SURFACE ROUGHNESS EFFECTS ON SLENDER BODY AERODYNAMICS: A REVIEW FOR SCALED ROCKET APPLICATIONS

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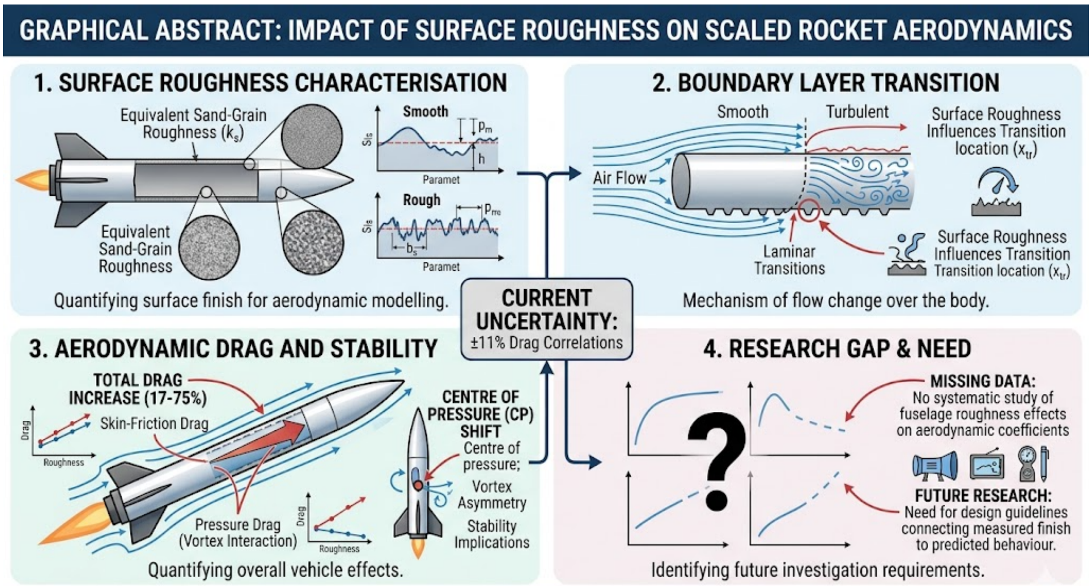
GRAPHICAL ABSTRACT



ABSTRACT

Surface roughness on rocket fuselage bodies has long been recognised as a factor in aerodynamic performance, yet how it specifically affects scaled rocket configurations is still not well understood. This paper reviews recent research on surface roughness effects in slender body aerodynamics, with a particular focus on scaled model rockets flying in the subsonic regime. The review covers four key areas: surface roughness characterisation and the equivalent sand-grain roughness; boundary layer transition mechanisms on cylindrical and slender bodies; quantitative drag and stability effects on complete vehicles; and how fuselage roughness influences centre of pressure and downstream flow behaviour. The findings show that roughness effects on slender bodies go well beyond skin-friction drag, modifying vortex asymmetry, control transition location, and alter the wake, all of which have stability implications. Current drag correlations carry ±11% uncertainty, and complete vehicle studies report drag increases of 17–75% for typical manufacturing roughness levels. Despite this body of work, a clear gap remains: no systematic study has isolated fuselage roughness effects on scaled rocket aerodynamic coefficients across a representative subsonic Mach and angle-of-attack envelope. This review lays the theoretical groundwork for such an investigation and highlights the need for design guidelines that connect measured surface finish to predicted aerodynamic behaviour in model rocketry.

KEYWORDS

surface roughness; slender body aerodynamics; scaled rocket, boundary layer transition; drag prediction; equivalent sand-grain roughness

INTRODUCTION

Surface roughness plays a bigger role in rocket aerodynamics than is often appreciated. It shapes the boundary layer characteristics that ultimately determine drag, stability, and transition behaviour. Because solid rocket motors used in research rely on a range of construction materials and manufacturing processes, they end up with quite different surface finishes and that makes accurate aerodynamic predictions difficult. Recent work has shown that surface imperfections interact with the boundary layer in complex ways: they can trigger early transition from laminar to turbulent flow, change the skin friction distribution, and shift overall vehicle stability.

