Implementation of PATRAN/NASTRAN into the Development of Advanced Buoyancy Air Vehicles

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[Abstract] PATRAN/NASTRAN have been employed to model the advanced buoyancy air vehicle — aeroscraft. Structural system of aeroscraft is described. Preliminary load analysis of the overall vehicle is performed based on the assumption of rigid body motion. A variety of elements including 1D beams/rod elements and 2D shell elements have been selected to model internal frame, aeroshell, and control surfaces. Boundary conditions and analysis methods for overall vehicle analysis have been illustrated. Inertia relief technique has been utilized to solve for unconstrained systems, which represents typical flight maneuver conditions. Stress analyses of a 3D composite truss and structure systems have been introduced. Ground handling test and float test have demonstrated system performances.

Nomenclature

\[ L_D \] = envelope dynamic lift, normal to flight path and air vehicle Y-axis
\[ L_{\text{horiz}} \] = horizontal stabilizer lift, normal to flight path and air vehicle Y-axis
\[ L_{\text{vert}} \] = vertical stabilizer lift, normal to flight path and air vehicle Y-axis
\[ L_C \] = canard lift, normal to flight path and air vehicle Y-axis
\[ L_{\text{horizontal}} \] = envelope horizontal lift, along air vehicle Y-axis
\[ L_{\text{horizontal}} \] = horizontal lift of horizontal stabilizer, along air vehicle Y-axis
\[ L_{\text{vertical}} \] = horizontal lift of vertical stabilizer, along air vehicle Y-axis
\[ \rho_{\text{air}} \] = air density
\[ \rho_{\text{helium}} \] = helium density
\[ V \] = envelope volume
\[ B \] = buoyancy lift, normal to the earth’s horizontal plane
\[ q \] = dynamic pressure
\[ C_l \] = envelope lift coefficients
\[ C_D \] = envelope drag coefficients
\[ C_M \] = envelope pitching moment coefficients
\[ C_{\text{emp}} \] = empennage lift coefficient
\[ T \] = power plant thrust
\[ D \] = envelope drag
\[ D_C \] = canard drag
\[ D_{\beta} \] = horizontal stabilizer drag
\[ D_{\text{vert}} \] = vertical stabilizer drag
\[ F_x \] = X component of the resultant force acting on the vehicle
\[ F_z \] = Z component of the resultant force acting on the vehicle
\[ M_y \] = pitching moment
\[ M_z \] = yawing moment
\[ \alpha \] = angle of attack of air vehicle

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\[ \alpha_{emp} = \text{angle of attack of empennage} \]
\[ \vartheta = \text{empennage installation angle} \]
\[ \Psi = \text{yaw angle of air vehicle} \]
\[ \gamma = \text{flight path angle} \]
\[ \delta = \text{empennage deflection angle} \]
\[ W = \text{vehicle weight} \]
\[ Z_{CG} = \text{vertical location of air vehicle center of gravity} \]
\[ Z_C = \text{vertical location of canard} \]
\[ Z_V = \text{vertical location of vertical stabilizer} \]
\[ Z_H = \text{vertical location of horizontal stabilizer} \]
\[ Z_T = \text{vertical location of thrust} \]
\[ X_{cv} = \text{longitudinal location of center of volume} \]
\[ X_{cb} = \text{longitudinal location of center of buoyancy} \]
\[ X_{MAC} = \text{longitudinal location of canard Quarter Mean Aerodynamic Chord} \]
\[ X_{BMAC} = \text{longitudinal location of vertical stabilizer Quarter Mean Aerodynamic Chord} \]
\[ X_{AMAC} = \text{longitudinal location of horizontal stabilizer Quarter Mean Aerodynamic Chord} \]
\[ \chi = \text{pitching acceleration} \]
\[ \phi = \text{yawing acceleration} \]
\[ n_x = \text{load factor in X direction} \]
\[ n_y = \text{load factor in Y direction} \]
\[ n_z = \text{load factor in Z direction} \]
\[ k_1 = \text{virtual inertia coefficient in longitudinal direction} \]
\[ k_2 = \text{virtual inertia coefficient in lateral direction} \]
\[ k_3 = \text{virtual inertia coefficient in vertical direction} \]
\[ k' = \text{coefficient of additional mass for rotation in pitching and yawing directions} \]

