Journal of Fluids and Structures 58 (2015) 216–235

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

# Response of skin panels to combined self- and boundary layer-induced fluctuating pressure

Rohit Deshmukh [a], Adam J. Culler [b], Brent A. Miller [a], Jack J. McNamara [a,*]

[a] Mechanical & Aerospace Engineering, The Ohio State University, E440 Scott Laboratory, 201. W 19th Ave., Columbus, OH 43210, USA
[b] Air Force Research Laboratory, Wright-Patterson AFB, OH 45433, USA

ARTICLE INFO

*Article history:*
Received 18 August 2015
Accepted 20 August 2015
Available online 20 September 2015

*Keywords:*
Panel flutter
Fluid–thermal–structural interaction
Aerothermoelasticity
Turbulence

ABSTRACT

Fluctuating pressures are a critical consideration in the life-prediction of thin-gauge hot-structures operating in high-speed flow. Sources include both boundary layer turbulence and self-induced components, where the latter arises from panel vibrations. While a considerable body of research is available for the structural response of thin-gauge panels to self-induced pressure fluctuations, the response to boundary layer turbulence is not well-understood due to the complexity in modeling the loads. Important open issues are the degree of coupling between the boundary layer induced fluctuating loads and the thermo-structural response, and also the potential for interactions between a turbulent boundary layer and structural response to result in structural instabilities. This study seeks to address these issues by incorporating a phenomenological model for turbulent boundary layer loads into an aerothermoelastic framework. The enhanced aero-thermoelastic model is then used to study the combined effect of self- and boundary layer-induced fluctuating pressures on responses of simple panels, and to characterize features in the turbulent boundary layer loads that can lead to large amplitude structural vibrations. The developed phenomenological model predicts that the magnitude of the boundary layer induced fluctuating pressure increases with increasing panel inclination, and decreases with increasing temperature. Furthermore, it is found that both RMS magnitude and phase angle of the boundary layer induced pressure loads play key roles in panel response. Certain combinations of these features, coupled with the self-induced pressure fluctuations, are found to cause onset of fluid–structural instabilities earlier than observed when pressure fluctuations from the turbulent boundary layer are either neglected or decoupled from the panel response.



## 1. Introduction

Accurate response prediction, and by extension life assessment, of high-performance aerospace structures is critical for responsive and sustained flight at high-speed (i.e., Mach 3 or higher). However, the current state-of-the-art is not sufficient to meet this need (Blevins et al., 1993; Liguore and Tzong, 2011; Zuchowski et al., 2011). For example, thin-gauge, hot-structure surface panels are highly desirable for weight reduction and serviceability. However, such structures are

* Corresponding author. Tel.: +1 614 292 6778.
*E-mail address:* mcnamara.190@osu.edu (J.J. McNamara).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.08.008
0889-9746/

