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SUBSPACE SIGNAL RETRIEVE METHOD FOR FLUTTER TEST

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1. INTRODUCTION

It is well known that due to the complexity of the testing environments and bad testing conditions, data obtained from aircraft flutter tests is in general of low quality, bearing features of low signal-to-noise ratio and dense modes. Besides, when the non-linearities, existing in structural construction or material and control systems, are significant, the signal processing of response and flutter boundary prediction will become more difficult. The difficulties arise from two aspects. First, there are some special signal characteristics, such as jump, catastrophe, notably non-stationary process, etc. Second, the conventional processing methods based upon linear system theory are no longer applicable. Hence it is necessary to develop new signal processing techniques for aircraft flutter tests.

In this paper, a new processing approach based on phase-space reconstruction is proposed. In this method, the flutter test data is treated by non-linearity detection to recognize its character and then the appropriate type of processing method is determined. Finally, a subspace signal retrieving technique is adopted to enhance signal quality, which is important for successive stages of analysis.

2. LOWPASS FILTER SUBSPACE METHOD

A dynamic system may be described by means of its data model $x_{i+1} = F(x_i)$. Here, x_i is the vector formed by the observed data through phase-space reconstruction. After obtaining the data model, the trajectories of the dynamic system under excitations can be predicted. Since noises and interference are inevitable in data acquisition processes (this problem is more serious in aircraft flutter), a data model is valid only after the above-mentioned impurities are cleared away by using suitable pre-processing techniques.

A kind of simple retrieving method is developed by finding the major vector directions in the dynamic phase space, and the motion in another direction will be regarded as being produced by noises. Then the aim of noise suppression can be achieved by projecting the motion vectors in the major vector directions. This is the basic concept of the so-called subspace method.

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The lowpass filter subspace method is one adopting the embedding technique. According to Takens' theorem of reconstruction [1], if the dimension of reconstruction is more than double of the dimension of the system attractors, then the constructed phase space is topologically equivalent to the original dynamic system. That means a phase space having the same topological dimension is selected. By the lowpass filter subspace method, the constructed n-dimensional vector x' is

$$x'_i = \begin{bmatrix} s'(i) \\ s'(i+1) \\ \vdots \\ s'(i+n-1) \end{bmatrix} = B \begin{bmatrix} s(i) \\ s(i+1) \\ \vdots \\ s(i+n-1) \\ \vdots \\ s(i+w-1) \end{bmatrix} = Bx_i,$$

where n is the number of frequencies lower than the truncation frequency, w is the window length and $x_i = [s(i), s(i+1), \ldots, s(i+w-1)]^{\mathrm{T}}$ is the original signal registered on the continuous time axis with w. The matrix $B = T_2 T_1 T_0$, transforms x_i to a vector x'_i composed of n new signals $s'(i), s'(i+1), \ldots, s'(i+n-1)$, which is used to span a new phase space.

The linear operators T_0, T_1, T_2 are defined in reference [2].

- T_0: discrete Fourier transformation (FFT) with order w.
- T_1: all components but the lowest $n/2$ frequency components are set to zero.
- T_2: inverse discrete Fourier transformation (IFFT) using the lowest $n/2$ frequency components.

The transform matrix B is essentially a local lowpass filter, which retains the n/w low-frequency parts of the original signal. Almost no useful information is lost through the transformation from x_i to x'_i, while noise contamination are effectively cleared away. Through a relative inverse transform $\hat{B}$, the new vector x'_i will retrieve the real state, i.e., the objective of the test with sufficient accuracy.

The selection of the parameter n and w is important. The number w will be selected to be greater than the fundamental period length, and the selection of the number n is based upon the truncation frequency concerned.

To sum up, the lowpass filter subspace method is carried out as follows:

Each ith set of the original signal $[s(i), s(i+1), \ldots, s(i+n-1)]$, $(i = 0, 1, \ldots, N-w)$, produces by transform B a corresponding point x'_i in an n-dimensional space. In the new phase space, all points $x'_{i,j}$ in the neighbourhood U_i with radius r and center x'_i are found. A centroid c_i of all points in U_i is defined, and the new directional vector $v_{i,j} \sim x'_{i,j} - c_i$ is formed. This directional vector will have greater length along the direction of the attractor than along other directions. Then singular value decomposition to the matrix formed by $v_{i,j}$ is performed. The number of major vectors N_{sv} is selected to be the dimension d_A of the chaotic attractor, and for flutter tests the number of modes, relevant to flutter analysis will be taken as N_{sv}. Then the vectors $v_{i,j}$ are projected on the linear space spanned by the right eigenvectors denoted by $\tilde{v}_{i,j}$. By applying the inverse transform $\hat{B}$, the set $\tilde{v}_{i,j}$ plus the centroid c_i is transformed to $[\tilde{s}(i), \tilde{s}(i+1), \dots, \tilde{s}(i+n-1)]$, which is what is expected to be obtained, i.e., a new predicted value of the original signal $[s(i), s(i+1), \dots, s(i+n-1)]$. Finally, the modified signal $\tilde{s}(i)$, $i = 0, 1, \dots, N-1$, is obtained by averaging all the $\tilde{s}(i)$ predicted above.

