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Metallic Thermal-Protection-System Panel Flutter Study

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Panel flutter of a metallic thermal protection system (TPS) for a reusable launch vehicle is investigated. The study covers both panel flutter analysis tool development as well as an analysis of a specific metallic TPS configuration for the X-33 experimental vehicle. An analytical tool was developed to predict panel flutter at hypersonic flow conditions and at arbitrary flow angles to a structural panel. The nonlinear, hypersonic aerodynamic terms were found to have an insignificant effect on the panel flutter predictions for the X-33 TPS. The honeycomb sandwich that comprises most of the outer surface of the X-33 TPS panel was found to have large margins of safety for panel flutter for all flight conditions. However, the outer overlapping, panel-to-panel seals were predicted to be susceptible to panel flutter when nearly parallel to the flow.

Nomenclature

$[A]$	=	aerodynamic force matrix, lb/in.
$[A_e]_y$	=	aerodynamic matrix with yaw angle, lb/in.
a	=	plate reference length, in.
D	=	plate bending stiffness, in.-lb
$[G]$	=	aerodynamic damping matrix, lbm
g_a	=	aerodynamic damping
h	=	panel thickness, in.
$[K]$	=	structural stiffness matrix, lb/in.
$[M]$	=	mass matrix, lbm
M_∞	=	flight Mach number
q	=	flight dynamic pressure, lb/in.^{2} or psf
$\{\boldsymbol{q}\}$	=	modal eigenvector
V	=	flight speed, in./s
$\{\boldsymbol{W}\}$	=	displacement vector, in.
x, y, ξ, η	=	coordinates, in.
κ	=	complex eigenvalue
Λ	=	flow yaw angle, rad
ρ	=	air density, lbm/in.^{3}
$\{\phi\}$	=	eigenvector
Ω	=	complex frequency, 1/s
ω	=	frequency, 1/s

Introduction

METALLIC thermal protection systems[1] (TPS) are being studied as a potentially more robust, lower maintenance alternative to the existing reusable ceramic TPS for future reusable launch vehicles (RLVs). Metallic TPS panels are constructed from foil-gauge materials to reduce weight. These lightweight, foil-gauge metallic panels are subjected to a wide range of flow conditions during ascent and entry of an RLV. Flow conditions range from subsonic continuum flow to hypersonic rarified flow with a wide variation in dynamic pressure and aerodynamic heating. One of the many design considerations for metallic TPS is to ensure that under all of these flow conditions the panels are not susceptible to the phenomenon of panel flutter. This paper presents recent results of metallic TPS panel flutter analysis conducted at NASA Langley Research Center.

Panel flutter is a self-excited aeroelastic motion of a plate or shell under the action of unsteady aerodynamic forces. Panel flutter behavior is illustrated in Fig. 1. Unsteady aerodynamic forces perturb a structural panel causing it to oscillate. If the oscillations decay and the panel resumes its equilibrium position, there is no panel flutter. However, flutter is initiated if the panel oscillations do not decay. If the oscillations continue in a stable manner, which can be caused by structural nonlinearities that limit flutter amplitudes, the panel can be subjected to fatigue failure. Unbounded or divergent oscillations lead to catastrophic panel failure. A cantilever plate tends to be more susceptible to panel flutter than a plate with all four edges supported. For a cantilever plate the flutter mode might not be the coalescence of the lowest modes. Instead flutter occurs at the higher modes.

Panel flutter of metallic TPS raises some issues that have not been thoroughly investigated in the previous four decades of panel flutter research. One of the key questions that has received little discussion in recent panel flutter-related publications is what type of aerodynamics should be used in flutter calculations. Metallic TPS panels experience a wide range of Mach numbers, dynamic pressure, and aerodynamic heating during ascent and entry. Typical panel flutter calculations use a simplified piston theory to model aerodynamic pressures. In the aerodynamic pressure equation given by piston theory, the second- and third-order terms have a M_∞ and M_∞^2 in the coefficients. As M_∞ increases, the higher-order terms become more important, but there are not many investigations concerned with this topic. McIntosh[2] was the earliest researcher who studied nonlinear aerodynamic effects in conjunction with structural nonlinearities. His findings indicated that the higher-order aerodynamic theory can produce a "soft-spring" effect. The critical dynamic pressure predicted might be 15% lower than linear results. Gray and Mei[3] used the finite element method to study hypersonic panel flutter. They concluded that the third order term with M_∞^2 of the piston theory aerodynamics is the most important.