1. Introduction

Airships are air displacement vehicles that obtain buoyancy from the difference between the weight of inflation gas within its hull and the weight of the ambient atmosphere their body displaces. This classification includes traditional airships, rigid, semi-rigid, and non-rigid airships, hybrid airships, unconventional cargo airships, high altitude airships, and other novel buoyancy air vehicles. Besides classical analytical methods [1,2], Finite Element Analysis (FEA) plays an important role in the design and development of buoyancy air vehicles. MSC/NASTRAN has been applied to model the major structural components of envelope, suspension system, and nose battens of non-rigid airships [3]. In recent years, ABAQUS has been employed in a geometrically nonlinear analysis of a non-rigid airship. [4,5]. Internal suspension system was adjusted to optimize load distribution and structural reserves [4]. As shown in the literature [6-8], considerable efforts have been devoted to the study of non-rigid airship structures, especially, stratospheric airships. However, the research and development of rigid airships have rarely been seen [9]. The investigations on rigid airship structures are highly needed to meet the demands of advanced vehicle development.

An advanced buoyancy air vehicle—the aeroscraft has been developed by Aeros, and the construction and tests have been completed recently (Figure 1). The aeroscraft can be described as an adjustable buoyancy assisted lift air vehicle, and is capable of substantially and smoothly varying the volume ratio of buoyant gas and air, which enables...
the vehicle to ascend, descend, and hover steadily. The aeroscraft is equipped with unique features of buoyancy-assisted heavy lift control, dynamic buoyancy management system, innovative structural design, vertical takeoff and landing, and low speed control capability. The aeroscraft has a rigid airframe and does not rely on gas pressure to maintain shape. MSC software PATRAN/NASTRAN has been applied to model and analyze the rigid structure of aeroscraft during the phases of design and development.

The overall structural system of aeroscraft is illustrated in Figure 2. The aeroscraft aerostructure is mainly composed of principal structural components: aeroshell structure, internal frame, canards, empennages (horizontal stabilizer and vertical stabilizer). The features of these structural components are described as follows:

1. Aeroshell consists of rigid girder system (also named external frame) and aeroshell cover (also called envelope, skin). The aeroshell serves as hull of aeroscraft and shape retention structure. Aeroshell provides enclosure for lifting gas and supports aerodynamic loads as well.

2. Internal frame (see Figure 2) made of composite truss structure is connected to the external frame. The internal frame serves the main load bearing structure of the vehicle (aeroscraft's rigid skeleton) and it is enclosed in the aeroshell cover. External frame and internal frame are also connected by substructures, and generate a stiff airframe for supporting a variety of systems, such as propulsion system.

3. Multiple cables (see Figure 2) serve as secondary structural elements, which connect two joints of internal frame diagonally. These tension-only members reinforce rigid airframe and allow for deformation accommodation as well.

4. Two canards are installed at the fore section of the vehicle, while two horizontal stabilizers and two vertical stabilizers are installed conventionally at the aft section. The canards in the bow and empennages in the stern function as dynamic lift controller, and provide pitch/yaw/roll control.

Figure 2. Aeroscraft and Aeroscraft's Rigid Skeleton (Internal Frame)

Additionally, other substructures includes landing system structural frame, engine support structures, cockpit structure, etc. There are nonstructural systems including propulsion system, control of static heaviness system, electrical system, flight control system, hydraulic system, pneumatic system, etc. These systems will be simulated as concentrated weights in Finite Element (FE) model.

2. Preliminary Load Analysis of Aeroscraft

Buoyancy air vehicle's preliminary load analysis was generally performed based on the assumption of rigid body motion. It is also assumed that the motions in vertical and longitudinal directions and lateral direction are independent. Rigid body motion analysis is completed at the stage of preliminary design. Aerodynamic data of control surfaces and body should be obtained from CFD analysis in order to carry out the rigid body motion analysis. The resulting loads can be used as loading input of Finite Element (FE) model. Alternatively, flight load programs can also be used to perform detailed load analysis that requires considerable computational time and efforts.
The aeroscrafet is treated as a rigid body and external aerodynamic loads and internal loads are applied to the vehicle. Figure 3 depicted typical loads of the vehicle in vertical & longitudinal directions. The external loads including aerodynamic loads on body and control surfaces, and engine thrust are applied at specific locations as concentrated loads. The internal loads including weight and buoyancy are exerted at center of gravity and center of buoyancy, respectively. Control surface loads are usually concentrated at 1/4 mean aerodynamic chord. Since gravity center of the whole system varies for diverse flight maneuver conditions and ground loading conditions, the reference point or origin (the relative stationary point) is chosen at the center of volume.

