Empirical Predication of Fluctuating Pressure Environments Around a Rocket Fairing

Rui Zhao, Jili Rong
School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China

Zhaohong Qin, Haibo Li
Science and Technology on Reliability and Environment Engineering Laboratory, Beijing Institute of Structure and Environment Engineering, Beijing, China

ABSTRACT: When transonic flow passes the fairing shoulder, it gets separated and interacted with shock waves, resulting in a server fluctuation-pressure level and lower frequency vibration. The flow structures generating the buffet environment are found unsteady and interacted with each other through large-eddy simulation method. The space-correlation corrections are then introduced into the classical empirical functions with predication accuracy largely improved. Also, the entropy function is employed to denote the boundary-layer region, in order to accurately identify the input parameters at the layer edge. Finally, a standard workflow of empirical prediction of fluctuating pressure environment is recommended.

1 INTRODUCTION

During flight through the atmosphere, the external surface of the rocket fairing will be exposed to high intensity acoustic and fluctuating pressure environments. These buffet environments will be critical to the design and success of the complete rocket system. When buffet occurs on a launch vehicle, the fluctuating pressure loads can excite vehicle bending modes and local shell/panel modes, even lead to launch failures (Rainey 1965). The buffet environment is typically most extreme in the transonic regime as the vehicle approaches the speed of sound (Piatak et al. 2012, 2015). At this point in the trajectory, shocks form on the vehicle and interact with other phenomena at locations where changes in the vehicles geometry occur, as Figure 1 shows.

Definition of the environments is necessary, therefore, in order to insure structural integrity, reliability and economic operational requirements of the rocket. In order to arrive at an optimized rocket system, accurate definition of the critical transonic acoustic environments which will be encountered during rocket flight is required at the earliest possible time during the development stage. Recently, unsteady computational fluid dynamics (CFD) techniques like large eddy simulation (LES) and direct numerical simulation (DNS) have been developing; however, it is still difficult to apply them directly to high Reynolds number flow fields. Besides, experimental buffet pressure techniques in the wind tunnel are deemed too costly to obtain a refined spatial resolution, let alone the flight tests (Kazuyuki et al. 2012). Therefore, empirical model for fluctuating pressures based upon wind tunnel and flight data is still the effective method for engineering applications. However, the classical empirical formulas are proposed based on the statistical observations with limited predication accuracy. For the past forty years, encouraging improvements of empirical functions have been rarely reported in the published literatures since NASA proposed a set of standard formulas in 1973 (Plotkin & Robertson 1973).

In the present work, the transonic buffet mechanism around a generic rocket fairing was investigated with LES method in Section 2. Based on the unsteady simulation results, the potential deficiencies of the classical empirical functions were discussed, and corresponding space-correlation corrections were introduced in Section 3. Section 4 presents a standard workflow of the empirical
predication of the transonic fluctuating pressure environments around the same rocket fairing model. The entropy function which is used to denote the boundary-layer region was emphasized. Section 5 was dedicated to the summary of the research.

2 LARGE-EDDY SIMULATION PROCEDURE

2.1 Numerical method

The governing equations describing the flowfield are the Favre-filtered Navier-Stokes equations.

\[
\frac{\partial \bar{p}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{p} \bar{u}_i) = 0
\]

(1)

\[
\frac{\partial}{\partial t} (\bar{p} \bar{u}_i) + \frac{\partial}{\partial x_j} (\bar{p} \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}
\]

(2)

\[
\frac{\partial \bar{p}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{p} \bar{u}_i \bar{e}) = \frac{\partial}{\partial x_j} (-\bar{u}_i \bar{p} + \bar{u}_j \tau_{ij} + q_i)
\]

(3)

Restrictions on the equations include the perfect gas assumption, constant specific heats, and the Sutherland viscosity law. For the discretization of the inviscid terms, the 5th order WENO scheme (Nichols et al. 2008) is employed. For the viscous terms, 4th order accurate central finite differencing scheme (Shen et al. 2008) is adopted. Second-order accuracy is obtained in the temporal discretization via dual-time stepping with sub-iterative procedure. As no explicit subgrid model is adopted, this method is a kind of implicit large-eddy simulation (Boris et al. 1992).

2.2 Numerical fairing model

A rocket fairing model was generated as the work of Seiji & Ryoji (2012), which has a generic cone-cylinder geometry with wind tunnel data (Fig.2).

![Figure 2. Geometry of the rocket fairing model.](image)

The inflow Mach number is 0.8, and the attack angle is 0°. The Reynolds number based on the diameter of the cylinder is 2.66×10^6. The distance of the first grid line to the wall is 10^-5 which corresponds to a y⁺ less than 1.0. Grid refinement was localized to the cone-cylinder junction region. After grid resolutions study, a mesh comprised of 3.64 million cells for 1/4 model was utilized for LES calculation, shown in Figure 3.