Another very important factor in hypersonic panel flutter is the local flow condition to which the panels are exposed.[4] A vehicle flying hypersonically at an angle of attack has a local flowfield that is different from freestream conditions. On the compression surfaces the local Mach number is lower behind a shock, and the local dynamic pressure is generally much higher. The local flow conditions present a more severe flowfield to the panel from a flutter viewpoint than the freestream. In general, quasi-steady aerodynamics (piston theory) yields acceptable results at Mach numbers from 2.0 to 5.0. Below a Mach number of about 2.0, it appears that three-dimensional unsteady aerodynamics will provide the most accurate solution. Of course, three-dimensional unsteady aerodynamics should be used for subsonic flow condition as well.

There are two components of current metallic TPS designs (Fig. 2) that are potentially susceptible to panel flutter: the outer, foil-gauge honeycomb sandwich panel and the overlapping shingle seals on

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the trailing edges of the TPS panel. These TPS components will be oriented in a wide range of angles to the flow at various locations over the surface of a vehicle. Until recently, panel flutter analysis techniques have assumed rectangular panels with one edge parallel to the flow. A new method for analyzing panel flutter for panels at an arbitrary angle to the flow has been developed[5] and is used in the current study of metallic TPS.

The current paper covers both panel flutter analysis tool development as well as parametric panel flutter study of a specific metallic TPS configuration. The theoretical background for the current study can be found in Ref. 5. An advanced panel flutter analysis capability was built into a commercial finite element code with the goal of providing a useful tool for aerospace engineers. The resulting analytical tool was used to investigate the importance of panel flutter at high Mach numbers and to analyze metallic TPS being built for the X-33 experimental vehicle.

Analysis Method

Investigation of panel flutter at high Mach numbers and at arbitrary angles to the flow required solving more general, nonlinear equations than the classical linear equations of motion. However, solutions of the linear equations of motion were also calculated for comparison with the nonlinear solutions. Second-order piston theory was used to calculate the unsteady aerodynamic forces in the high-Mach-number flight regime. A coordinate transformation was used to calculate panel flutter for arbitrary flow direction. The governing system nonlinear equations of motion are derived by the principle of virtual work for a complex plate of arbitrary shape subjected to supersonic/hypersonic airflow loads with arbitrary yaw angles. Material properties are assumed to be independent of temperature in this study. The virtual work is done by internal forces and external aerodynamic forces. Modal reduction is employed to solve the nonlinear equations of motion. This nonlinear panel flutter analysis capability was programmed into a commercial finite element code and used to investigate panel flutter of metallic TPS panels.

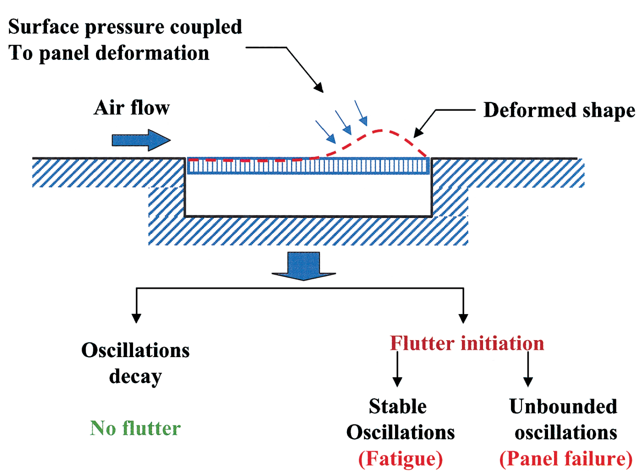

Fig. 1 Illustration of panel flutter.

Linear Panel Flutter

The linear system equation of motion governing panel flutter can be written as

$$\left(1/\omega_0^2\right)[M]\{\ddot{W}\} + (g_a/\omega_0)[G]\{\dot{W}\} + ([K] + \lambda[A])\{W\} = 0 \quad (1)$$

where ω_0 is the reference circular frequency; $[K]$, $[M]$, and $[G]$ are stiffness, mass, and damping matrices, respectively.