These roughness effects become especially important in scaled model testing, where the Reynolds number mismatch between model and full-scale vehicles tends to amplify surface-related phenomena. Model rocket fuselages range from smooth polished composites to rough fibre-reinforced plastics, with arithmetic mean roughness (Ra) values spanning from less than 1 µm to over 100 µm depending on the material and fabrication technique. How these surface conditions affect boundary layer development, transition location, and the resulting aerodynamic coefficients is still not well characterised, particularly for the subsonic flight regimes that model rockets fly in.

This review synthesises recent research on surface roughness effects relevant to slender body aerodynamics and scaled rocket applications. The goal is to build the theoretical foundation for a CFD-based investigation of fuselage roughness effects on scaled rocket aerodynamic performance, and to pin down the specific research gap that such a study would fill. Section 2 covers surface roughness fundamentals and boundary layer transition mechanisms. Section 3 looks at drag and stability effects on fuselage surfaces and complete vehicles. Section 4 discusses research methods and surface characterisation techniques. Section 5 pulls the findings together and identifies the research gap that the authors' ongoing work aims to address.

2. SURFACE ROUGHNESS FUNDAMENTALS AND BOUNDARY LAYER TRANSITION

2.1 Surface Roughness Characterisation

Surface roughness characterisation requires standardised parameters that capture the geometric features influencing fluid flow. The arithmetic mean roughness (Ra) represents the average absolute deviation from the mean surface line, providing a basic measure of surface texture. However, aerodynamic applications typically employ the equivalent sand-grain roughness height (ks), introduced by Nikuradse's seminal pipe flow experiments, which relates actual surface topography to the hydraulic roughness of uniform sand grains producing equivalent flow resistance [4]. Table 1 summarises the common surface roughness parameters used in aerodynamic analysis.

Surface roughness classification further distinguishes between k-type (sand grain) and d-type (groove) roughness based on the mechanism of drag generation. K-type roughness, characterised by isolated protrusions, generates form drag through pressure differences around individual elements. D-type roughness, featuring closely spaced grooves or cavities, primarily increases drag through modified turbulent stress distributions. For fuselage bodies, manufacturing-induced roughness typically exhibits k-type characteristics, making this classification particularly relevant for rocket [4, 9].

The dimensionless roughness height $ks+ = ks\, u\tau / \nu$ characterises the roughness regime, where $u\tau$ is the friction velocity and ν is the kinematic viscosity. Flow is classified as hydraulically smooth when $ks+ < 5$, transitionally rough when $5 < ks+ < 70$, and fully rough when $ks+ > 70$. This dimensionless framework enables direct comparison of roughness effects across different Reynolds numbers and flow regimes, which is essential for correlating scaled model data with full-scale vehicle performance.

Table 1: Common surface roughness parameters and their definitions.

Parameter	Symbol	Definition
Arithmetic mean roughness	Ra	Average absolute deviation from mean surface line
Root mean square roughness	Rq	Root mean square of surface deviations

Parameter	Symbol	Definition
Maximum peak-to-valley height	Rz	Average of five highest peaks and five lowest valleys
Equivalent sand-grain roughness	ks	Height of uniform sand grains producing equivalent flow resistance

2.2 Boundary Layer Development and Transition Mechanisms

Surface roughness fundamentally alters boundary layer development through multiple mechanisms. The comprehensive review by [13] established that roughness elements perturb velocity profiles, increase turbulent mixing, and modify the Reynolds stress distribution throughout the boundary layer. These effects extend beyond the immediate roughness sublayer, influencing the outer layer structure according to Townsend's outer-layer similarity hypothesis. Within the roughness sublayer, flow patterns depend strongly on element geometry and spacing, with hairpin vortices and counter-rotating streamwise vortices forming in element wakes and subsequently destabilising the shear layer [16].

Boundary layer transition from laminar to turbulent flow on fuselage bodies is particularly consequential. Unlike airfoils where pressure gradients dominate transition behaviour, cylindrical fuselage sections experience relatively mild pressure gradients, making surface roughness a primary transition trigger. NASA's comprehensive analysis spanning subsonic to hypersonic Mach numbers established that roughness plays both beneficial and adverse roles in transition control, depending on the application and implementation approach [2]. Studies have demonstrated that roughness heights as small as 0.32 mm can trigger transition on cone-cylinder configurations at subsonic speeds [7].