3. EXAMPLES OF AIRCRAFT FLUTTER TEST

Using the subspace method for signal retrieving, the length of original data acquired should obey the following requirements. When the length of the valid sample of the data is relatively small, and if the noise reduction process is adopted in the whole data range, the noises will produce serious distortion to the distribution and the dynamic trajectory of the signal in the phase space. The impulse response, such as aircraft response due to small rocket excitation in flight flutter tests, belongs to the above-mentioned case, and a small sample length should be used. On the contrary, for atmospheric or wind tunnel turbulence excitation and frequency sweep excitation employed in flutter tests, the sample length taken should be as large as possible.

Example 1. *Wind tunnel flutter test of a semi-rigid model.* The solid wooden swept wing model had two degrees of freedom, i.e., flapping and pitching about two perpendicualr axes. It was used for studying the non-linear clearance effects on the flutter of all-moving tail surface. The low-speed wind tunnel had a circular test

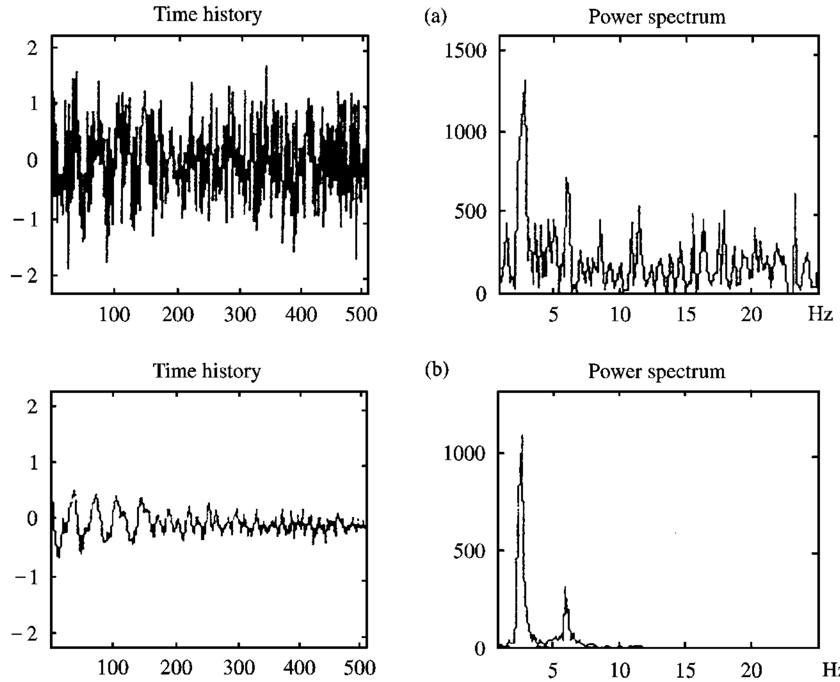

Figure 1. Wind tunnel test data of a semi-rigid wing model. (a) before noise reduction, (b) after noise reduction.

section of 1 m diameter. The pitching acceleration data at air speed 11 m/s is shown in Figure 1(a). The sample length was 512 and sampling rate was 51·2 Hz. It can be seen that due to background noise interference and clearance non-linearity at the wing root junction, the signal acquired has the feature of wide spectrum and very dense spectra peeks. Thus, an accurate judgement of flutter mode is very difficult to make.

The lowpass filter subspace method was used to carry out the noise reduction process. Computational parameter were $n = 16$, $w = 64$, $N_{sv} = 2$. The results in Figure 1(b) clearly show that the time history gets rid of the original chaotic character, and in the spectrum plot the flapping and pitching structural modes stick out, having suppressed the false peaks produced by miscellaneous irrelevant modes and noises.

Example 2. *Wind tunnel test of rear fuselage flutter model of a fighter aircraft*. The model consists of an elastic rear fuselage with vertical tail, rudder and all-moving horizontal tail, for which a set of springs were used to simulate the control system stiffness. A flutter test was carried out in a low-speed wind tunnel with a 3 m $\times$ 2 m rectangular test section.

The structural response signals collected from accelerometers on the horizontal tail at air speed 33 m/s are shown in Figure 2 with sample length 1024 and sampling rate 51·2 Hz.