In the preceding equation $[G] = [M]$ (Ref. 6). The displacements are assumed to be exponential functions of time:

$$\{W\} = \{\bar{W}\}e^{\Omega t} \quad (2)$$

where $\Omega = \alpha + i\omega$, α and ω are the panel damping rate and frequency, respectively. Substituting Eq. (2) into Eq. (1) leads to an eigenvalue problem of the form

$$\kappa[M]\{\varphi\} = ([K] + \lambda[A])\{\varphi\} \quad (3)$$

with eigenvalues given by

$$(\Omega/\omega_0) = -g_a \pm \sqrt{g_a^2 - 4\kappa}\Big/2 \quad (4)$$

Complex eigenvalues κ are expected for the λ values corresponding to flutter motions.

The air density and Mach number are combined into a nondimensional dynamic pressure λ, which is defined as

$$\lambda_{cr} = 2qa^3/\beta D, \qquad \beta = \sqrt{M_\infty^2 - 1} \quad (5)$$

The effect of Mach number M on dynamic pressure q can be calculated from λ_{cr}. Then the critical velocity V can be obtained from the dynamic pressure $q = \frac{1}{2}\rho V^2$.

Flow Direction

Figure 3 shows that if the flow direction is not parallel to the x axis, but is instead along the ξ axis, the slope $\partial W/\partial \xi$ must be

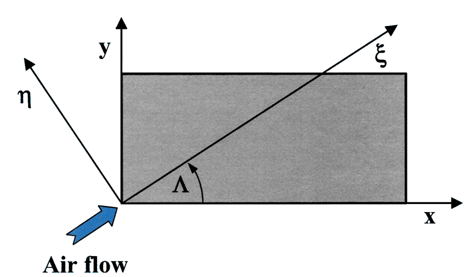

Fig. 3 Coordinate system used in panel flutter analysis.

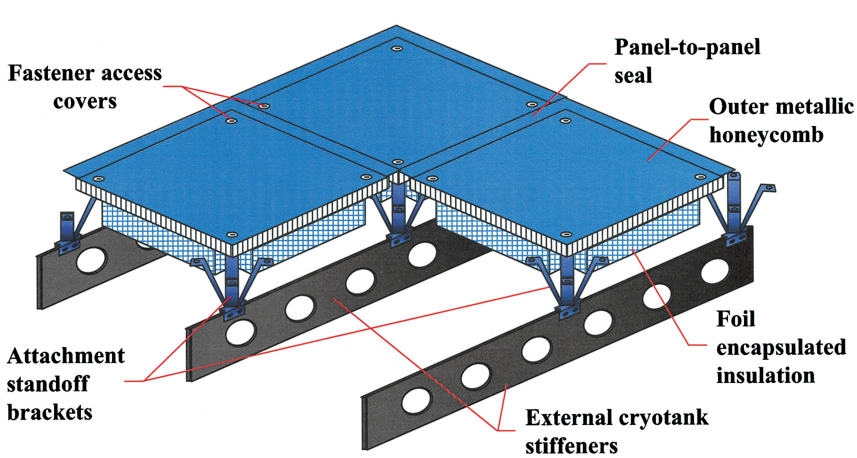

Fig. 2 X-33 metallic TPS.

calculated using a coordinate transform as follows:

$$y = \eta\cos\Lambda + \xi\sin\Lambda, \qquad x = \xi\cos\Lambda - \eta\sin\Lambda$$

$$\frac{\partial w}{\partial \xi} = \frac{\partial w}{\partial y}\frac{\partial y}{\partial \xi} + \frac{\partial w}{\partial x}\frac{\partial x}{\partial \xi} = \frac{\partial w}{\partial y}\sin\Lambda + \frac{\partial w}{\partial x}\cos\Lambda$$

$$[A_e]_y = \bar{a}\int\int[\phi]^T\left[\frac{\partial}{\partial\xi}[\phi]\frac{\partial\xi}{\partial y} + \frac{\partial}{\partial\eta}[\phi]\frac{\partial\eta}{\partial y}\right]\begin{vmatrix}\frac{\partial x}{\partial\xi} & \frac{\partial x}{\partial\eta}\\ \frac{\partial y}{\partial\xi} & \frac{\partial y}{\partial\eta}\end{vmatrix}\,\mathrm{d}\xi\,\mathrm{d}\eta \tag{6}$$

where Λ is the flow angle with the x axis.

