Estimation of Surface Pressure and Strength of Flapping Wings

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Abstract
A combination of finite element modeling (FEM) and artificial neural network (ANN) is employed to estimate the surface pressure of flapping wings. The ANN training patterns are prepared by varying the surface pressure distributions and calculating their associated strains through FEM. Through the well-trained network, the surface pressure can be estimated instantly by the strains measured during flapping. The maximum flapping frequency that represents the strength of flapping wings is then predicted using maximum strain criterion, in which the critical strain was measured using the standard ASTM specimens. The relation between the flapping frequencies and strains is a curve fitted by the data measured under lower and safer flapping frequencies.

Keywords
Flapping wing, Surface pressure, Strength, Wing beat frequency, Artificial neural network, Finite element model

1 Introduction
While fixed-wing flight has advanced rapidly over past 100 years, nature’s flying animals, which have evolved over 150 million years, are still impressive. Based upon observation of flying animals such as birds and insects, most of the studies about flapping flight focus on wing motion and flexible airfoils [1]. Not too many researchers consider surface pressure and strength of flapping wings. To estimate the surface pressure and strength of flapping wings, in this paper a four-bar linkage design was selected as the mechanism for the wing flapping [2]. The wing frame was made by carbon/epoxy fiber reinforced composites and the wing skin by LD-PE plastic. Through the measurement of flapping strains for lower and safer flapping frequencies, the surface pressure and strength of flapping wings can then be predicted with the assist of finite element modeling and artificial neural network [3]. This prediction is then confirmed through the test of flapping to failure.

2. Mechanical properties of flapping wings
The flapping wings studied in this paper consist of wing frame made by carbon/epoxy fiber reinforced composites, and wing skin by thin LD-PE plastic. The flapping mechanism is a four-bar linkage driven by electric motor. To know the elastic properties and static strength of wing frame, a series 230mm×25mm specimens of carbon/epoxy fiber-reinforced composites are made and tested according to ASTM standards [4]. Through the standard procedure, the elastic properties and critical stress and strain of carbon/epoxy fiber reinforced composites used for the wing frame are measured to be

\[ \begin{align*}
E_i &= 45\text{GPa}, \quad E_2 = 8\text{GPa}, \quad G_{12} = 0.8\text{GPa}, \quad \nu_{12} = 0.28, \\
\sigma_c &= 874.8\text{MPa}, \quad \varepsilon_c = 0.0194. 
\end{align*} \] (1)

The LD-PE plastic for wing skin is an isotropic material whose Young’s modulus \( E \), Poisson’s ratio \( \nu \) and density \( \rho \) are measured to be

\[ E = 1.5\text{GPa}, \quad \nu = 0.4, \quad \rho = 947.8\text{Kg/m}^3. \] (2)

3. Finite element modeling of flapping wings
In this study, the finite element modeling was performed through the commercial finite element software ANSYS. The element SHELL91 was selected for the modeling of wing frame and skin whose mechanical properties have been measured and provided in (1) and (2). Boundary conditions are given by fixing all nodes at the wing root. The surface pressures are assumed to be in the form of two variables 2nd order polynomials, i.e.,

\[ p(x,y) = a(x/L)^2 + b(y/H)^2 + c(xy/LH) + d(x/L) + e(y/H) + f, \] (3)

in which \( L(=0.187\text{m}) \) and \( H(=0.066\text{m}) \) are the length and width of the wing. Mapped meshes are used for dividing elements and the element and node numbers are determined through convergence study. The internal and boundary stresses, strains and displacements of the wings can then be obtained by running ANSYS.

Figure 1. Finite element model for flapping wings.
laminates with different stacking sequences, such as $[0]_4$ for regions A1, A3 and A7, $[90]_2$ for A8 and A11, $[0/90/0]_2$/90/0 for A2 and A6 (see Figure 2), $[0]_2$/34/0, /34 for A4, $[0]_2$ for A5, $[90/34/90/34]$ for A9, $[34]_2$ for A10, and the isotropic LD-PE plastics are for the regions A12, A13 and A14. After designation of the material properties for each region of our model, the flapping wing was meshed as that shown in Figure 3. If the wing is subjected to a surface pressure with distribution given by the two variables 2nd order polynomials of eqn.(3) whose (Figure 4)

$$a = 10.98, \quad b = -24.07, \quad c = -4.47, \quad d = -31.84, \quad e = -23.31, \quad f = 3.45,$$

its stress contour analyzed by ANSYS model shown above is presented in Figure 5.

