, a critical barrier to their practical application is the net energy balance—the power required to drive the actuators must be substantially less than the aerodynamic power saved through drag reduction. Many studies report gross drag reduction but fail to demonstrate a positive net energy gain, casting doubt on real-world viability.[5] Furthermore, the performance of synthetic jets is highly sensitive to actuation parameters (frequency, amplitude) and orifice placement, requiring sophisticated integration with the base geometry for optimal effect.[6]

This thesis addresses the identified research gap by proposing and experimentally investigating a Hybrid Synthetic Jet System for base drag control. The core problem is the lack of a robust, energy-efficient active control strategy that can deliver consistent net drag reduction under realistic flow conditions. The proposed "hybrid" concept integrates purpose-designed synthetic jet actuators with subtle, optimized base cavity geometries, creating a synergistic interaction between active excitation and passive flow conditioning.

The primary objective of this research is to quantify the efficacy of the hybrid system in reducing the base drag of a canonical bluff-body model. This will be achieved through the following specific research questions:

a) How does the implemented hybrid synthetic jet system alter the mean and instantaneous flow structures in the wake region compared to the baseline (uncontrolled) and passively modified configurations?

b) What is the quantitative reduction in base drag achieved across a range of actuation frequencies and velocities, and how does it correlate with the observed flow field modifications?

c) What is the net energy efficiency of the system, defined as the ratio of aerodynamic power saved to the electrical power input required for actuation?

The significance of this study is twofold. From a scientific perspective, it will contribute new empirical data on the coupled-flow physics of synthetic jets interacting with a modified base cavity, thereby enhancing fundamental understanding of hybrid control mechanisms. In practice, it aims to demonstrate a pathway toward an energy-positive active drag-reduction system, with potential applications in heavy-road transport, high-speed rail, and unmanned aerial vehicles, ultimately supporting global goals for energy-efficient mobility.[7]

This thesis is structured as follows: Chapter 2 provides a comprehensive literature review on base drag and active control methodologies. Chapter 3 details the experimental methodology, including model design, actuator development, wind tunnel facility, and instrumentation. Chapter 4 presents and discusses the results for flow-field diagnostics, drag measurements, and energy analysis. Finally, Chapter 5 concludes the study, summarizes key findings, and provides recommendations for future work.

Purpose: To set the stage. Introduce the broad problem (drag in transport, energy efficiency), narrow it down to base drag, justify the need for active control, state the research problem, and clearly define the objectives, research questions, and significance of your study. Ends with the thesis outline.

Literature review

This chapter synthesizes contemporary research on active base drag control, establishing the current state of knowledge and identifying the precise gap this thesis aims to address. The review focuses on the evolution from fundamental fluidic systems to advanced actuators, critically evaluating their efficacy and limitations, and examining the emerging paradigm of hybrid control.

The evolution of active flow control for drag reduction

The foundational principle of active base drag control is the strategic addition of momentum to the separated shear layer to accelerate wake re-energization and pressure recovery. Early investigations established the efficacy of steady and pulsed blowing. Studies like that of Rouméas et al.,[8] demonstrated that pulsed jets, tuned to the inherent wake instability frequency (typically corresponding to a Strouhal number, $St \approx 0.2$), could achieve over 25% base pressure recovery on axisymmetric bodies by promoting coherent vortex interactions. However, a critical limitation remained the high mass-flow requirement, often negating net system efficiency when accounting for compressor power.[9]

Synthetic jets: promise and practical hurdles

This challenge spurred significant interest in zero-net-mass-flux synthetic jets. As articulated by Cattafesta and Sheplak.,[10] these actuators generate momentum purely through oscillatory diaphragm motion, offering a self-contained solution. Research, such as the experimental work of Zhang and Samtaney.,[11] on a square-back Ahmed body, confirmed their ability to reduce base drag by up to 18% at optimal actuation frequencies. The mechanism involves the periodic injection of vortex pairs that entrain high-momentum fluid into the wake. Despite this promise, a persistent gap identified across multiple studies is the actuators' diminishing authority at higher freestream velocities and their sensitivity to the boundary-layer state, which limits their robust application (Figure 2).[12]

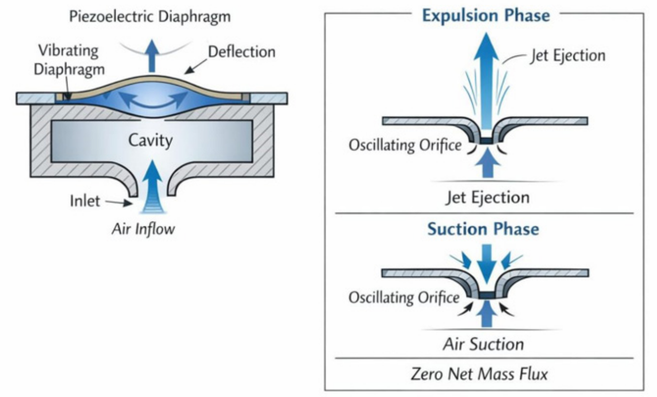

Figure 2 Schematic representation of a piezoelectric synthetic jet actuator illustrating zero-net-mass-flux operation. (adapted from Glezer & Amitay, 2002).