Hypersonic Panel Flutter

For hypersonic panel flutter analysis the second-order piston theory is used. Therefore, the equations of motion become nonlinear. A modal reduction method is employed to reduce the computation time.

Aerodynamic Loads

Second-order piston theory (not the third-order theory) is employed to calculate the unsteady aerodynamic loads for hypersonic speed. Although this theory neglects the effects of three-dimensional flow and flow memory, it gives very satisfactory approximation for supersonic/hypersonic Mach numbers ($M_\infty > 2.0$). The aerodynamic pressure is given by

$$\Delta p = -\frac{2q}{\beta}\left[\frac{\partial w}{\partial x} + \frac{M_\infty^2 - 2}{M_\infty^2 - 1}\frac{1}{V}\frac{\partial w}{\partial t} + \frac{(\gamma+1)}{4}M_\infty\left(\frac{\partial w}{\partial x}\right)^2\right] \tag{7}$$

where $q = \rho V^2/2$ is dynamic pressure and $\beta = \sqrt{(M_\infty^2 - 1)}$.

Modal Reduction

The nonlinear system equation of motion that must be solved are as follows:

$$\left(1/\omega_0^2\right)[M]\{\ddot{\boldsymbol{W}}\} + (g_a/\omega_0)[G]\{\dot{\boldsymbol{W}}\} + ([K] + \lambda[A])\{\boldsymbol{W}\} + [A1_f(W)]\{\boldsymbol{W}\} = 0 \tag{8}$$

where $[A1_f(w)]$ is the nonlinear aerodynamic force term.

The system equations of motion presented in Eq. (8) are not suitable for numerical calculations because of two shortcomings: 1) the number of physical degrees of freedom of the system is too large, and 2) the nonlinear aerodynamic matrix is a function of the system displacement vector, and it needs to be calculated in every iteration. Therefore, Eq. (8) has been transformed into a set of properly chosen modal coordinates with significantly fewer degrees of freedom. This is accomplished by the following modal transformation:

$$\{\boldsymbol{W}\} = \sum_{r=1}^{N}\{\varphi\}_r q_r \tag{9}$$

where $\{\varphi\}_r$ corresponds to the rth normal mode from the linear eigenvalue solution of the system

$$\omega^2[M]\{\varphi\} = [K]\{\varphi\} \tag{10}$$

then the modal equation can be obtained as

$$\frac{1}{\omega_0^2}[\bar{M}]\{\ddot{\boldsymbol{q}}\} + \frac{g_a}{\omega_0}[\bar{G}]\{\dot{\boldsymbol{q}}\} + ([\bar{K}] + \lambda[\bar{A}])\{\boldsymbol{q}\} + \sum_{r=1}^{N}[\bar{A}\bar{1}_f^r(q_r)]\{\boldsymbol{q}\} = 0 \tag{11}$$

Iteration Solution of Modal Equations

The iteration solution procedure can be prescribed as follows:

1) Select an initial modal coordinates $\{\boldsymbol{q}_0\}$.
2) Calculate nonlinear aerodynamic matrices.
3) Solve eigenvalue problem to get new solution $\{\boldsymbol{q}\}$.
4) Compare new $\{\boldsymbol{q}\}$ and old $\{\boldsymbol{q}\}$; if the difference is less than a certain value, iteration is stopped.

Finite Element Panel Flutter Analysis

The panel flutter analysis capability has been incorporated into the commercial general-purpose finite element code MARC.[7] The panel flutter analysis capability consists of three parts: linear flutter analysis with x-axis direction flow, linear flutter analysis with arbitrary flow direction, and nonlinear hypersonic flutter analysis.