It can be seen that both time history and power spectrum reflect strong background noise interference and the complexity of the modal composition. The data given by flutter design analysis and aircraft ground vibration tests suggested

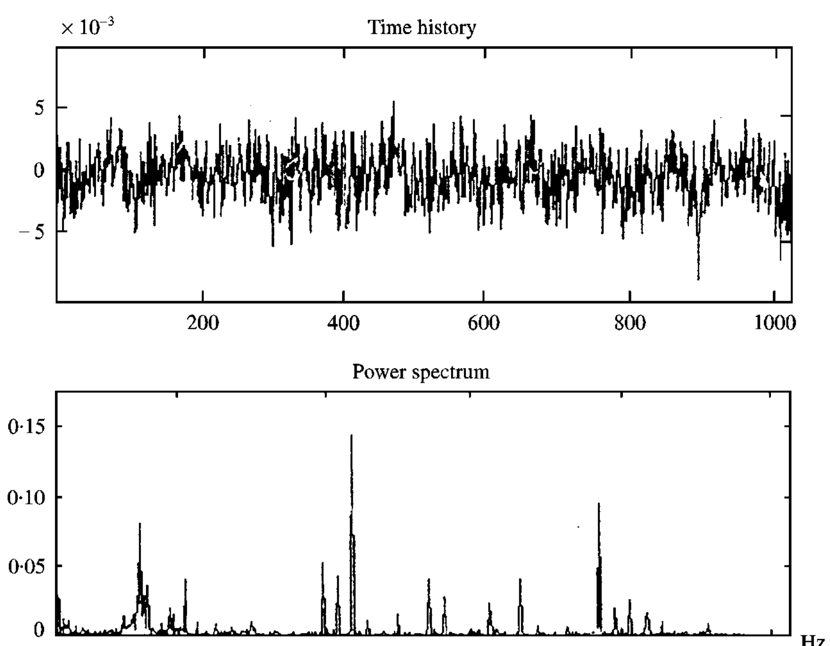

Figure 2. Wind tunnel test data of an aeroelastic rear fuselage model of a fighter aircraft.

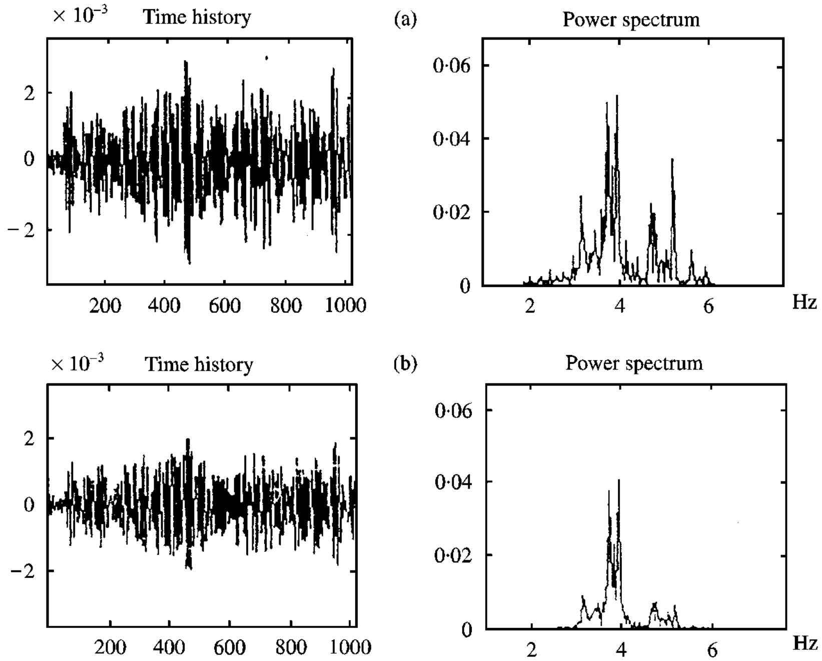

Figure 3. The data of the rear fuselage model after signal processing: (a) after conventional filtering, (b) after noise reduction by the lowpass filter subspace method.

that the most critical flutter mode was fuselage first bending coupled with horizontal tail first symmetric bending, both corresponding frequencies being in the region from 3 to 4 Hz. The flutter frequency recorded in wind tunnel tests was 3·85 Hz, and the flutter speed was 40 m/s. The original signal recorded at air speed 33 m/s was first treated by a conventional band pass filtering process, the results of which are shown in Figure 3(a). Then the lowpass filter subspace method was used to get noise reduction, with $n = 32$, $w = 64$, $N_{sv} = 3$. The results shown in Figure 3(b) depict that the two flutter dangerous modes are pushed forward, and its modal parameter identified has fairly good agreement with the ground vibration test results.

