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AERO-STRUCTURAL MODELING AND PREDICTION OF TRANSONIC SHOCK-BUFFET LOADS ON AN F-16 WING

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Buffet refers to unsteady aeromechanic phenomena in which flow instabilities over lifting surfaces generate oscillatory forces that can degrade handling qualities and structural integrity. Although buffet originates from the flow, its characteristic frequencies often overlap the aircraft's natural structural modes, potentially amplifying dynamic loads through aeroelastic resonance. As a result, buffet is a major design and certification challenge in flight-envelope expansion, structural substantiation, and fatigue-life assessment for both commercial and fighter aircraft

The current study focuses on transonic, or shock buffet, characterized by self-sustained shock oscillations arising over a range of Mach numbers and moderate angles of attack due to shock boundary layer interaction. The phenomenon has been extensively investigated numerically [1–11] and experimentally [12–22] since the 1980s. Most studies examined 2D airfoils and simple wing–fuselage configurations to clarify the governing flow physics, validate computational and experimental methods, and develop buffet-mitigation strategies. For commercial aircraft, transonic buffet is particularly important because it limits the usable flight envelope.

Shock-buffet studies on fighter jets are very limited in the public domain and primarily involve instrumented flight test measurements [23–31]. Fifth-generation fighters typically operate at a wide angle of attack range within the transonic flow regime and therefore are more prone to encounter buffet conditions. The F-35 is an example of a fighter platform that exhibits multiple buffet phenomena, including transonic wing buffet, which had a significant impact on its structural design and certification processes [32]. Traditional rigid-model wind-tunnel tests do not capture aeroelastic effects, and CFD predictions remain challenging for the complex flows and geometries of fighter aircraft with external stores, making reliable buffet-load models available only at later design stages. These limitations underscore the need for improved understanding and efficient assessment strategies for transonic buffet in fighter aircraft.

This study is conducted as part of multi-year effort by the Israeli Air Force (IAF) to develop and validate a buffet-load prediction capability aimed at enhancing fighter aircraft external store certification processes. In earlier work [33], the authors conducted wind-tunnel experiments on a rigid F-16 scale model with several external store configurations to characterize the transonic shock-buffet phenomenon. The unsteady surface-pressure measurements collected in that study enabled mapping of the buffet envelope and identification of dominant frequencies associated with shock motion and flow separation. The results also showed that external stores influence the buffet boundaries but have only a limited effect on the dominant buffet frequency, and the findings were consistent with available F-16 flight-test data.

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1 WORK DESCRIPTION

In this paper, a coupled aero-structural modeling framework is developed to integrate experimentally derived unsteady aerodynamic forces with a structural dynamic model of the F-16 wing. The methodology reconstructs time-domain buffet forces and computes the resulting wing loads, enabling a detailed evaluation of how unsteady pressure fluctuations associated with shock motion interact with the wing's vibration modes. The total dynamic load acting on the wing is represented as a combination of inertial loads, buffet-induced loads, and unsteady aerodynamic loads, allowing a clear assessment of their respective contributions to the structural response.

Several external store configurations, consistent with those tested in the wind-tunnel campaign, are analyzed to investigate how configuration changes influence the magnitude and spanwise distribution of buffet-induced loads. Loads are computed at multiple locations along the wing to capture variations in structural response and to identify potential load-amplification mechanisms associated with transonic buffet.

By combining reconstructed unsteady aerodynamic pressures with the structural dynamic characteristics of the F-16 wing, the framework provides predictive capability that rigid wind-tunnel models alone cannot offer. The resulting buffet-induced load predictions are validated through comparisons with available F-16 flight-test measurements and wind-tunnel results, demonstrating the applicability and accuracy of the approach for realistic fighter aircraft configurations. This integrated methodology offers a quantitative and experimentally informed tool for predicting structural response under buffet excitation and supports the development of improved buffet-load assessment strategies for fighter aircraft wings.