The element used is a four-node thick-shell element (MARC element 75) with global displacements and rotations as degrees of freedom. Bilinear interpolation is used for the coordinates, displacements, and the rotations. The membrane strains are obtained from the displacement field and the curvatures from the rotation field. The transverse shear strains are calculated at the middle of the element edges and interpolated to the integration points. The resulting element is very efficient and simple, yet exhibits correct behavior in the limiting case of thin shells. Because of its simple formulation, it is less expensive in computation and, therefore, very attractive in nonlinear analysis. In the analysis the partial second-order piston theory is used to calculate the unsteady aerodynamic pressure.[8]

Results

The panel flutter analysis implemented in the MARC finite element program was used to investigate the potential for panel flutter of metallic TPS panels. Panel flutter of an isotropic square plate (which could be compared with previous solutions) was investigated over the hypersonic flight regime. The outer honeycomb sandwich of a typical X-33 metallic TPS panel was analyzed for susceptibility to panel flutter. The panel-to-panel foil seals on the outer surface of the TPS were also analyzed for panel flutter. Finally, the current analysis is used to predict the experimentally observed flutter of a perimeter seal on an array of metallic TPS panels tested in a Mach 7 wind tunnel.

Hypersonic Flutter of an Isotropic Square Plate

A simply supported isotropic square panel ($12 \times 12 \times 0.05$ in. aluminum plate) was studied to verify the current analysis and to investigate the importance of panel flutter during hypersonic flight. This study uses a 16 by 8 (128 elements) mesh for half of the plate. The predicted nondimensional critical dynamic pressure λ for the onset of panel flutter is 520.0. This result is close to the published value of $\lambda = 512.0$ (see Fig. 1 of Ref. 5) for an identical aluminum plate.

In some cases it is possible to use a panel at dynamic pressures above the onset of panel flutter in a stable oscillation. To investigate this possibility, the nondimensional critical dynamic pressure was calculated for several amplitudes of oscillations. These nonlinear results for Mach number $M = 10$, number of modes $N = 16$ is shown in Table 1. The λ are predicted to decrease with increasing vibration amplitudes—an unstable situation. Table 1 shows that when the $W\max/h$ increases from 0.0 to 1.2, the critical dynamic pressure λ is reduced 3%. Therefore, this analysis indicates that in these

Table 1 Nonlinear aerodynamic effects: $M = 10$, $N = 16$

$W\max/h$	λ
0.0	520.0
0.2	517.7
0.4	514.7
0.6	511.9
0.8	509.6
1.0	507.2
1.2	504.9

Table 2 Nondimensional critical dynamic pressure-isotropic square plate (64 elements)

M_∞	2	5	10	11	12	13	14	15	16
$W\max/h$	——	——	——	——	——	——	——	——	——
0.1	557.4	——	557.4	——	——	——	——	——	——
0.2	557.0	——	555.8	——	——	——	——	——	——
0.3	556.8	——	553.6	——	——	——	——	——	——
0.4	556.5	555.8	551.6	——	——	——	——	——	——
0.5	——	——	549.8	549.8	548.8	547.8	547.4	546.6	——
0.6	——	——	548.8	——	——	——	——	——	——
0.8	——	——	545.9	——	——	——	——	——	——
1.0	——	——	543.9	——	——	——	——	——	534.9
1.6	——	——	——	——	——	——	——	——	522.9

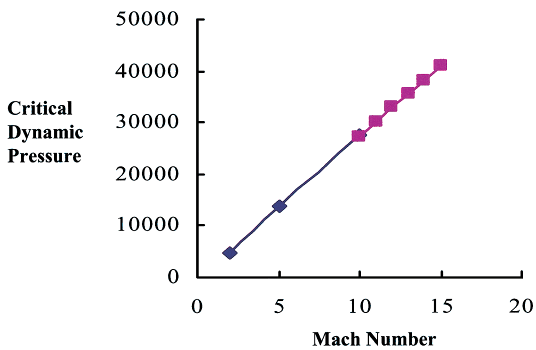

Fig. 4 Predicted critical flutter dynamic pressure vs Mach number.

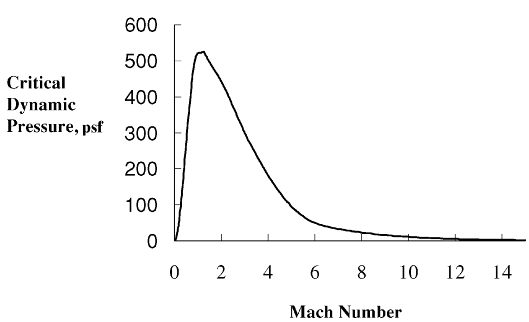

Fig. 5 Dynamic pressure vs Mach number for a single-stage-to-orbit reusable launch vehicle.

hypersonic flight conditions the onset of panel flutter should be avoided because the resulting panel oscillations will not be stable.