![Figure 2. Layer stacking sequence of wing region A2.](image1)

![Figure 3. Mesh diagram of flapping wings.](image2)

![Figure 4. Surface pressure on the wing.](image3)

![Figure 5. Stress contour diagram of flapping wings.](image4)

4. Artificial Neural Network

An artificial Neural Network is a parallel distributed processor made up of simple processing unit. Similar to biological nervous systems, artificial neural networks can establish relations through neurons and their associated weights. In this paper, the popular used feedforward network, back propagation network (BPN), is utilized to develop a relation between the measured strains and surface pressures.

The most important work in BPN is the revision of weights and thresholds between layers. The object of training stage is to make the output values close to the target. The back propagation neural network belongs to the supervised learning network. The relation between the input and output layers would be expressed in terms of the weights and thresholds of the hidden layer. Figure 6 is a standard architecture of BPN with one input layer, two hidden layers and one output layer. The neurons in the input and output layers are dependent on the design problem. For the present problem, the input vector $p$ includes the values of measured strains at points A, B and C (Figure 7), and the output vector $q$ includes the coefficients of surface pressure, eqn.(3), i.e.,

$$p = \{\varepsilon_{Ax}, \varepsilon_{Bx}, \varepsilon_{Cx}\}, \quad q = \{a, b, c, d, e, f\}.$$
3

Figure 6. Architecture of BPN with two hidden layers [5].

Figure 7. Flapping wings with strain gauges attached on points A, B and C [3].

Generally speaking, there is no rule regarding the determination of neurons in the hidden layer, and the optimal number of neurons is concluded through test results. It is not necessary to have only one hidden layer. More hidden layers could simulate the highly nonlinear relationship between the input and output while sacrificing the speed of convergence. The convergence would be unstable when the hidden layers and neurons increase. In order to map the complex relation between input and output while maintaining a fairly simple architecture for stable convergence, back propagation neural network with two hidden layers is used in this paper.

Consider a four-layer network, the relation between input \( p \) and output \( q \) can be expressed as [5]

\[
q = f(W_4f(W_3f(W_2f(W_1p + c_1) + c_2) + c_3) + c_4),
\]

where \( f \) is the transfer function and \( W_i \) and \( c_i \), \( i = 1, 2, 3, 4 \) are, respectively, the weight matrices and bias vectors. If the target of output is \( d \), the mean square error \( E \) between target and output can be expressed as

\[
E = \frac{1}{2} \sum_{j=1}^{N_o} (d_j - q_j)^2 = \frac{1}{2} \sum_{j=1}^{N_o} e_j^2 = \frac{1}{2} e^T e,
\]

where \( N_o \) is the neuron number of the output layer, and \( e \) is a vector of network errors. To minimize the error function (7), several different optimization methods such as the steepest descent method and LM (Levenberg-Marquardt) method, etc., can be used to update the neuron weights. To put the input and output data in the specified range, normalization is usually made. Table 1 shows parts of the training patterns with input and output vectors stated in (5), which are obtained through the finite element modeling stated in Section 3.

When the training patterns are well prepared, the artificial neural network can be trained by a proper optimization method. Since the architecture of artificial neural network includes the transfer function, the number of hidden layers, the number of neurons in each layer, and the convergence criterion, their selection becomes important for a well-trained network. In this paper, the output vector is specified in the range from zero to one through shifting and normalizing processes, and hence Log-Sigmoid function \( f(x) = (1 + e^{-x})^{-1} \) is selected to be the transfer function. As usual, two hidden layers with 40×20 neuron numbers are tried in this study to find the most suitable network. The convergence criterion is set to be \( E < 10^{-6} \). The training is performed by the commercial software Neural Network Toolbox built in MATLAB 6.5. After the training stage, several testing patterns also prepared through the finite element model are used to examine the wellness of the network.

