Thermo-mechanical Characteristics and Improvement of Antenna Structures in Supersonic Flows

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Abstract. In a supersonic airflow, smart skin antenna structure is analyzed to investigate the thermo-mechanical characteristics and stability boundaries. The skin is modeled as a multi-layer sandwich structure with a dielectric polymer. Especially, the layer is embedded on the middle surface of the face sheets similar to the honeycomb core to perform the role of antenna or radar structures. First-order shear deformation theory of plate and von Karman strain-displacement relations are adopted in this work. Also, aerodynamic pressure is based on the first-order piston theory for the aerodynamic loads. Newton-Raphson iterative method is applied to solve the nonlinear equations of motion. Special thermo-mechanical characteristics and improvement of the structural model are discussed.

Introduction

For the modern structures, metals have been increasingly replaced by the composite materials due to the high specific strength, stiffness and light weight of the materials. In this regard, the thermal buckling and post-buckling behaviors are a primary concern for the structures. Mannini [1] investigated the thermal buckling of laminated composite plate model based on the first-order shear deformation theory. Based on these research works, development of stealth function for military aircraft has been one of the interesting topics during 20 years. Specifically, advanced technologies for new material composition have been proposed, and then many engineers have been involved to embed the conformable load bearing antenna structures (CLAS). Main advantage of the skin makes the antenna to reduce the radar cross section (RCS) as well as to increase the stealth functions. In this regards, Varadan and Varadan [2] proposed a concept of the skin antenna structure using smart materials. Also, Lee and Kim [3] studied thermal stability regions and limit cycle oscillation of the structures.

This paper is based on the first-order shear deformation theory of plate, and von-Karman strain-displacement relations are adopted in each layer of the smart skin. To solve the nonlinear equations of motion, Also, the thermal stability boundaries of the antenna structure are evaluated, and the deformed shape of the skin is presented.

Modeling of the Skin

Figure 1 shows a smart skin antenna structure model in this work. The structure is consisted of multi-layer sandwich composite plate with the whole five layers. From the left side of the model, the staking sequences are the face sheet, dielectric enclosure layer with dielectric layer, face sheet, honeycomb core and face sheet. And then, face sheets are made up of Glass/Epoxy. The face sheets are designed to protect the dielectric enclosure layer from external disturbances such as aerodynamic loads forces and thermal disturbances. Further, the Carbon/Epoxy layer covers around the dielectric layer.
Structural Formulations.

Usually, plate is assumed to consist of n-layers with arbitrary fiber orientation in each layer.

Displacements fields based on the first-order shear deformation theory:

\[ u_\alpha(x, y, z, t) = u^0_\alpha(x, y) + z\phi_\alpha(x, y, t) \quad (\alpha = 1, 2) \]

\[ w(x, y, z, t) = w_0(x, y, t) \]

where \( u^0_\alpha(x, y, t) \) and \( w_0 \) are the mid-plane displacements in the \( \alpha \) and \( z \) directions, respectively, and \( \phi_\alpha \) is the rotation of originally perpendicular to the longitudinal plane.

Using the von Karman strain-displacement relations, the displacement-strain relations can be obtained. Through the integration in the thickness direction of the plate, the force and moment resultant vector can be expressed as

\[
\begin{bmatrix}
N_b \\
M_b
\end{bmatrix} = \begin{bmatrix}
A & B \\
B & D
\end{bmatrix} \begin{bmatrix}
e^0 \\
k
\end{bmatrix} - \begin{bmatrix}
N_{ST} \\
M_{ST}
\end{bmatrix}, \quad \{Q\} = [S]\{\gamma\}
\]

(2)

To derive the governing equations, the principle of virtual work is applied as

\[ \delta W = \delta W_{int} - \delta W_{ext} = 0 \]

(3)

where \( \delta W_{int} \) and \( \delta W_{ext} \) are the internal and external virtual work, respectively.