A less refined (64 elements) model that required much less computer time was used to investigate panel flutter of the isotropic plate over a range of Mach numbers and oscillation amplitudes. Table 2 shows the nondimensional critical dynamic pressures from Mach 2 to Mach 16. Only a few representative values were calculated to identify to variation with Mach number. The values of λ were found to decrease very slightly with increasing Mach number. The critical dynamic pressures corresponding to the nondimensional data for Table 2 ($W\max/h = 0.4, 0.5$) are also shown in Fig. 4. The flutter critical dynamic pressure increases very rapidly with Mach number. The dynamic pressure for a single-stage-to-orbit reusable launch vehicle is shown on Fig. 5. The dynamic pressure reaches a maximum near Mach 1 and decreases rapidly with Mach number. Therefore the critical panel flutter conditions for metallic TPS will likely be at low Mach numbers.

Metallic Thermal Protection System Panel

Two components of the X-33 metallic TPS shown in Fig. 2 might be susceptible to panel flutter: the outer honeycomb sandwich panel and the foil panel-to-panel seals. Both of these TPS components were analyzed for panel flutter. The honeycomb sandwich panel was much too stiff to flutter, but the seals can be susceptible to panel flutter under some conditions. Seals were investigated at various angles to the flow, and predictions were made for a seal flutter observed during hypersonic wind-tunnel testing.

Honeycomb Sandwich Panel

The 18 × 18 in. honeycomb sandwich panel is modeled as a laminated plate. The plate is supported at four points near the corners by springs that simulate the attachment standoff brackets. The material properties and dimensions used in the model are shown in Table 3. A nonstructural mass of 0.000912 lb/in.^{2} is included in the facesheet density to account for the braze used to join the facesheets to the core.

The panel flutter analysis of the honeycomb sandwich was completed during the X-33 program while there were much more detailed structural analyses of the TPS panels being performed at BF Goodrich in Chula Vista, California. The support spring constants K_{xy} (the spring coefficient in the in-plane x and y directions) and K_z (the spring coefficient in the out-of-plane z direction) were adjusted to match the frequencies and mode shapes with BF Goodrich's results. After parametrically varying the location and stiffness of the corner spring supports, two support cases (A and B) were chosen to calculate flutter dynamic pressure. Support case A is supported at the corner nodes with $K_{xy} = 440$ lb/in. and $K_z = 60\text{E}6$ lb/in. Support case B is supported at nodes inboard from the panel corners with $K_{xy} = 500$ lb/in. and $K_z = 9000$ lb/in. Table 4 shows the first six natural frequencies calculated for the two different support conditions and their ratio to the results from the much more detailed BF Goodrich models. There is good agreement for most of the modes. For support case A the simplified plate analysis underpredicts the BF Goodrich results for mode 4 by 17%, and for support case B the results for mode 3 are underpredicted by 15%. Therefore panel flutter calculations are made using both of these support conditions.

Results of panel flutter calculations using the plate model and the two boundary conditions already discussed are shown in Table 5. The nondimensional critical dynamic pressures for support cases A and B are 76.5 and 51.0, respectively. For the typical ascent trajectory shown in Fig. 5, the maximum dynamic pressure of 530 psf

Table 3 Material properties for metallic TPS panel

Property	Value
Facesheet (Inconel 617)	
ρ	0.304 lbm/in.^{3}
h	0.006 in.
E_{11}, E_{22}, E_{33}	30.1E6 psi
ν	0.278
G_{12}, G_{23}, G_{31}	11.77E6 psi
Core (Inconel 617)	
ρ	0.00689 lbm/in.^{3}
h	0.5 in.
E_{11}, E_{22}, E_{33}	7.175E5 psi
ν	0.0
G_{12}, G_{23}, G_{31}	132 psi

Table 4 Natural frequencies (Hz): metallic TPS panel

Model	$f1$	$f2$	$f3$	$f4$	$f5$	$f6$
Support case A	86	86	153	182	367	367
Plate model/ BF Goodrich	1.00	0.99	0.91	0.83	1.00	0.99
Support case B	92	92	143	207	362	362
Plate model/ BF Goodrich	1.07	1.06	0.85	0.94	0.98	0.98