Example 3. *Flight flutter test of a light civil aircraft.* A set of test results obtained from an accelerometer installed on the rear spar near the right wing tip is shown in Figure 4. The flight speed was 281 km/h with data length 1024 and sampling rate 64 Hz. The time history record shows that the impulse response decays quickly, and the signal after the 200th point can be regarded as the structural response to atmospheric turbulence. Hence, the whole signal was divided into two parts with data length 512, one representing the impulse response and the other the turbulence response. Both sets of data were treated for noise reduction by the lowpass filter subspace method with the same algorithm parameter, i.e., $n = 64$, $w = 128$, $N_{sv} = 4$. From the results shown in Figure 5, two conclusions can be drawn. First, after noise reduction, three major modes are distinguished from other mixed modes. Second,

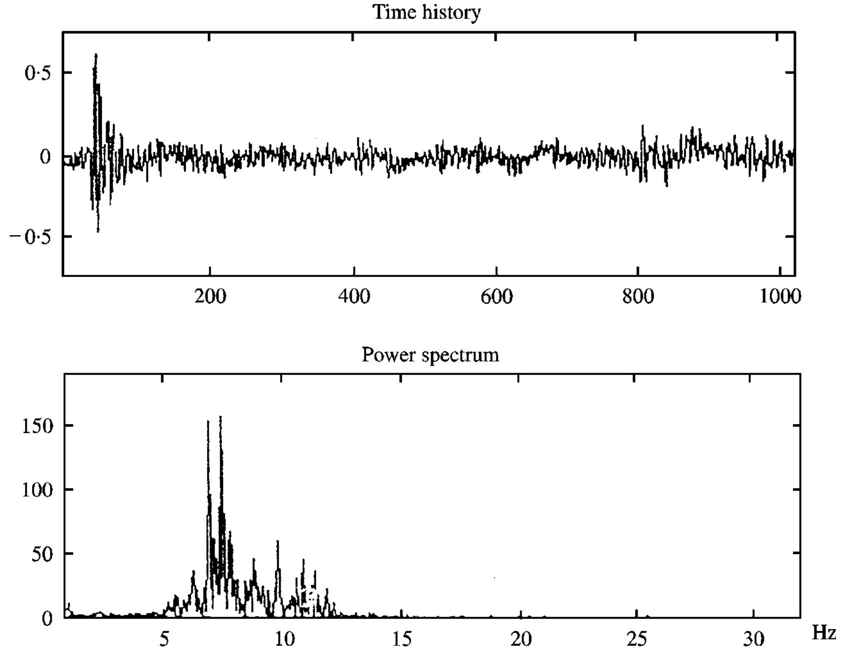

Figure 4. Flight flutter test data of a light civil aircraft.

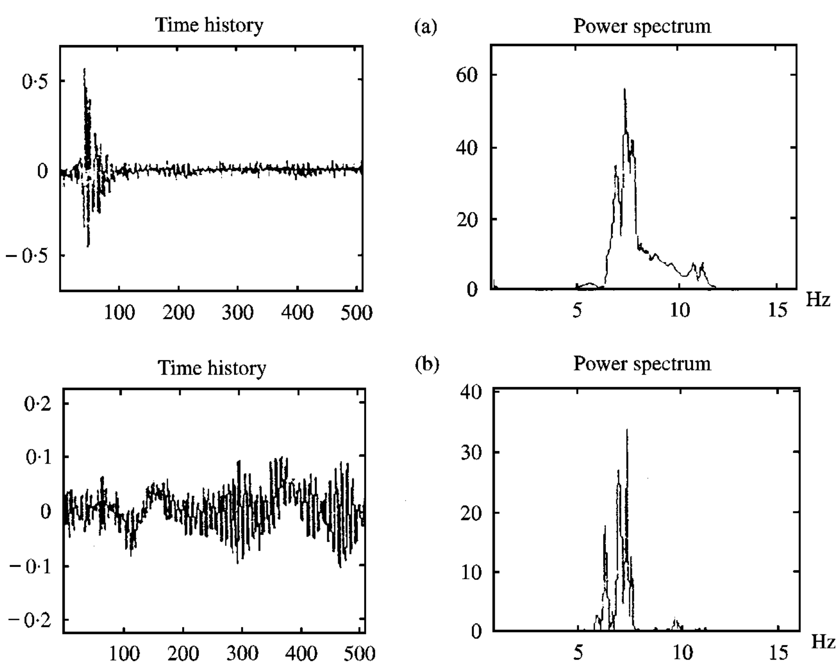

Figure 5. Results after application of the lowpass filter subspace method to the third example: (a) the impulse response, (b) the turbulence response.

the subspace processing has rendered the turbulence response having nearly the same features as those of the impulse response. That means, if only the appropriate data processing method is adopted, the more economic excitation such as atmospheric turbulence can also supply enough information in flutter testing.

4. CONCLUDING REMARKS

A kind of vibration data processing method, the subspace signal retrieving method, is introduced for aircraft flutter tests. It is simple and effective and especially useful for flight flutter tests. The results have shown that the method is suitable and feasible in practice.

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