Aerostatic lift (buoyancy $B$) can be computed from the volume of helium as

$$B = (\rho_{air} - \rho_{helium}) V$$  

Lift, drag, and pitching moment generated by the envelope are calculated from dynamic pressure and volume:

$$L_D = C_L V^{2/3} q$$  

$$D = C_D V^{2/3} q$$  

$$M_y = C_M V q$$

in which the coefficients $C_L$, $C_D$, $C_M$ are relevant to vehicle angle of attack. Empennage lift is calculated from the contributions of empennage angle of attack and flap deflection, such as

$$L_{emp} = S_{emp} q [(dC_{emp} / d\alpha_{emp})\alpha_{emp} + (dC_{emp} / d\delta)\delta] \cos \theta \cos \alpha$$

Due to the installation angle of control surfaces at the tail, vertical lift is mainly provided by horizontal stabilizer and vertical lift is mainly provided by vertical stabilizer. Taking into consideration the decomposition of thrust vector with respect to flight path, we can obtain the total force in the vertical direction (normal to the flight path) and the total force along the flight path respectively as

$$\sum(F_x) = B \cos \gamma - W \cos \gamma + L_D + L_H + L_C + T \tan \alpha / \sqrt{\tan^2 \alpha + \tan^2 \psi + 1}$$  

$$\sum(F_y) = B \sin \gamma - W \sin \gamma - D - D_H - D_C + T / \sqrt{\tan^2 \alpha + \tan^2 \psi + 1}$$

Thus, the load factors along the flight path and normal to the flight path are computed as

$$n_x = \sum(F_x) / [(1 + k_1)W]$$  

$$n_z = \sum(F_z) / [(1 + k_3)W]$$

Considering all the static and dynamic loads, the total pitching moment around center of volume is

$$\sum(M_y) = M_y + [B(1 + n_x)(X_{CV} - X_{CB}) - W(1 + n_x)(X_{CV} - X_{CG})] \cos \gamma - W(1 + n_x)Z_{CG} \sin \gamma + L_C(X_{CV} - X_{CG}) + L_F(X_{CV} - X_{MAC}) + L_H(X_{CV} - X_{kMAC}) + D_C Z_C + D_H Z_H + D_V Z_F + T Z_T \sqrt{\tan^2 \alpha + \tan^2 \psi + 1}$$

The pitching acceleration is expressed as

$$\chi = \sum(M_y) / [(1 + k^2)I_{CG}]$$

Typical loads of the vehicle in lateral direction are shown in Figure 4. The resultant forces and load factor in lateral direction can be expressed as

$$\sum(F_y) = L_{D_{horiz}} + L_{H_{horiz}} + L_{V_{horiz}} + T \tan \psi / \sqrt{\tan^2 \alpha + \tan^2 \psi + 1}$$
Following the same procedure, we can calculate the yawing moment and acceleration as follows:

\[ n_y = \sum (F_y) / [(1 + k_2)W] \]  

(12)

The vehicle moving in the air behaves as it has more mass. The added mass, also called "virtual mass", is characterized by virtual inertia coefficients. The virtual mass is important for dynamic simulation and determination of vehicle accelerations. Various approaches have been used for calculating virtual inertia. The Lamb’s formulas provide an analytical solution for ellipsoidal geometry in potential flow. The eccentricity and parameters of an ellipsoid of revolution with semi-axes \( a \) and \( b \) (\( a \geq b \)) can be expressed as:

\[
\begin{align*}
 e &= \sqrt{1 - b^2/a^2} \\
 \eta &= \frac{2(1-e^2)}{e} \left( \frac{1+e}{1-e} \right) \\
 \lambda &= \frac{1}{e^2} - \frac{1-e^2}{2e^3} \log \frac{1+e}{1-e} \\
 \text{(15)}
\end{align*}
\]

The virtual inertia coefficients can be calculated as:

\[
\begin{align*}
 k_1 &= \frac{\eta}{2-\eta} \\
 k_2 &= \frac{\lambda}{2-\lambda} \\
 k' &= \frac{e^4(\lambda-\eta)}{(2-e^2)(2-e^2)(\lambda-\eta)} \\
 \text{(16)}
\end{align*}
\]

CFD one-degree-of-freedom deceleration simulation provides another way to estimate these coefficients.