Table 5 Critical dynamic pressure (psf): honeycomb sandwich panel

Description	λ_{cr}	$q(M = 1.4)$	$q(M = 1.05)$
Support case A	76.5	21,320	6,967
Support case B	51.0	14,214	4,644
Max. flight q	——	<530	~530

Table 6 Critical dynamic pressure (psf): TPS panel seal

Description	λ_{cr}	$q(M = 1.4)$	$q(M = 1.05)$
50 element model	2.20	613	200
Max. flight q	——	<530	~530

Table 7 Nondimensional critical dynamic pressure vs flow angle: TPS panel seal

Λ, deg	λ_{cr}	f, hz
0	2.26	803
10	2.35	823
20	2.45	843
30	2.64	865
40	2.95	888
50	3.56	917
60	4.54	957
70	6.55	1023
80	12.7	1190
90	69.9	2363

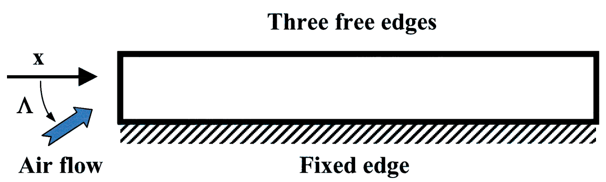

Fig. 6 Simplified model for panel flutter of TPS panel seal.

Table 8 Comparison of test and analysis of panel seal

	Test				Analysis	
Run	M_{local}	ρ_{air}, lb/in.^{3}	q, psf	Flutter	q_{cr}, psf	Flutter
1	6.0	0.73E–6	848	No	982	No
2	6.0	0.73E–6	848	No	982	No
3	5.5	0.14E–5	1617	Yes	900	Yes

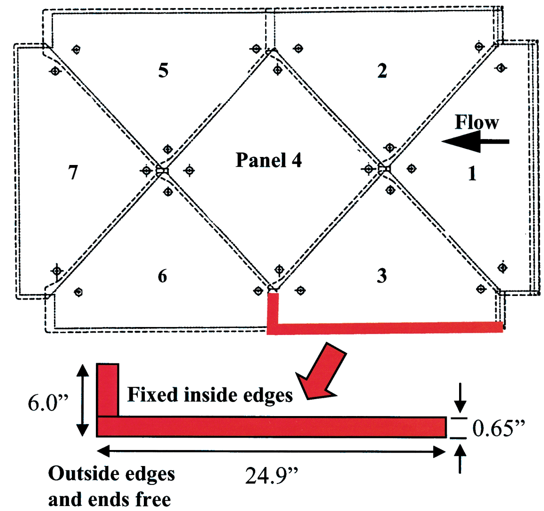

Fig. 7 Idealized edge seal analyzed to predict X-33 TPS test results.

occurs between Mach 1 and 1.4. Although the linear flutter analysis used in these calculations is not very accurate in this low-Mach-number range, it can be used to indicate whether more accurate panel flutter analysis is required. The predicted flutter critical dynamic pressures calculated using Eq. (5), shown in Table 5, are nearly an order of magnitude higher than the flight dynamic pressure. Therefore, the honeycomb sandwich panels are stiff enough that they will not be susceptible to panel flutter.

Panel-to-Panel Seal

The outer panel-to-panel seal for the X-33 TPS shown in Fig. 2 is an extension of the outer facesheet of the honeycomb sandwich. For panel flutter analysis a simplified strip, 18 × 0.5 × 0.006 in. thick, was used to approximate the seal, as shown in Fig. 6. The behavior of the seal is greatly affected by its orientation to the flow. It is clearly undesirable to orient this seal such that flow impinges on the long free edge because that would allow flow to get under the seal and might cause the seal to deflect into the flow. The next most critical case is for the seal to be parallel to the flow (along the x direction).

A linear panel flutter analysis was performed for the idealized seal shown in Fig. 6. The calculated natural frequencies for the lowest six modes are (in hertz) $f1 = 833$, $f2 = 834$, $f3 = 838$, $f4 = 847$, $f5 = 860$, and $f6 = 880$. The results of the panel flutter analysis are shown in Table 6. The nondimensional critical dynamic pressure is low, $\lambda_{cr} = 2.20$. The critical dynamic pressures predicted using Eq. (5) are lower than the anticipated flight dynamic pressures indicating that the seals might be susceptible to panel flutter.