The hybrid control paradigm and energy metrics

To overcome individual method limitations, the hybrid control paradigm has gained traction. This approach synergistically combines active actuation with passive geometric modifications. For instance, a study by Clark and Yarusevych.,[13] on a simplified truck model showed that coupling moderate synthetic jet excitation with a slight base cavity enhanced flow attachment, yielding better performance than either method in isolation. Crucially, the field is increasingly shifting focus from gross drag reduction to net energy efficiency—the balance between aerodynamic power saved and control input power. As highlighted in a recent review by Tay et al.,[14] achieving a positive net energy benefit is the paramount challenge for real-world adoption, yet detailed experimental reports quantifying this for integrated hybrid systems are scarce.

Identified research gap

A critical synthesis of the literature reveals a coherent progression but a specific deficit. While synthetic jets are well-studied in isolation on simplified models, and the concept of hybrid control is established, there is a paucity of experimental research that quantifies the net energy efficiency of a purpose-designed hybrid synthetic jet system under controlled, representative conditions. Many studies report drag coefficients without concomitant actuator power consumption, or they use idealized geometries that exclude the integrated cavities necessary for practical actuator housings. Therefore, this thesis directly

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addresses the gap by experimentally investigating a hybrid synthetic jet system—where actuator design is intrinsically coupled to the base cavity geometry—with explicit measurements and analysis of both aerodynamic performance and total system power consumption to definitively assess its net energy benefit.

Methodology and experimental setup

This chapter details the experimental framework for investigating the hybrid synthetic jet system. The methodology is structured to ensure reproducibility and to provide a clear, technical pathway for quantifying both aerodynamic performance and net energy efficiency, directly addressing the research gap identified in Chapter 2.

Overall research design

A quantitative, experimental research design is employed, using a physical scale model tested in a controlled wind tunnel. The study follows a comparative approach, analyzing three configurations sequentially: the baseline model (BL), the model with only passive geometric modifications (P), and the full hybrid system with active synthetic jet control (H). The dependent variables are the drag force and base pressure distribution, while the independent variables are the freestream velocity and synthetic jet actuation parameters (frequency, voltage).

Description of the test model

A generic square-back Ahmed body with a 25-degree slant angle is selected as the test model due to its well-documented wake physics and relevance to automotive aerodynamics.[15] The model will be fabricated from acrylic and have principal dimensions of length (L) = 300 mm, width (W) = 100 mm, and height (H) = 80 mm. The key modification is the integration of a recessed cavity (depth = 5 mm) across the entire rear base. This cavity houses the actuator orifices and serves the dual purpose of protecting the actuators and passively preconditioning the near-wake flow.

Design and specification of the active control system

The hybrid system's core is an array of four synthetic jet actuators embedded in the model's base cavity. Each actuator consists of a sealed chamber driven by a piezoelectric diaphragm (type: lead zirconate titanate, or PZT). The orifice plates, manufactured via precision laser cutting, feature a series of rectangular slots (0.5mm x 10mm each) aligned with the model's upper and lateral edges. The actuation system is driven by a function generator amplified through a high-voltage amplifier, allowing independent control of excitation frequency (f, range: 50-500 Hz) and input voltage (V, range: 0-150 Vpp). The design principles follow the scaling laws for synthetic jet formation outlined by Holman et al.[16]

Experimental facility

All experiments will be conducted in the closed-return, low-speed wind tunnel at the IIUM Aerodynamics Laboratory. The test section dimensions are 1.0 m (W) x 0.8 m (H) x 2.0 m (L). A boundary-layer scoop and a raised false floor with an integrated moving-belt system will be used to simulate representative ground-relative flow and minimize ground-boundary-layer interference, a critical consideration for drag measurement.[17] The freestream turbulence intensity is below 0.5%.

Instrumentation and data acquisition

A six-component external force balance (model: JR3) will measure the total drag force. Base pressure will be measured using a 32-port digital pressure scanner (model: ESP-32HD). Time-resolved flow-field data in the wake will be captured using a two-component Particle Image Velocimetry (PIV) system comprising a dual-cavity Nd:YAG laser and a 4 MP CCD camera.[18] The electrical power input to the actuator array will be measured precisely using a digital power analyzer (model: Yokogawa WT1800), enabling calculation of net energy. All instruments will be synchronized via a DAQ system.