Review by [17] synthesised decades of research on high-speed boundary layer artificial transition, highlighting that surface roughness effectively fixes transition location, producing more predictable aerodynamic behaviour at the cost of increased turbulent skin friction over the affected region. Direct numerical simulation by [6] examined boundary layers adjusting from smooth to rough surfaces at Mach 0.3 and Mach 2, revealing that the adjustment process involves complex interactions between pressure gradient effects and turbulent stress redistribution — findings directly applicable to fuselage surfaces downstream of smooth nose cone regions.

3. Drag and Stability Effects of Fuselage Roughness

3.1 Skin Friction and Drag on Slender Bodies

The fuselage body contributes the largest skin-friction drag component for rocket configurations due to its extensive wetted area. NASA Langley studies established that skin friction constitutes approximately 50% of the drag budget for long-haul transport aircraft fuselages, with surface roughness significantly affecting this component [11]. For rocket fuselages with similar length-to-diameter ratios, comparable skin-friction contributions are expected. CFD analysis of rocket configurations has demonstrated methodologies for calculating skin-friction contributions from body surfaces, with studies on 122 mm rocket configurations showing that wetted area and surface conditions strongly influence drag predictions [1]. This is particularly significant for scaled model rockets, whose high length-to-diameter ratios and predominantly cylindrical bodies make the fuselage the dominant wetted surface; at the lower Reynolds numbers of sub-scale flight, where a longer laminar run is possible, the influence of surface finish on where and how that skin-friction drag develops is correspondingly greater.

Predicting drag for rough fuselage surfaces remains challenging despite decades of research. The Annual Review by [4] documented that state-of-the-art correlations exhibit scatter of approximately ±11% when predicting roughness effects on drag. For developing flows characteristic of fuselage bodies, the friction coefficient depends on both the roughness Reynolds number (ks/x) and the local Reynolds number (Rex), creating additional complexity compared to fully developed channel flows.

3.2 Quantitative Effects on Complete Vehicles

Recent investigations have quantified roughness effects on complete aerospace vehicles with particular attention to body surface contributions. Analysis of sand-grain roughness effects on the X-33 reusable launch vehicle configuration demonstrated drag increments between 17% and 75% depending on roughness thickness, with operations spanning transonic to supersonic Mach [10]. Notably, that study found that fuselage roughness dominated the overall drag increment.

Although the X-33 operates well above the subsonic envelope of interest here, the finding that the fuselage governs the overall roughness sensitivity is the key result for scaled rockets: it is precisely this fuselage-dominated behaviour, on bodies of comparable slenderness, that motivates isolating the fuselage contribution rather than treating the vehicle as a whole. Wind tunnel experiments on transonic aircraft at ONERA facilities demonstrated that even sub-micron surface roughness (Ra ~ 0.5 µm) significantly affects aerodynamic coefficients at Mach numbers up to 0.95 [14]. While that study concerns an aircraft rather than a slender rocket body, the relevant lesson is the demonstrated sensitivity of the aerodynamic coefficients to very small roughness heights at Mach numbers up to 0.95 — a range that overlaps the upper bound (M = 0.8) of the scaled-rocket regime considered here, indicating that surface finish cannot be neglected even at the modest roughness levels of well-finished models.

Flow control applications have also demonstrated that riblet-type surface modifications on missile bodies can achieve a 2.4% decrease in total drag coefficient and 3.4% reduction in surface friction [3], suggesting that controlled surface roughness represents a viable drag-management strategy rather than being purely detrimental. Of the configurations reviewed above, the missile body is the closest geometric analogue to a scaled rocket fuselage, so this result is the most directly transferable: it indicates that, for slender rocket bodies, surface texture can be exploited as a deliberate drag-management measure rather than merely tolerated as a manufacturing artefact. Table 2 summarises representative quantitative roughness effects from the recent literature.

Table 2: Summary of roughness effects on drag from recent literature.