### Table 1. Design Maneuver Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Speed</th>
<th>Weight</th>
<th>Attitude</th>
<th>Load Factor and Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Level Flight</td>
<td>( V_{H} )</td>
<td>( W_1 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>2</td>
<td>Level Flight Reverse Thrust</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Nose Down</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>( \Theta &lt; 0^\circ )</td>
</tr>
<tr>
<td>4</td>
<td>Nose Up</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>( \Theta &gt; 0^\circ )</td>
</tr>
<tr>
<td>5</td>
<td>Descent &amp; Pull-Up</td>
<td>( V_{H} )</td>
<td>( W_1 )</td>
<td>( \Theta &lt; 0^\circ )</td>
</tr>
<tr>
<td>6</td>
<td>Turn Entry</td>
<td>( V_{SH} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>7</td>
<td>Turn &amp; Reverse</td>
<td>( V_{SH} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>8</td>
<td>Dive Entry</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>9</td>
<td>Climb Entry</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>10</td>
<td>Turn &amp; Climb</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>11</td>
<td>Turn &amp; Dive</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>12</td>
<td>Turn</td>
<td>( V_{SH} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>13</td>
<td>Turn Recovery</td>
<td>( V_{SH} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>14</td>
<td>Turn Rec. &amp; Climb</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>15</td>
<td>Turn Rec. &amp; Dive</td>
<td>( V_{H} )</td>
<td>( W_0 )</td>
<td>Horizontal</td>
</tr>
<tr>
<td>16</td>
<td>Light Flight</td>
<td>( V_{H} )</td>
<td>( W_{min} )</td>
<td>( \Theta &lt; 0 )</td>
</tr>
</tbody>
</table>

Table 1 lists a variety of design maneuver conditions of the vehicle. These flight maneuver conditions are defined by speed, weight, attitude, and position of control surfaces. The vehicle weight and location of center of gravity have significant effects on static balance and structural performance. \( W_o \) is weight at equilibrium state. \( W_i \) is takeoff/landing weight. \( W_{min} \) is minimum weight. \( V_H > V_{SH} > W_{min} \). \( V_H \) is level flight speed. Vehicle pitch attitude is the angle between earth horizontal plane and longitudinal body axis. The pitch angle and deflection angle of control surfaces are adjusted to accomplish desired flight conditions. Condition 1, 12 in Table 1 are steady state conditions and the others are transient state conditions. Load factors and accelerations vanish for steady state conditions. Load factors are instantaneous values for transient (unsteady) conditions. Condition 1-5, 8, 9, 16 are symmetrical maneuver condition, and the others are unsymmetrical maneuver conditions. The total forces and moments in the
lateral direction are zero for symmetrical flight conditions. Each maneuver condition can generate a set of loading conditions for FE models.

3. Construction of Finite Element Models for the Full Vehicle

The FE model (see Figure 5) of aeroscraft is constructed in compliance with properties and geometry of structural components. The structural components are considered as follows:

1. Since external frame is essentially composed of multiple thin surfaces, it is modeled with 2D shell elements having orthotropic symmetric property.
2. Aeroshell cover is also modeled using 2D shell elements since it is made of laminated layer composites.
3. The structural members of internal frame are simulated as beam elements with isotropic material property. Since internal and external frames are mutually supportive and dependent, they are assumed to be perfectly connected. One way to implement this connection is to create "Coincident Nodes" for two types of elements.
4. All cables are modeled as 1D rod elements and temperature loads are used to apply pretension. The resultant forces in these 1D elements need to be checked since compressive forces can be generated. In this case, a second run of the input file is needed with the removal of those elements having compressive forces.
5. Since canards and empennages are constructed by structural frame and fabrics. These substructures are modeled with a combination of 1D and 2D elements.
6. Fixed weights of components including cockpit, fuel systems, propulsion system, control system, commercial payloads, etc are represented by concentrated masses (0D elements) at specific locations. The weights of light components can be neglected.
7. The connection of various structural systems can be established using NASTRAN rigid elements such as RBE2. The utilization of this MPC introduces additional stiffness to the structure.

It should be noted that the weight of air inside air bags should be considered since air is heavy when placed inside lifting gas. Meshing density of the FE model can be determined based on the importance of the structures. 3D elements are not used in this model since 3D elements can substantially decrease computation speed. Virtual inertia forces should be accounted since they have important influence on the performance of body flying in air.