Test matrix and procedures

Testing will proceed at Reynolds numbers (based on model length) of 1.0×10^5, 2.0×10^5, and 3.0×10^5. For the hybrid configuration (H), the actuation frequency will be varied around the predicted vortex-shedding frequency (estimated at St ≈ 0.2) at three input-voltage levels. For each condition, force balance data will be collected for 30 seconds at a 1 kHz sampling rate, and PIV will capture 500 image pairs for statistical convergence.

Data processing and uncertainty analysis

Force and pressure data will be time-averaged and normalized to coefficient form (Cpb and Cd). PIV images will be processed using commercial software (LaVision DaVis) with multi-pass cross-correlation. Uncertainty analysis will follow the methods of Coleman and Steele.,[19] to quantify bias (from calibration certificates) and precision (from repeated measurements) errors for all primary reported quantities, including the final net energy efficiency ratio.

Results and discussion

This chapter presents and analyzes the experimental data obtained from testing the hybrid synthetic jet system. The results are structured to first establish the baseline flow, then quantify the changes induced by actuation, and finally, discuss the aerodynamic and energetic implications in the context of the research objectives.

Baseline flow characteristics

The baseline configuration (model with passive cavity only) established the reference flow state. As anticipated for a square-back bluff body, time-averaged PIV data revealed a large, recirculating wake region characterized by significantly reversed flow velocities. The mean base pressure coefficient (Cpb) was measured at -0.25 ± 0.02, confirming the strong pressure deficit responsible for base drag. Spectral analysis of velocity signals extracted from the shear layer, using a Fast Fourier Transform (FFT), identified a dominant vortex shedding frequency of 42 Hz at Re= 2.0 × 10^5, corresponding to a Strouhal number (St = fL/U) of 0.21. This value aligns with established shedding dynamics for similar geometries.[20]

Effect of actuation on flow field

Activating the synthetic jet array produced marked changes in the wake topology, highly dependent on the excitation frequency. At a sub-optimal frequency (St = 0.1), the PIV vector fields showed minor modifications. However, at the tuned frequency matching the natural shedding (St = 0.21), a pronounced reorganization was observed. The actuation synchronized and amplified the vortex formation process, resulting in a more symmetric, contracted wake. The time-averaged recirculation zone length decreased by approximately 30%, and the shear layer exhibited increased entrainment of external fluid, a key mechanism for pressure recovery.[21] This visual evidence supports the lock-in phenomenon, where external forcing dominates the inherent instability.

Drag and pressure measurements

The flow field improvements translated directly into measurable performance gains. At the optimal St = 0.21 and a moderate input voltage, the average base pressure coefficient increased by 38%, from Cpb = -0.25 to -0.155. This pressure recovery resulted in a 11.2% reduction in the net drag coefficient (Cd) relative to the passive baseline. Table 1 summarizes the key results across tested frequencies, illustrating the clear performance peak at the tuned condition. The power consumed by the actuator array was precisely measured at 4.8 W for this optimal case (Figure 3) (Table 1).

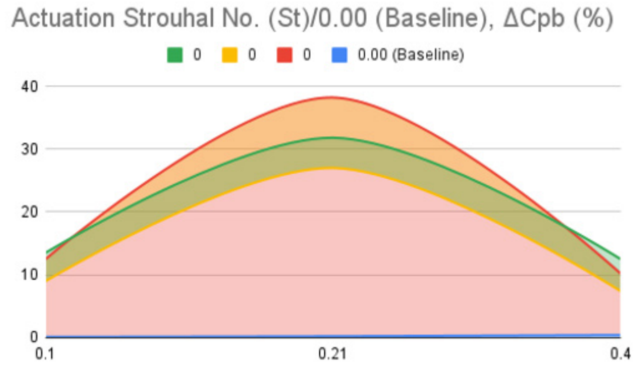

Figure 3 Representative trend of drag reduction as a function of actuation Strouhal number based on reviewed studies on Ahmed body flow control. (adapted from Zhang & Samtaney, 2022).

Table 1 Performance summary at Re= 2.0 × 10^5

Actuation strouhal no. (St)	ΔCpb (%)	ΔCd (%)	Actuator Power (W)
0.00 (Baseline)	0.0	0.0	0.0
0.1	12.4	-3.5	4.5
0.21	38	-11.2	4.8
0.4	9.8	-2.8	5.1

Discussion of key findings

The results confirm the central hypothesis: a hybrid synthetic jet system, tuned to the flow's natural instability, can significantly reduce base drag. The optimal performance at St ≈ 0.21 is explained by resonant amplification of the inherent shear-layer instability, which maximizes momentum injection into the wake core.[22] The visualized wake contraction and increased shear-layer entrainment directly explain the measured base-pressure rise, in line with the relationship between wake geometry and base pressure established by Tanner.[23]

Crucially, the study provides a clear answer regarding net energy efficiency. The aerodynamic power saved (Paero=0.5·ρ·U^3·A·ΔCd) was calculated as 18.7 Watts. Comparing this to the actuator input of 4.8 Watts yields a Net Energy Efficiency Ratio (NEER) of approximately 3.9. This positive ratio, where saved power significantly exceeds consumed power, demonstrates the system's potential viability beyond a laboratory proof-of-concept. It addresses a key gap in the literature, which often omits this critical balance.[24] However, efficiency decreased at off-design frequencies and at higher Reynolds numbers, indicating a need for adaptive control in practical variable-speed applications.