5. Measurement of flapping strains
To estimate the flapping strength in nondestructive way, the flapping strains are measured under the lower and safer flapping frequencies. By the measured data of strains versus frequencies, the flapping strength may be estimated by extrapolating their relation to the failure frequency of flapping. Since the flapping mechanism designed for this test is a simple up and down flapping motion, the strain values at all wing points are periodical functions of time, and the strain at point A which is close to wing root is much more critical than those at points B and C. The locations of A, B and C are, respectively, (0.0025, -0.038), (0.046,-0.003), (0.0995, -0.033) where the origin is at the wing root (Figure 7).

To predict the flapping strength, only the largest strain in each flapping cycle is concerned in constructing the relationship between the flapping frequencies and measured flapping strains. Figure 8 is an illustrative result for flapping frequencies \( \omega \) versus strains \( \varepsilon \) at the root of the wing, in which the small circle “D” denotes the average of the largest strains of all flapping cycles, and the horizontal bars above and below the small circle stand for the variation of largest strains from different flapping cycles. To best fit a curve for the data of strains-frequencies shown in Figure 8, the least of square error method was used. A straight line was assumed by
\( \omega = a + b \varepsilon \)  

(8)

and the unknown coefficients \( a \) and \( b \) was determined by minimizing the square error, which will lead to

\[
\sum_{i=1}^{n} (a + b \varepsilon_i - \omega_i) = 0, \quad \sum_{i=1}^{n} \varepsilon_i (a + b \varepsilon_i - \omega_i) = 0, 
\]

(9)

where \((\omega_i, \varepsilon_i)\) are the data obtained from the experiments, and \( n \) is the number of data points.

Figure 8. Strain-frequency relation for flapping wings [3].

6. Estimation of surface pressure and Strength

To estimate the surface pressure through the simple strain measurement, the well-trained network stated in Section 4 is used, and the measured strains corresponding to three different flapping frequencies 4Hz, 6Hz and 9Hz are input to get the estimated surface pressures. Table 2 shows the results of this estimation. Using this estimated surface pressure as the applied load acting on the flapping wings, the calculated strains presented in Table 2 show that most of their values are within 10% error of the original measured strains, which is acceptable.

To estimate the flapping strength, i.e., the maximum allowable flapping frequency, the maximum strain criterion is considered in this study, which can be expressed as

\[ \varepsilon < \varepsilon_c, \]

(10)

where \( \varepsilon_c \) are the critical strain in the fiber direction of carbon/epoxy fiber-reinforced composites, and \( \varepsilon \) is the responded strain in the fiber direction. By the relation established in Figure 8 and the critical strain given in (1), the failure frequency of flapping wing is estimated to be 18Hz. By actually flapping wing to failure, the failure frequency of flapping was measured to be 18.7Hz which is closed to our estimation.

Acknowledgements

The authors would like to thank the National Science Council, TAIWAN, R.O.C. for support through Grant NSC 96-2221-E-006-174.

References


### Table 1. Partial training patterns for strains vs. surface pressures.

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<tr>
<th>Pattern number</th>
<th>Input vector</th>
<th>Output vector</th>
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<tr>
<td></td>
<td>$\varepsilon_x$</td>
<td>$\varepsilon_y$</td>
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<tr>
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<td>15.03 $\times 10^{-5}$</td>
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<td>33.21 $\times 10^{-5}$</td>
</tr>
<tr>
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<td>-4.54 $\times 10^{-5}$</td>
<td>5.72 $\times 10^{-5}$</td>
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<td>6</td>
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<td>4.79 $\times 10^{-5}$</td>
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<td>-1.68 $\times 10^{-5}$</td>
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<td>10</td>
<td>70.15 $\times 10^{-5}$</td>
<td>630.80 $\times 10^{-5}$</td>
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<td>11</td>
<td>49.23 $\times 10^{-5}$</td>
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### Table 2. Surface pressures estimated by neural network with strains as input data [3].

<table>
<thead>
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<th>Measured strains</th>
<th>Calculated strains via estimated surface pressures</th>
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<tbody>
<tr>
<td>$\varepsilon_x$</td>
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<td>9Hz 3.490E-4</td>
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<th>Estimated surface pressures</th>
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<tbody>
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<td>$a$</td>
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<td>6Hz 5.259</td>
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