2 AERO-STRUCTURAL COUPLED MODEL

The structural response to buffet excitation is computed using a coupled aero-structural model governed by

$$[\mathbf{M}]\,\{\ddot{\mathbf{x}}(t)\} + [\mathbf{C}]\,\{\dot{\mathbf{x}}(t)\} + [\mathbf{K}]\,\{\mathbf{x}(t)\} = \{\mathbf{F}_a(t)\} + \{\mathbf{F}_b(t)\}, \tag{1}$$

where $\{\mathbf{F}_b(t)\}$ denotes the buffet-induced unsteady aerodynamic forces reconstructed from the wind-tunnel measurements, and $\{\mathbf{F}_a(t)\}$ represents the unsteady aerodynamic forces associated with elastic motion. Applying the modal transformation

$$\{\mathbf{x}(t)\} = [\mathbf{\Phi}]\,\{\mathbf{q}(t)\}, \tag{2}$$

yields the generalized modal form

$$[\mathbf{GM}]\,\{\ddot{\mathbf{q}}(t)\} + [\mathbf{GC}]\,\{\dot{\mathbf{q}}(t)\} + [\mathbf{GK}]\,\{\mathbf{q}(t)\} = \{\mathbf{GF}_a(t)\} + \{\mathbf{GF}_b(t)\}, \tag{3}$$

where the generalized matrices are defined as:

$$[\mathbf{GM}] = [\mathbf{\Phi}]^T[\mathbf{M}][\mathbf{\Phi}] \quad \text{and} \quad [\mathbf{GK}] = [\mathbf{\Phi}]^T[\mathbf{K}][\mathbf{\Phi}]. \tag{4}$$

The generalized aerodynamic and buffet-induced force vectors are given by:

$$\{\mathbf{GF}_a\} = [\mathbf{\Phi}]^T\{\mathbf{F}_a\} \quad \text{and} \quad \{\mathbf{GF}_b\} = [\mathbf{\Phi}]^T\{\mathbf{F}_b\}. \tag{5}$$

The equations are solved in the frequency domain using the discrete Fourier transform (DFT), and the inverse DFT reconstructs the time-domain modal displacement, velocity, and acceleration vectors.

The structural loads are evaluated using the summation-of-forces (SOF) method, expressed as

$$\{\mathbf{L}_{\mathrm{tot}}(t)\} = \{\mathbf{L}_{\mathrm{int}}(t)\} + \{\mathbf{L}_a(t)\} + \{\mathbf{L}_b(t)\}, \tag{6}$$

where the inertial load is given by

$$\{\mathbf{L}_{\mathrm{int}}(t)\} = -[\mathbf{M}]\,\{\ddot{\mathbf{x}}(t)\}, \tag{7}$$

$\{\mathbf{L}_a(t)\}$ is the unsteady aerodynamic load reconstructed from the generalized aerodynamic forces, and $\{\mathbf{L}_b(t)\}$ denotes the buffet-induced load.

This aero-structural coupled model enables direct computation of buffet-induced wing loads and provides a quantitative basis for assessing the structural response under buffet excitation.

3 PRELIMINARY RESULTS

Preliminary results are presented for the unloaded-wing configuration with empty launchers and pylons at a free-stream Mach number of 0.85. Figure 1 shows the RMS distribution of the unsteady surface-pressure coefficient over the upper wing surface as computed based on experimental data. The blue line indicates the wing outline, and the red markers denote the pressure-sensor locations used for the two-dimensional interpolation of the pressure field. The RMS map, computed at $\alpha = 10.5°$, highlights regions of intensified pressure fluctuations associated with shock motion and flow separation/reattachment during the buffet cycle. Figure 2 presents the frequency content of the unsteady pressure measured by sensor No. 14 across a range of angles of attack, based on a continuous one-dimensional wavelet transform. A broadband spectral region centered around a reduced frequency of approximately 3.5 is observed, representing the dominant signature of the shock-buffet phenomenon. The reduced frequency is defined as:

$$\bar{f} = 2\pi f c / U_\infty \tag{8}$$

where f is the dimensional frequency, c is the chord length and U_∞ is the free-stream velocity. Figure 3 shows the power spectral density (PSD) of the computed structural loads, represented here by the F_z component at the wing root. The red dashed lines denote the aircraft's reduced natural frequencies. The PSD exhibits distinct peaks at several of these frequencies, along with broadband amplification near the buffet reduced frequency identified in Fig. 2. This behavior reflects the structural response to buffet-induced excitation and motivates the full investigation to be presented in the complete paper.