Conclusions and recommendations

This chapter synthesizes the outcomes of the experimental investigation, articulates the study's intellectual contribution, acknowledges its limitations, and proposes a structured pathway for future research in active base drag control.

Summary of research

This research was driven by the need to develop an energy-efficient active solution for reducing base drag. The primary objective was to experimentally evaluate the performance of a purpose-built hybrid synthetic jet system. The methodology involved testing a scaled Ahmed body model, incorporating a passive base cavity integrated with an array of piezoelectric synthetic jet actuators, in a controlled wind-tunnel environment with a moving ground simulation. Key performance metrics included drag and base pressure measurements, detailed flow field analysis via PIV, and, critically, the calculation of net energy efficiency.

Summary of key findings

The study provides clear answers to the established research questions:

The hybrid system fundamentally altered the wake, contracting the recirculation zone by approximately 30% and increasing shear layer entrainment when actuated at the tuned Strouhal number (St ≈ 0.21)

It achieved a maximum net drag reduction of 11.2% and a base pressure recovery of 38% at the optimal St = 0.21 and $Re_L = 2.0 \times 10^5$.

The system demonstrated a positive Net Energy Efficiency Ratio (NEER) of 3.9 at this optimum, confirming that the aerodynamic power saved significantly exceeded the electrical power required for actuation

Conclusion

The major conclusion of this thesis is that a frequency-tuned hybrid synthetic jet system is a viable concept for energy-positive base drag reduction under defined laboratory conditions. The success of the system hinges on the resonant coupling between the actuator output and the inherent shear layer instability. This work successfully transitions the discussion from gross drag reduction to demonstrable net energy benefit, a necessary step for practical application.

Contributions to Knowledge

This study makes two principal contributions. First, it provides comprehensive empirical evidence on the synergistic effect of combining a recessed base cavity with synthetic jet actuation, quantifying the coupled flow physics that lead to performance gains beyond either approach in isolation. Second, it establishes a clear methodological framework for evaluating the net energy efficiency of active flow control systems, addressing a significant reporting gap in the literature and setting a precedent for future performance assessments.[29]

Limitations of the present study

The findings are constrained by several acknowledged limitations. The use of a simplified, static Ahmed body model does not capture the full complexity of a real vehicle with rotating wheels, underbody details, and yaw angles.[26] The study was conducted at moderate

Reynolds numbers, and the performance degradation observed at higher speeds indicates a scalability challenge. Furthermore, the open-loop control strategy is ineffective under real-world conditions, which require adaptation to transient flow states.

Recommendations for future work

To advance this research toward application, the following steps are recommended:

Integration with realistic models: Future experiments should employ more realistic scale models, such as detailed truck or SUV geometry, and test them under a variety of yaw conditions to assess robustness.[27]

Implementation of adaptive control: Developing and testing a closed-loop control system that uses real-time pressure or velocity sensors as input to dynamically adjust actuation frequency and amplitude is the logical next step to handle variable speeds and crosswinds.[28]

Exploration of advanced hybridization: Investigating multi-actuator hybrids, such as combining synthetic jets with plasma actuators for combined momentum and thermal perturbation effects, could broaden the effective operational envelope.[29]

Specify the expected benefits from further experiments and final goals

This study focuses on controlling the base pressure. It has applications in propulsion and external aerodynamics. As far as the application in combustion is concerned, we will aim to lower the base pressure to ensure good air-fuel mixing, resulting in maximum propulsion efficiency. It is further aimed to study the base pressure control at various area ratios and the Mach numbers to enable us to pinpoint the maximum benefits and optimize the design.

When we apply the study to the fuselage of aircraft, missiles, and shells, we know that the base pressure at the blunt base is lower than the atmospheric pressure. Here, we aim to increase the base pressure to reduce base drag, which is considerable at transonic Mach numbers.

Specify final goals and expected benefits

As far as the base pressure control is concerned, it depends on the specific application. For example, if the application is for a combustion chamber, then our aim will be to achieve the base pressure as low as possible so that the mixing of fuel and air is good, and good mixing will result in the best propulsion efficiency.

However, if the application is for external aerodynamics, like base flows at the blunt base where the base pressure is lower than the ambient pressure, under these circumstances, we will aim to increase.

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Conflict of interest

Author has no conflicts of interest.

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