![Figure 3. Grid topology for the rocket fairing.](image)

Confidence of the LES method employed in this work could be confirmed in the following comparisons (Figs 3-4). Excellent agreements are obtained with the experimental data (Seiji & Ryoji 2012), both in terms of magnitude and overall trend. Also, this method shows superiority over the improved delayed detached eddy simulation (IDDES) with 11 million cells employed by Seiji & Ryoji (2012).

![Figure 4. Comparison of root-mean-square (RMS) pressure coefficient C_{p, rms} distributions along the axi-direction.](image)

![Figure 5. Comparisons of mean streamwise velocity profiles after the reattachment.](image)

2.3 Instantaneous results

The transonic flow is accelerated to the supersonic speed and forms an expansion fan over the cone-cylinder junction. Then, the flow must quickly decelerate to the freestream velocity, which results in a separation shock. Due to the adverse pressure gradient caused by the shock, the flow may get separated near the junction. After the separation bubble, the turbulent flow is fully developed with a comparatively thicker boundary-layer (Figure 6). Previous empirical functions assume the above flow features are isolated in space (Plotkin & Robertson...
The flow around the fairing can be subdivided into discrete aerodynamic flow regions, i.e. attached turbulent boundary-layer, shocks, and separation bubble. Each region has an independent buffet condition, defined by its own root-mean square (RMS) pressure, autospectrum and cross-spectrum (Yang & Wilby 2008). Figure 7 shows the time-series snapshots of numerical schlieren at the central plane, also the separation region on the wall. When the flow passed the cone-cylinder junction, a λ-type shock wave is formed and flow separation appears. The acoustic wave is radiated due to the breakdown of the separated shear layer and propagates upstream. The upstream propagating acoustic wave interacts with the separation shock wave and regenerates an instability. Focusing on Figure 7a-d, the former leg of the λ-type shock moves back and forth. When the former leg is at its most upstream position ($x=260\text{mm}$), the boundary-layer is separated from the foot of the shock. As the former leg starts moving downstream, the flow reattaches. When it reaches its most downstream position ($x=270\text{mm}$), the boundary-layer undergoes a progressive thickening until it separates and the former leg starts moving back upstream. Moreover, the interspace between the junction and the shocks is also changing, which means the flow after the expansion fan accelerates and decelerates intensely in time and space.

3 IMPROVEMENT OF EMPIRICAL FORMULA

From the discussions above, the flow structures generating the fluctuating wall pressure are varying in time and space, and also interacting with each other. However, the previous empirical functions are described entirely in terms of local-flow features, which maybe the essential defect to predict the transonic buffet environment. In this research, we are attempting to introduce the space-correlation information, and to develop simple modifications (within the limitations of the algebraic formation) that could improve the overall buffet prediction. The character length scale adopted here is the separation bubble length $L_{sep}$, the critical locations are the separation point $x_s$ and reattachment point $x_r$. These parameters could be identified from the sign alterations of skin friction coefficient $C_f$ along the axi-direction. The flow regions are also redefined, accounting for the effect of interaction and spatial disturbance.

① Attached turbulent boundary-layer. Pressure fluctuations arise from the intermittent eruptions of the viscous sublayer (Laganelli & Martellucci 1983). The empirical function is the same as before.

$$C_{p_{rms}} = \frac{0.006}{1+0.14Ma^2}$$

(4)

② Expansion fan/shocks/separation bubble interaction. Pressure fluctuations arise from the significant flow acceleration and deceleration by shocks in a relatively short distance, and also from the movement of separation point. This interaction causes the first “peak” in the $C_{p_{rms}}$ profile shown in Figure 4, which whereas was simply considered as spurious by Seiji T & Ryoji (2012). The empirical function is developed to account for the above space-correlation and recommended to be employed in the region between the junction $x_j$ and the separation point $x_s$ ($x_j - x_s$).

$$C_{p_{rms}} = \frac{0.09}{1+Ma_j^2(x)}e^{\frac{x_s-x_j}{\lambda}} + \frac{0.045}{1+Ma_r^2(x)}\left(1-e^{\frac{x_s-x_j}{\lambda}}\right)$$

(5)

③ Shocks/separation bubble overlying effect. From the LES result, the separation λ-type shocks traverse around the first half of the separation bubble. The $C_{p_{rms}}$ is increased, leading to a “plateau” in the profile gradually. The empirical function accounts for the overlying effect by the unsteady shocks and the underneath separated shear layer, which is recommended to be employed in the first half of the separation bubble ($x_s - x_s + L_{sep}/2$).

$$C_{p_{rms}} = \frac{0.045}{1+Ma_j^2(x)}e^{\frac{x_s-x_j}{0.5L_{sep}}} + \frac{0.06}{1+Ma_r^2(x)}\left(1-e^{\frac{x_s-x_j}{0.5L_{sep}}}\right)$$