Then, the internal virtual work is given by

\[
\delta W_{int} = \int_V \{\delta e\}^T \{\sigma\} dV
\]

\[ = (\delta d)^T \left( [K] - [K_{ST}] + \int [N1] + \int [N2] \right) \{d\} - (\delta d)^T \{P_{ST}\} \]

(4)

On the other hand, the external work is given by

\[
\delta W_{ext} = \int_A \left[ -I_o (\ddot{\varphi}_\alpha \ddot{\varphi}_\alpha + \dddot{\varphi}_\alpha \ddot{\varphi}_\alpha) - I_1 (\ddot{\varphi}_\alpha \ddot{\varphi}_\alpha + \dddot{\varphi}_\alpha \ddot{\varphi}_\alpha) + p_\alpha \delta w \right] dA
\]

\[ = - (\delta d)^T \{M\} \{\dot{d}\} + (\delta d)^T \{f\} \]

(5)

where the moment of inertias \( (I_0, I_1, I_2) \) are defined as \[ \int_0^{h/2} \rho(1, z, z^2) dz \] while \( \{p_\alpha\} \), \( \{M\} \) and \( \{f\} \) are the aerodynamic pressure, mass matrix and external force vector, respectively.

The external force is an aerodynamic pressure resulting from a supersonic air flow. The aerodynamic pressure according to the first order piston theory for \( \sqrt{2} < M_\infty < 5 \) can be expressed as in Ref. [4].
In this work, thermal post-buckling and stability boundaries are investigated using finite element method. In the numerical analysis, Newton-Raphson iteration method is applied to solve the nonlinear governing equations.

**Results and Discussions**

For numerical analysis, finite element method is using \(7 \times 7\) meshes for nine-node plate elements. The reference temperature \(T_0\) is 300K.

**Code Verification**

To verify the code for the thermal buckling analysis, the thermal buckling analysis of a composite sandwich plate structure that is compounded \([0/90/.../0]^{10}\) core \([90/0/.../0]^{10}\) is performed. Table 1 shows the present result has good agreement with the data in Ref. [5].

<table>
<thead>
<tr>
<th>(a/h)</th>
<th>(h/f)</th>
<th>Matsunaga [5]</th>
<th>Present</th>
</tr>
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<tr>
<td>20</td>
<td>0.05</td>
<td>0.0949</td>
<td>0.0949</td>
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<tr>
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<td>0.0887</td>
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</tr>
<tr>
<td>0.15</td>
<td>0.0795</td>
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</table>

**Thermal Post-buckling Analysis**

First of all, there are generally four types of panel behaviors in the thermal stability boundaries as shown in Figure 2: (A) flat and stable, (B) statically buckled but dynamically stable, (C) flutter and (D) chaos. At region (A), the panels remain flat and statically stable as well as dynamically stable. On the other hand, the panels are buckled but dynamically stable at region (B) as increasing the temperature. The region (B) is defined by thermal post-buckling and the boundaries between the regions (A) and (B) indicate critical conditions for buckling. Furthermore, the dynamic pressure increases, flutter occurs in the region (C). And the boundaries between the regions (A) and (C) can be determined by linear flutter analysis. Additionally, chaotic motions can be observed in region (D).

For more emphasis on the specific characteristic of antenna structure in Figure 3. The results show that the peak of the deflection is moving backwards direction as the aerodynamic load increases. Also, the aerodynamic pressure increases, center of the structure is more moving downward direction due to the flexible characteristics of the dielectric layer.

![Figure 2. Thermal stability boundaries of model according to the size of the dielectric regions.](image2.png)  
![Figure 3. Deformed shapes of the model as the increase of aerodynamic pressure.](image3.png)

These may lead to severe deviations of the phase information of the signals and affects the degradation of the antenna performance. To improve the structural performance of the phenomena in Figure 3, the design variables are chosen as two parameters such as ply angles and the honeycomb...
core thickness. At first, Figure 4 (a) shows the non-dimensional center deflections according to the ply angles. Next, Figure 4 (b) shows the non-dimensional center deflections with the variations of honeycomb core thickness. The thickness of the core is chosen as 40% and 80% of total thickness for the model.

![Figure 4. Non-dimensional deflections with the variations of parameters for improvement of structural behaviors.](image)

(a) Deflections with the variations of ply angles  
(b) Deflections with the variations of honeycomb core thickness

Conclusions

In this work, the thermo-mechanical behaviors of multi-layered composite structure as a smart skin antenna are investigated under supersonic airflows. The dielectric layer is essential part of the skin structure, and then the layer is specially focused in this paper. The characteristics are analyzed with sizes and shapes of the dielectric region of the model. The deflection increases as the area of dielectric layer increases due to low stiffness characteristics of the layer. Furthermore, sudden decreased of the deformation shapes are observed at the center of the model due to the increase of flexibility of the dielectric layer.

References