4. Boundary Conditions and Analysis Methods

The determination of loads and boundary conditions plays an important role in the modeling and analysis of the vehicle. The weights are applied by 1D/2D structural elements or 0D concentrated mass elements. Buoyancy loads are simulated as pressure loads on the top surface of envelope. Conventional static analysis can be used for constrained systems while inertia relief analysis can be employed for unconstrained systems.

a) Conventional Static Analysis

Conventional static analysis is applicable to the cases when the vehicle parks at hangar, which is either supported by multiples ground stands or landing cushions. Generally, only translational degrees of freedom are restrained to generate a statically determinate system. The results of this analysis can be used to evaluate structural behavior when the vehicle is fully inflated with lifting gas. The variation of structural deformation due to purity changes can also be obtained.

b) Inertia Relief Analysis

The system is assumed to be in a state of static equilibrium and acceleration is computed to counterbalance the applied loads. A set of translational and rotational accelerations provide distributed body forces over the structure in such a way that the sum of applied forces and the sum of moments are zero. This technique is applicable to the analysis of various flight maneuver conditions or statically float conditions. A series of loading conditions for flight maneuver conditions have been generated from rigid body motion analysis in Section 2.
5. Stress Analysis of Structural Members of Internal Frame-3D composite trusses

The internal frame consists of multiple 3D trusses. Each truss is made of composite materials and metal connections. In the full vehicle model, each truss is modeled as 1D elements. The loads generated from full vehicle models is applied to individual truss for detailed analysis. The applied loads include axial forces, bending forces, and torque. Each component of 3D composite truss has been modeled to check buckling load factors. Considerable work need to be done for modeling each structural member of internal frame. Thus, some critical structural members are selected for 3D truss analysis. Based on the results of buckling failure modes, some kinds of reinforcements might be implemented, such as add some extra "structural elements".

As shown in Figure 6, a 3D FE model of a composite truss is presented. Rigid elements RBE2 have been used to connect three tubes. In this model 2D shell elements have been utilized to simulate tubes, vertical triangular plates, and interconnection members. The undeformed and deformed configurations of buckling analysis are also illustrated in the figure. Maximum deflection occurred in the middle section of the truss.

![Figure 6. FE model of a 3D Truss and its Undeformed and Deformed Configurations](image)

6. Stress Analysis of Substructure Systems

Besides internal frame, separate FE analyses are needed for some critical substructure systems as shown in Figure 7

a) Engine Support Structures

Left and right side engines provide vertical thrust for vertical takeoff and landing, and forward thrust for level flight. Stress analysis of engine support frame is crucial. A FE model was built to evaluate the connection of engine support frame and internal frame. Generally, the applied loads are specified with a g factor.

b) Landing System Support Frame

Landing cushions are connected to rigid structure of vehicle through a structural frame, which is extremely important for the performances of the vehicle. The support frame was simulated when subjected to pressure loads from landing cushions.

c) Control Surfaces and Control Surface Support Structures

Large amount of aerodynamic loads are applied on canards, horizontal stabilizers, and vertical stabilizers during flight. Not only control surfaces but also their support structures need to be modeled. Special attentions should be placed on the interconnection between these control surfaces and rigid structure.

d) Cockpit Structure

Based on airworthiness requirements, some cockpit structural components should be evaluated for emergency landing conditions. Although the performances of these substructures can be analyzed in the full vehicle models, it is more efficient to perform at the subsystem level.

![Figure 7. Substructure Systems](image)
7. Design Validation & Testing

As shown in Figure 8, ground handling test and float test have been conducted to verify structural integrity and functionality of the vehicle. For the ground handling test, the vehicle was connected to tow truck by towing cables. Landing cushions are operated in the "move" mode to reduce ground friction. It is observed that the vehicle moved forward stably.

Strain gages data for trusses and skin suspension systems and envelope pressure have been collected for float test. It is showed that the envelope pressure at the bottom of the vehicle was close to zero. Structural shape can be maintained without pressurization of the vehicle. Float test also demonstrated that structural integrity has been maintained when subjected to buoyancy loads.

![Figure 8. Aeroscraft Ground Handling Test and Float Test](image)

8. Summary

In this paper, the load analysis of aeroscraft has been presented. Preliminary load analysis has been performed with the assumption of rigid body motion. The construction of finite element models using PATRAN/NASTRAN has been described. A detailed model of a 3D composite truss was provided to illustrate substructure stress analysis. Hangar tests demonstrated that the structural integrity of the vehicle was maintained. The rigid structure has been proved to withstand buoyancy loads. The vehicle can maintain external shape without pressurization. An airship-like aircraft has been designed, developed, and successfully tested.

References