(6)

④ Separation disturbance. From the LES result, the acoustic wave is also radiated downstream due to
the breakdown of the separated shear layer. The empirical function is developed to account for the space-correlation, which is recommended to be employed in the rest of the separation bubble and the next one separation length \((x_i + L_{sep}/2 - x_i + L_{sep})\).

\[
C_{p,\text{rms}} = \frac{0.045}{1 + Ma_c^2} \left[ e^{\frac{x_i - 0.5L_{sep}}{1.5L_{sep}}} + 0.006 \frac{1 - e^{\frac{x_i - 0.5L_{sep}}{1.5L_{sep}}}}{1 + 0.14Ma_c^2(x)} \right]
\]

\[\text{(7)}\]

In view of Equations (4)-(7), \(Ma_c\) is the Mach number at the local boundary-layer edge. With a steady CFD calculation, the unknown parameters, i.e. \(x_{st}, x_{r}, L_{sep}, C_f\) and \(Ma_c\), could be determined. However, the traditional concept of the boundary-layer, which defines the edge where the velocity is recovered to 99% or 95% of the freestream, fell in a dilemma where the separation bubble or the shock exist. Zhao et al. (2014) proposed an entropy function \(f_s\), which could reliably denote the turbulent boundary-layer from the point of energy dissipation.

\[
f_s = 1.0 - \tanh\left(\frac{x_{se}}{l_s}\right)
\]

\[\text{(8)}\]

where \(x_{se}\) is the entropy increment ratio, indicating the viscous dissipation rate of per unit mechanic energy.

\[
\frac{\Delta x_{se}}{x_{se}} = \frac{\Delta x}{\Delta x_{max}} = \frac{\Phi}{\Phi + \alpha \psi} \times \frac{\Delta T}{\Delta x_{max}}
\]

\[\text{(9)}\]

\(\Delta T = c_t \ln \left[ \frac{\rho}{\rho_{\infty}} \right] \); \(k = \mu \rho R (\gamma - 1) Pr\) is the thermal conductivity, \(c_t = R(\gamma - 1)\) is the specific heat at constant volume, \(\mu\) is the molecular viscosity, \(\mu_t\) is the turbulent viscosity, \(R\) is the gas constant, \(\gamma = 1.4\) is the specific heat ratio, and \(T\), \(p\) and \(\rho\) are the local temperature, pressure and density, respectively, subscript \(\infty\) means the quantity in the far field.

\(l_s\) is the length-scale ratio, which is designed to be less than 1.0 in the boundary-layer and increase quickly in the external flows. We construct \(l_s\) following the spirit of DES97 (Spalart et al. 1997) but with minor revision:

\[
l_s = \left\{ \begin{array}{ll}
C_s f(a_1, a_2) d / C_{DES}^2 & \text{if } \frac{\Delta x_{se}}{x_{se}} > 0.05 \\
d / C_{DES}^2 & \text{otherwise}
\end{array} \right.
\]

\[\text{(10)}\]

in which \(C_s = 0.12\) is an empirical constant, \(f(a_1, a_2)\) is an anisotropic function recommended by Scotti et al. (1993), \(d\) is the distance normal to the wall, \(C_{DES} = 0.65\) and \(A\) is the grid spacing defined by \(A = \max(\Delta x, \Delta y, \Delta z)\).

The performance of the proposed empirical functions is evaluated. Shown in Figure 9, the proposed functions take into account the influence of the expansion fan at the junction, predicting the first peak at \(x = 240\)mm successfully. Also, by including the interaction and space disturbance effect, the results of the proposed functions are compared well with experimental data, especially at the locations after the reattachment point.

\[
\begin{array}{c}
\text{Empirical Result}\quad \text{(Kolbe)} \quad \text{Exp. (PID)} \\
\text{Empirical functions (Pliskin \& Robertson 1973)} \quad \text{Empirical functions with space-correlation}
\end{array}
\]

\[\text{Figure 9. Comparisons of empirical results at the junction.}\]

5 CONCLUSIONS

The buffet environment is typically most serious in the transonic regime due to the complex flow phenomenon around the fairing body. Based on the instantaneous LES results, the flow structures, i.e. shocks, separation bubble, and turbulent boundary-layer, were found to be varied in time and space, and also interacted with each other.

Therefore, the space-correlation corrections were introduced into the empirical functions for the first
time. The prediction accuracy of the empirical functions was improved remarkably without adding much complexity. Although a standard workflow of the empirical formulas was presented, further improvement should focus on the effects of attack angles and flow Mach numbers.

6 ACKNOWLEDGEMENT

The research is supported by the National Natural Science Foundation of China (11402024), Civil Aerospace Technology Advanced Research Project and Excellent Young Scholars Research Fund of Beijing Institute of Technology.

REFERENCES