**Nomenclature**

| | |
|---|---|
| $b$ | compressibility exponent |
| $c$ | specific heat of panel |
| $E$ | modulus of elasticity |
| $f$ | magnitude, generalized load |
| $F_c$ | compressible flow transformation function |
| $h$ | panel thickness (2.5 mm) |
| $H$ | enthalpy |
| $k$ | thermal conductivity |
| $k'$ | parameter representing compressibility and heat transfer effects |
| $L$ | length of the panel (1 m) |
| $M$ | Mach number |
| $m$ | viscosity power law exponent, $\eta/\eta_e = (T/T_e)^m$ |
| $N$ | number of time instant values for time variant TBL fluctuating pressure load (256) |
| $n$ | velocity power law exponent, $U/U_e = (y/\delta)^{(1/n)}$ |
| $p$ | pressure |
| Pr | Prandtl number |
| $p_{ref}$ | reference pressure (20 μPa) |
| $\tilde{p}$ | RMS fluctuating pressure |
| $q$ | $\rho U^2/2$, dynamic pressure |
| $Q_{aero}$ | aerodynamic heat flux |
| $Q_{rad}$ | radiation heat flux |
| $r$ | $\mathrm{Pr}^{1/3}$, turbulent flow recovery factor |
| $t$ | time |
| $T$ | temperature |
| $t_{max}$ | duration of time domain signal |
| $s$ | time delay |
| $U$ | velocity, air |
| $w$ | transverse panel displacement |
| $x$ | chordwise coordinate |
| $x_{ref}$ | reference location on the panel about which the space–time correlation is evaluated |
| $Y$ | Fourier domain signal |
| $y$ | normal distance into boundary layer from wall |
| $y_t$ | time domain signal |
| $z$ | coordinate in the direction perpendicular to the panel surface |
| $\alpha$ | thermal expansion coefficient |
| $\beta$ | shock angle |
| $\gamma$ | ratio of specific heats |
| $\Delta$ | incremental change |
| $\delta$ | boundary layer thickness |
| $\delta_1$ | boundary layer displacement thickness |
| $\epsilon$ | parameter to evaluate spatial phase angle |
| $\zeta$ | separation distance of two points on the panel |
| $\eta$ | viscosity |
| $\Theta$ | overall phase angle |
| $\theta$ | wedge angle |
| $\lambda$ | viscous/velocity power law exponent |
| $\nu$ | Poisson's ratio |
| $\rho$ | density |
| $\rho_P$ | density of panel |
| $\tau$ | temporal phase angle |
| $\phi(\omega)$ | power spectral density |
| $\psi$ | spatial phase angle |
| $\omega$ | frequency (rad/s) |
| $\omega_{max}$ | maximum frequency of TBL fluctuating pressure load considered |

*Subscripts*

| | |
|---|---|
| $a$ | attached flow |
| $AE$ | aeroelastic |
| $AT$ | aerothermal |
| $aw$ | adiabatic wall |
| $e$ | edge of boundary layer |
| $TBL$ | Turbulent Boundary Layer |
| $w$ | wall |
| $\infty$ | freestream |

*Superscripts*

| | |
|---|---|
| $*$ | reference enthalpy condition |

inherently compliant, and must withstand both intense aerodynamic heating and fluctuating pressure loads from multiple sources. This leads to: a propensity for nonlinear fluid–structural interactions; a continually evolving structural state; and hierarchical, systemic uncertainties. Furthermore, fully understanding and accounting for these complexities are challenging since: the flight conditions cannot be adequately replicated in ground based facilities; comprehensive flight testing is impractical; and tightly integrated computational analysis, using state-of-the-art tools in all the relevant disciplines, is intractable (Blevins et al., 1993; Liguore and Tzong, 2011; Zuchowski et al., 2011; McNamara and Friedmann, 2011; Culler and McNamara, 2010, 2011; Wieting et al., 1991; Bertin and Cummings, 2003; Dugundji and Calligeros, 1962; Miller et al., 2011; Ostoich et al., 2012; Crowell et al., 2011). Thus, basic research is needed in order to identify the relevant physics, and develop tractable multi-disciplinary models for structural lifting.

One important capability is structural fatigue prediction due to strong fluctuating pressures. In particular, self-induced fluctuating pressures, due to fluid–structure interaction between a vibrating surface panel and the mean flow, can lead to panel flutter (Culler and McNamara, 2010; Mei et al., 1999; McNamara and Friedmann, 2011; Dowell, 1970). Alternatively, forced pressure fluctuations, due to either engine excitation noise or boundary layer turbulence (Spottswood et al., 2010, 2009; Gordon and Hollkamp, 2009; Blevins et al., 1993; Hollkamp et al., 2008; Liguore and Tzong, 2011; Zuchowski et al., 2011), are a concern since they are continually present for long duration. Historically, the structural behavior to these different sources has been considered separately. In the first class of problems, the quasi-static panel response (Kontinos, 1997; Culler et al., 2009), and dynamic instabilities (McNamara et al., 2005; Mei et al., 1999; Culler et al., 2009) due to self-induced fluctuating pressures have been studied. Whereas, in the second class of problems the forced structural response