Source	Configuration	Roughness Range	Drag Effect
[10]	X-33 RLV	Variable ks	17–75% drag increase
[14]	Transonic aircraft	Ra ~ 0.5 µm	Significant CD change
[3]	Missile body	Riblet surface	2.4% drag reduction
[18]	Slender body	0.8–100 µm	Modified flow asymmetry

3.3 Stability Implications and Centre of Pressure

Slender fuselage bodies develop asymmetric vortex patterns at high angles of attack, producing lateral forces that affect vehicle stability. Detached-eddy simulation studies demonstrated that surface roughness modifies these asymmetric vortex phenomena, with roughness levels from 0.8 to 100 µm producing measurable changes in flow asymmetry [18]. The adverse pressure gradient increases with roughness, affecting vortex development on the leeward side of the fuselage. Numerical investigation of cone-cylinder configurations by [7] further revealed that roughness-induced transition significantly reduces global lateral forces by promoting more symmetric vortex development, suggesting that controlled fuselage roughness could improve stability robustness.

Rocket stability depends on the relative positions of the centre of pressure (Xcp) and centre of gravity (Xcg), with the static margin SM = (Xcp − Xcg) / d determining response to disturbances. Surface roughness on the fuselage affects the pressure distribution along the body, potentially shifting Xcp. Modified boundary layer development also changes the effective body shape seen by the outer flow, altering normal force distributions. For scaled model testing, ensuring representative roughness characteristics on the fuselage is therefore essential for obtaining stability derivatives applicable to full-scale vehicles [12].

4. Research Methods for Roughness Investigation

Numerical simulation of roughness effects on fuselage bodies employs various turbulence modelling approaches with different fidelity and computational cost. Reynolds-Averaged Navier–Stokes (RANS) methods with transition models including Transition SST have been applied to predict roughness-induced transition on cylindrical bodies, though calibration against experimental data remains essential [7]. The k-ε realisable model has demonstrated capability for complete vehicle analysis including body roughness effects [10], while the k-ω SST model has proven particularly effective for boundary layer flows with adverse pressure gradients.

Higher-fidelity approaches including Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) resolve turbulent structures directly, capturing roughness effects with greater physical accuracy. DNS studies have established benchmark data for roughness effects at Mach 2 and 4, enabling validation of lower-fidelity methods [5]. Semi-empirical tools such as RASAero II provide rapid aerodynamic prediction capability incorporating surface texture effects on drag and stability coefficients [19], making them suitable for preliminary design iteration.

On the experimental side, wind tunnel testing provides essential validation data. Force and moment measurements using strain-gauge balances quantify integrated roughness effects on drag, lift, and stability derivatives. Surface pressure measurements reveal underlying pressure distribution changes, while flow visualisation techniques characterise boundary layer behaviour on rough fuselage surfaces [14,15]. Additive manufacturing has emerged as a key fabrication method for scaled rocket models, introducing characteristic surface roughness that depends on build parameters [8], further motivating systematic investigation of how build-induced roughness translates to aerodynamic performance.

5. Synthesis and Identified Research Gap

5.1 Key Findings from the Literature

Synthesising the reviewed work, a consistent physical chain emerges that links surface condition to vehicle-level behaviour. The foundation, established by the boundary layer studies of Section 2, is that surface roughness fundamentally alters boundary layer development on cylindrical bodies, perturbing the velocity profile, generating hairpin and streamwise vortices within the roughness sublayer, and redistributing turbulent stresses [13, 16]. Because the mild pressure gradients along a cylindrical fuselage leave roughness as the primary transition trigger [2], the most immediate consequence is a forward shift in transition location, fixing the boundary layer in a turbulent state earlier along the body [7, 17].

This earlier transition feeds directly into the drag behaviour reviewed in Section 3. A larger turbulent run raises skin-friction drag over the fuselage, the dominant wetted surface, and the difficulty of predicting this increment is reflected in the ±11% scatter that still characterises state-of-the-art roughness–drag correlations for developing flows [4]. At the complete-vehicle level the sensitivity is substantial, reported drag increments of 17–75% for representative manufacturing roughness, with the fuselage consistently identified as the dominant contributor, confirm that the body surface, not the nose cone or fins, sets the overall roughness sensitivity of slender configurations [10].