The full paper will present the complete aero-structural buffet-load model, a detailed evaluation of the structural response and wing loads under buffet excitation, and comparisons both with available F-16 flight-test data and across different external-store configurations.

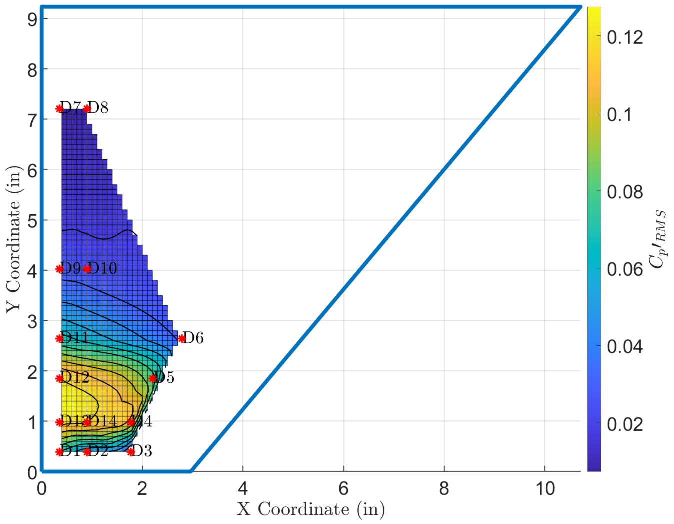

Figure 1: Surface-pressure coefficient RMS levels at $\alpha = 10.5°$ and Mach 0.85 under developed buffet

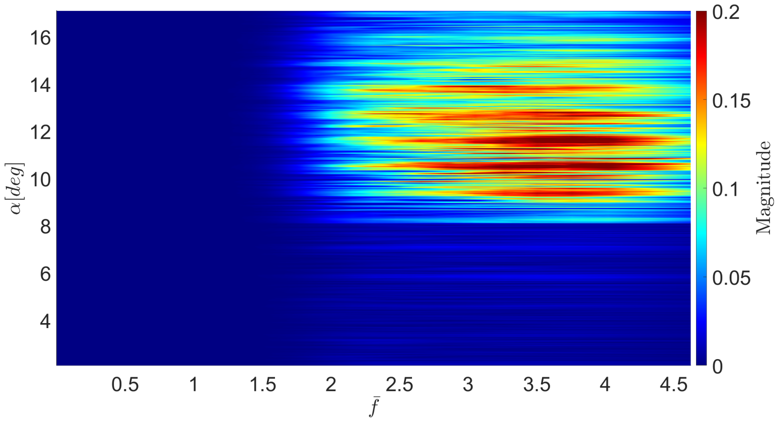

Figure 2: Continuous 1-D wavelet analysis at Mach 0.85 across varying angle of attack

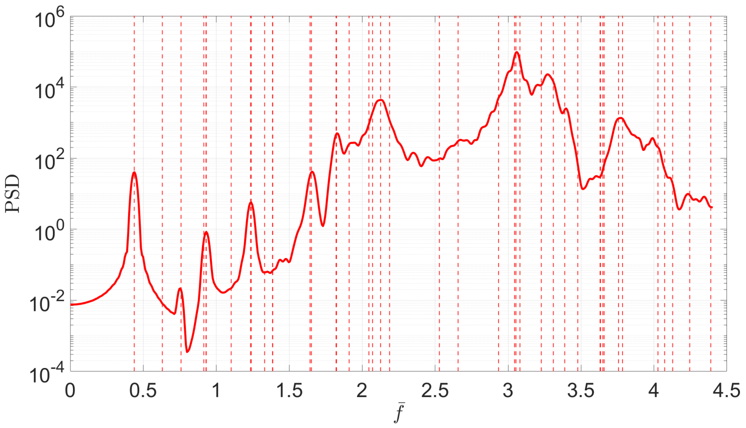

Figure 3: PSD of the wing-root structural load F_z at Mach 0.85

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