QUASISTATIC AND VIBRATION RESPONSE OF PROTOTYPE COMPOSITE DUCTS FOR AIRCRAFT COMPONENTS

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Introduction

Miniature unmanned aerial vehicles (UAV's) that are man-portable are ideally suited for remote surveillance in urban environments, inside buildings, and even within pipelines or tunnels [1]. A quad-rotor vertical take-off and landing UAV prototype was designed for close surveillance applications. The engines are housed in ducts in order to protect the rotor blades and other internal components from impact with objects such as buildings. The prototypes in this study consist of only the inner surface of the engine nacelle since initial flights will be tethered and indoors.

The objective of this paper is to compare the predicted and experimentally measured behavior of prototype composite ducts made from both prepreg and wet lay-up material systems. Development and fabrication of the composite ducts was described by Clark and O'Toole [2]. Quasistatic loading and natural frequency vibration analysis and experiments are performed and evaluated.

Description of Composite Ducts

The odd-shaped ducts form the inner surface of the UAV engine nacelles as shown in Figure 1. They were designed for a 254 mm diameter propeller. The length of the bottom of the duct is 205 mm and the length of the top is 410 mm. The back of the nacelle has a rectangular shape to accommodate controllable exhaust vanes.

Figure 1: CAD rendering of duct along with prepreg (center) and wet lay-up (right) prototypes

Prepreg Composite Ducts
The prepreg prototypes were made with six layers of unidirectional carbon fiber in an epoxy matrix with the following stacking sequence, [90/0/+45/-45/0/90], starting from the inside layer. The 0° direction is defined along the x-axis which runs from the back to the front of the nacelle, opposite to the airflow direction. Physical and elastic properties are displayed in Table 1.

Wet Lay-up Composite Ducts
The wet lay-up prototypes were made with four layers of satin weave carbon fiber fabric and unidirectional carbon fiber cloth. The inner and outer layers contained the 0/90 satin weave fabric. Unidirectional cloth was used to form the two inner plies at 45 and -45. The dry fabric was wet out with a room temperature curing epoxy resin and placed in a vacuum bag for about 16 hours.

Table 1: Elastic Material Properties

	Prepreg	Wet Lay-up
Ply Thickness (mm)	0.1	0.3
Elastic Modulus, E_1 (GPa)	130	45
Elastic Modulus, E_2 (GPa)	9	45
Shear Modulus, G_{12} (GPa)	49	21
Poisson's Ratio, ν_{12}	0.33	0.07

Quasistatic Load-Deflection Response

Experimental Procedure
The prototype nacelle ducts were placed in a 3-point bend test fixture as shown in Figure 2. The ducts rest on two 51-mm long support rollers. A similar roller is used to apply a downward force on the top of the duct. The force was recorded with a 50-kg load cell and deflection was measured directly under the applied load. Four specimens of each type of duct were tested and results were very repeatable.

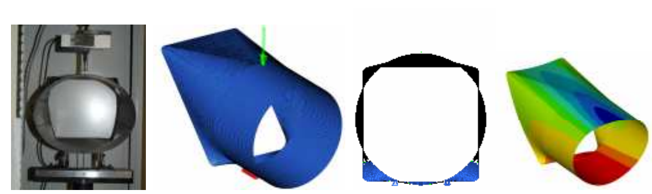

Figure 2: Experimental set-up showing wet lay-up woven fabric duct in fixture (on left), FEA model of loads and supports (center), and deflection contours (on right)

Computational Analysis
Laminate properties were defined in 2-D shell elements created for finite element analysis (FEA) with Altair HyperMesh. The prepreg stacking sequence is shown in Figure 3 where ply 1 is on the inside of the duct. Analyses were run using Altair Optistruct and Radioss. Nodes corresponding to the support roller locations were fixed to have all displacements equal to zero. A uniform force was applied along the length of the top roller and the deflection observed.

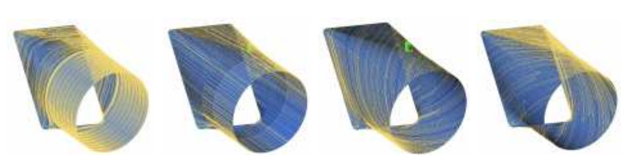

Figure 3: Ply Prepreg Duct Laminate Definition

Quasistatic Results

Loading was applied within the elastic limits of the material, however a slight non-linearity was observed in the load-deflection curve. The FEA simulations were conducted to determine the force required for a 25.4 mm deflection under the load roller. Results are shown in Table 2 for the prepreg and wet lay-up ducts. The FEA simulations and experimental measurements are very close for the wet lay-up ducts. However, the agreement is not so good for the prepreg ducts. It is believed that these ducts rotated on the fixture during loading and were not in contact along the entire length of the load or support rollers, causing the large difference with the FEA simulations.