The same roughness-induced changes propagate beyond drag into stability. By altering the pressure distribution and the effective body shape seen by the outer flow, fuselage roughness shifts the centre of pressure and modifies the normal-force distribution, thereby changing the static margin that governs a rocket's response to disturbances [12]. At higher angles of attack this is expressed through the asymmetric leeward vortex system, where roughness has been shown both to modify lateral forces and, in some cases, to promote more symmetric vortex development and improved stability robustness [7, 18]. Taken together, these findings establish that roughness on slender bodies cannot be treated as a skin-friction correction alone: a single surface condition simultaneously governs transition location, drag magnitude, centre-of-pressure shift, and stability — precisely the coupling that a scaled-rocket investigation must capture.

5.2 Research Gap

While extensive research has characterised roughness effects on drag, boundary layer transition, and heat transfer for various aerodynamic configurations, systematic investigation of fuselage body roughness effects on scaled rocket aerodynamic performance is notably absent from the literature. Existing studies have focused either on idealised geometries (flat plates, cones, infinite cylinders) or on complete vehicles without isolating the fuselage contribution from nose cone and fin effects.
Table 3 summarises what the reviewed literature has and has not addressed, mapped against the specific needs of scaled rocket aerodynamic prediction. The contrast makes the gap concrete and identifies the axes along which the proposed CFD investigation will contribute.

Table 3: Research gap mapping: literature coverage versus scaled rocket requirements.

Topic	Literature scope	Gap
Roughness characterisation	Flat plates, pipe flows, infinite cylinders [4, 9, 13]	Finite-length rocket fuselage bodies at subsonic Re
Boundary layer transition	Cone-cylinders, hypersonic vehicles, high-speed flows [2, 7, 17]	Transition on cylindrical fuselages at M = 0.5–0.8
Drag prediction	Complete vehicles (X-33, transonic aircraft) without	Fuselage-only drag increment

	fuselage isolation [10, 14]	vs. ks for scaled rockets
Stability and Xcp	High-AoA vortex asymmetry on generic slender bodies [18]	Xcp shift as a function of fuselage roughness at low AoA
CFD methodology	RANS validation on cones, flat plates, missile bodies [7, 10]	RANS with roughness model applied to full scaled rocket geometry

This gap matters most for scaled model applications, where the Reynolds number mismatch between model and full-scale vehicles tends to amplify roughness-related phenomena. Getting a clear picture of how fuselage surface roughness affects aerodynamic performance at model-scale conditions is key to translating wind tunnel or sub-scale flight test results into full-scale predictions, and to giving amateur and educational rocketry programmes practical manufacturing specifications they can work with. A focused CFD investigation at two representative subsonic Mach numbers (M = 0.5 and 0.8) and two angles of attack (α = 0° and 4°, the latter chosen to remain below half the stall angle for this class of slender body), with roughness levels spanning polished (ks ≈ 0.5 µm), painted (ks ≈ 60 µm), and unfinished (ks ≈ 150 µm) surface conditions, would directly address this gap.

6. Conclusion

This review has brought together recent research on surface roughness effects relevant to slender body aerodynamics and scaled rocket applications. The equivalent sand-grain roughness framework gives us a solid theoretical basis for translating measured surface parameters into aerodynamic predictions, though considerable uncertainty persists in the correlations, especially for developing flows on finite-length cylindrical bodies. What comes through consistently in the literature is that roughness effects go beyond skin friction: they also influence transition control, vortex asymmetry, and centre-of-pressure location, all of which bear directly on scaled rocket stability.

The main research gap is the lack of systematic, fuselage-isolated roughness studies on scaled rocket configurations within a subsonic envelope relevant to amateur and educational rocketry. A CFD-based investigation using the k-ω SST turbulence model with sand-grain roughness modification, applied to a representative rocket geometry featuring a Von Kármán nose cone and trapezoidal fin configuration, is the natural next step. The methodology and detailed CFD setup for this investigation are presented in a companion paper by the authors.

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