Further calculations were performed to investigate the effect of flow angle on the susceptibility of the seal to panel flutter. Table 7 shows the variation of λ_{cr} and flutter frequency with flow angle. The results indicate that the seal's susceptibility to panel flutter is not greatly reduced for small angles to the flow.

Although this simplified flutter analysis is not very accurate at these low Mach numbers, these results indicate that flutter is a serious design issue for the panel-to-panel seals and requires more detailed study for the exact seal configurations and loading.

Comparison with X-33 TPS Test Results

An array of X-33 metallic TPS panels was tested in the 8 ft High Temperature Tunnel at NASA Langley Research Center.[9] Overlapping foil seals around the perimeter of the model, parallel to the flow were observed to flutter during testing. These seals were specifically designed to interface with the panel holder and were not representative of the design panel-to-panel seals for the metallic TPS concept. Figure 7 shows the idealized seal geometry that was analyzed and how it related to the overall TPS array. All of the representative panel-to-panel seals were oriented at 45 deg to the flow and did not flutter.

Table 8 shows the comparison of the results predicted using the panel flutter analysis tool incorporated into MARC with wind-tunnel test results. Predictions were made using both freestream and local surface flow conditions. Predictions using freestream flow conditions did not match the observed behavior. However, for the local flow conditions shown in the table the correlation between experiment and analysis was good, although the test was not specially designed for panel flutter study. In the two cases where panel flutter did not occur, the analysis predicted a critical dynamic flutter above the test dynamic flutter. In the third run, in which panel flutter was observed, the analysis predicted a critical dynamic pressure below the test value.

Conclusions

Conclusions from this study indicate that 1) existing panel flutter tools that ignore higher-order aerodynamic terms are adequate for analysis of metallic TPS panels, 2) local flow conditions provide a more accurate panel flutter analysis than freestream conditions, 3) the outer honeycomb sandwich on the X-33 metallic TPS is not susceptible to panel flutter, and 4) under some conditions the panel-to-panel seals of the X-33 metallic TPS are susceptible to panel flutter.

References

[1]Blosser, M. L., "Advanced Metallic Thermal Protection Systems for Reusable Launch Vehicles," Ph.D. Dissertation, Dept. of Mechanical and Aerospace Engineering, Univ. of Virginia, Charlottesville, VA, May 2000.

[2]McIntosh, S. G., Jr., "Theoretical Considerations of Some Nonlinear Aspects of Hypersonic Panel Flutter," Dept. of Aeronautics and Astronautics, Stanford Univ., Final Rept., SUDAAR 491, Stanford, CA, Aug. 1970.

[3]Gray, C. E., Jr., and Mei, C., "Large Amplitude Finite Element Flutter Analysis of Composite Panel in Hypersonic Flow," *AIAA Journal*, Vol. 31, No. 6, 1993, pp. 1090–1099.

[4]Bein, T., Friedmann, P., Zhong, X., and Nydick, I., " Hypersonic Flutter of a Curved Shallow Panel with Aerodynamic Heating," AIAA Paper 93-1318, April 1993.

[5]Abdel-Motaglay, K., Chen, R., and Mei, C., "Nonlinear Flutter of Composite Panels Under Yawed Supersonic Flow Using Finite Elements," *AIAA Journal*, Vol. 37, No. 9, 1999, pp. 1025–1032.

[6]Xue, D. Y. X., "Finite Element Frequency Domain Solution of Nonlinear Panel Flutter with Temperature Effects and Fatigue Life Analysis," Ph.D. Dissertation, Dept. of Aerospace Engineering, Old Dominion Univ., Norfolk, VA, May 1991.

[7]"User Manual," MARC Analysis Research Corp., Palo Alto, CA, 1994.

[8]Ashley, H., and Zartarian, G., "Piston Theory—A New Aerodynamic Tool for Aeroelastician," *Journal of Aeronautical Science*, Vol. 23, No. 12, 1956, pp. 1109–1118.

[9]Sawyer, J. W., Hodge, J. S., Moore, B., and Sawyer, K., "Aerothermal Test of Thermal Protection Systems for X-33 Reusable Launch Vehicle," *Proceedings of Space Technology and Applications International Forum (STAIF '99)*, edited by M. S. El-Genk, American Inst. of Physics, New York, Feb. 1999.

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