Table 2: Force (N) Required for a 25.4 mm Deflection

Nacelle Duct Type	FEA	Exp	% Diff.
Prepreg	59	40	48 %
Wet lay-up	235	220	7 %

Dynamic Response

Computational Analysis

LS-DYNA is used to conduct dynamic analysis on the meshed model. The FE model comprises of 15,586 shell elements with orthotropic material properties. Four nodes at the bottom of the nacelle are constrained to restrict translation in the z-direction (vertical direction) and rotation in the x-direction mimicking the boundary conditions of the duct during experiment. The force curve from the experiment is used to simulate the impact on the FE model and record acceleration at the accelerometer location. The FE model is simulated for 18.5 ms.

Vibration Experiments

The experimental setup is shown in Figure 4. The nacelle is struck on one side with a force hammer and the acceleration is recorded with an accelerometer on the opposite side. The output voltage obtained from the force hammer and accelerometer is converted into waveform and displayed by the oscilloscope. A program in MATLAB is written to obtain the Fast Fourier Transform (FFT) of the output acceleration wave, from which the natural frequencies of the nacelle are determined.

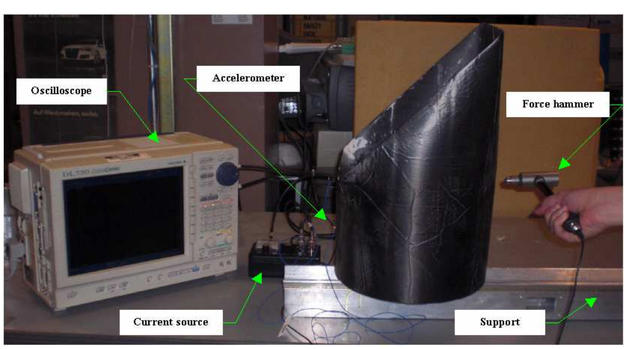

Figure 4: Experimental set-up for dynamic analysis

Dynamic Results

Frequency values are recorded at the peaks found from FFT plots constructed from the accelerometer data and summarized in Table 3. Comparing the simulated natural frequencies for both the nacelle cases it is clear that some of the frequencies are dependent on the shape of the nacelle (108, 810, 1676 Hz), while the rest of the listed frequencies are more dependent on material properties. Similar matching frequencies between the two nacelles can be found in the experimental comparison (277, 888 Hz). The material being composite, and hence orthotropic, it is demanding to accurately define the material model and hence get a good match between the experimental and simulated frequencies. Also, there are wrinkles on the nacelles which are not accounted for in the FE model and might cause suppression/domination of some frequencies. Overall, there is a very good comparison between the experimental and simulated frequencies for a complex shaped composite nacelle.

Table 3: Natural Frequencies (in Hz) of the Ducts

	Prepreg Ducts				Wet Lay-Up Ducts		
No.	**Exp.**	**Anal.**	**% Diff**		**Exp.**	**Anal.**	**% Diff**
1	111	108	2.7		-	108	-
2	277	324	17.0		166	162	2.4
3	388	432	11.3		277	270	2.5
4	554	540	2.5		666	594	10.8
5	721	702	2.6		888	810	8.8
6	887	810	8.7		1055	973	7.8
7	1110	1027	7.5		1140	1135	0.4
8	1665	1676	0.7		1388	1351	2.7
9	1810	1784	1.4		1499	1460	2.6
10	1942	1946	0.2		1721	1676	2.6
11	2109	2270	7.6		2000	2000	0.0
12	2386	-	-		2775	2700	2.7

Conclusion

It was shown that quasistatic and dynamic structural response could be simulated with reasonable accuracy for both prepreg and wet lay-up carbon fiber composite prototypes. The simulations were slightly more accurate for the wet lay-up structures than the prepreg ones. The quasistatic experimental fixture is being modified with smaller supports and load platen so that the boundary conditions are more accurately modeled in FEA.

References

[1] Goebel, Greg "[17.0] Miniature UAVs", **http://www.vectorsite.net/twuav_17.html**.

[2] Clark K., O'Toole B, "Development of a Prototype Composite Duct: A Comparison of Methods and Materials, *Proc. ICCE-17, July 27-31, Hawaii, USA.*