Minimum Attenuation Frequency Selection Method for Composite Tailplane Structural Health Monitoring

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ABSTRACT

Practical and reliable structural health monitoring for composite structures using PZT based active sensing scheme significantly depends on effective frequency selection. It is found that the attenuation coefficient of the guided wave may become disproportionate to frequency in a real application when the structure under concern is loaded, which may cause difficulties to select ideal frequencies for the diagnostic guided waves. Hence, this paper presents a surface fitting-based frequency selection method for composite plates with attached or embedded sensor network to automatically realize *in-situ* actuation frequency selection. Using this method the expression of attenuation coefficient can be obtained by polynomial fitting. And hence the frequencies of the guided wave with maximum amplitude can be found in the serched frequency range.

Key words：Composite, structural health monitoring, attenuation coefficient, frequency selection method

INTRODUCTION

The use of composite materials has substantially increased in the area of high performance mechanical structures due to their high strength-to-weight and stiffness-to-weight ratios[1, 2]. Due to the designability of fiber orientation and layer of composite structures, their strength varies in different regions. Accordingly, compared with metallic structures, structural health monitoring of composite structures has several challenges. First of all, viscoelasticity property of composite materials,

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seriously attenuate lamb wave energy along its propagation path[3]. Therefore, an appropriate signal excitation method must be implemented in order to obtain better signal to noise ratio and energy concentration. Secondly, the signal modal analysis of anisotropic laminated plates is more complex[4] and also, frequency selection for single-mode signal production is more difficult. Finally, since composite structures have regional properties, the lamb wave propagation characteristics depend to both frequency and region. To resovle these challenges, many researchers have focused on frequency selection methods to reduce signal attenuation which results in better SNR and energy concentration[3, 5-7].Solie and Auld have solved the dispersion equation of anisotropic laminated plates in medium wave frequency by using wavelet method[5, 6]. They have shown that, although anisotropic laminated board has more complex form compared with isotropy one, their signal attenuation are the same. Rose and Cawley have demonstrated that the minimum attenuation coefficient can be obtained by using frequency selection methods[3, 7].

According to these challenges of composite structural health monitoring, this study, focuses on the effect of composite tailplane feature to its health monitoring signal, and presents a frequency selection method to reduce signal attenuation. A set of experiments are carried on to verify the proposed method. Experimental results are demonstrated that the signal amplitude of each path has been maximized with the help of the proposed minimum attenuation frequency selection method.

FREQUENCY SELECTION METHOD

Viscoelasticity Attenuation and Regional

To present frequency selection method, structural characteristics and lamb waves propagation characteristic should be analyzed. Compared with traditional material, composite tailplane structural characteristics mainly include viscoelasticity attenuation and regional heterogeneity.

Viscoelasticity structural is provided with the ability of spread energy as elastic material and ability of attenuation energy as viscous medium. In order to analysis wave propagation behaviour of viscoelasticity medium, viscoelasticity model was constructed, model was constituted by spring and damper, where spring represent elastic behavior, corresponding wave propagation, damper represent viscous behavior, corresponding waves attenuation, as shown in Fig.1.

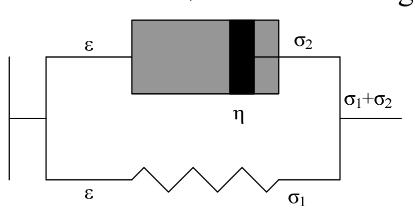


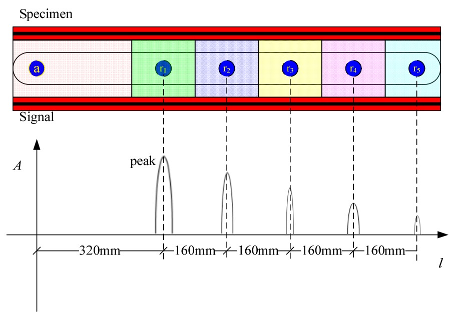
Fig.1 Kelvin-Voight viscoelasticity model

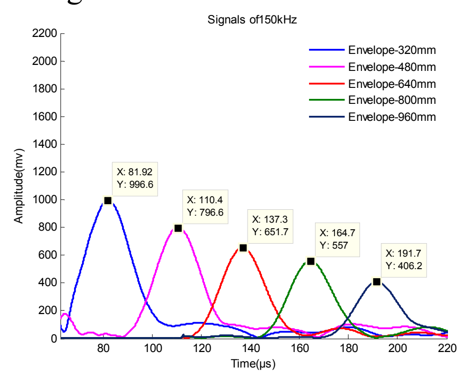
As shown in the Fig. 1 the format of Kelvin-Voight viscoelasticity model was Spring parallel with damper. Structural constitutive equation parameters change into a plural, real part represent elasticity component, imaginary part represent viscous component [6]. So lamb waves displacement field was shown as:

$$u_k(x,y) = U_k(y,k)e^{i(kx-\omega t)} = U_k(y,k)e^{i(\alpha x-\omega t)}e^{-\beta x} \quad (1)$$

Where $e^{-\beta x}$ represent attenuation of lamb waves , β represent attenuation coefficient, was expressed as $\beta = \frac{\ln(A_1 / A_2)}{x_2 - x_1}$ .The attenuation coefficient describes the extent to which the intensity of an energy beam is reduced as it passes through a specific material, it is the inherent nature of structure and important consideration for determining structural health monitoring strategy. Rose and Cawley assume attenuation coefficient linear correlation with frequency ω on the basis of Kelvin-Voight viscoelasticity model.

Composite which used in practical situation always reflect regional. Concept of regional was expounded by experiment as shown in Fig.2.





(a) *(b)*

Fig.2 Regional effected lamb waves propagation characteristic diagram: (a)composite tailplane structural diagram (b) signal Hilbert envelope diagram

Fig.2 shows that regional effected lamb waves propagation characteristic. Arrange six sensors on tailplane parallel to stiffeners, In the array ,a is actuator, while r1~r5 are sensors. There are 5 paths:a-r1, a-r2, a-r3, a-r4, a-r5, excitation frequency is 150kHz. In case of traditional material or general composite result should be like diagram shown in Fig.2(a), because of that wave velocity was identical on the same direction, peaks arrival times should be proportional to the length of path, scale factor is wave velocity; however, signal actual accept by the sensors which was shown in Fig.2(b), we find that peaks arrival times weren't proportional to the length of path, means in the process of transmission wave velocity were changing. This means lamb waves propagation characteristic weren't only depend on frequency but also depend on regional.

Because of the viscoelasticity attenuation and structural regional features of composite tailplane make the frequency selection method which goal is generation single mode lamb waves no longer appliance.

Minimum Attenuation Frequency Selection Method

In response to features of composite tailplane structural, researchers has presented two frequency selection methods, 1.select one frequency for all sensors, which is determine by experience of sensor application 2.Select different frequency for different sensors, and on the basis of signal amplitude, Iterative adjustment frequency. The first method is very efficiently, but it's insufficient to deal with the complicated reality structural characteristics base on laboratory experience ; The second method requires a lot of time to prepare and motivate the time is reduced, the detection efficiency. This article present frequency selection method to obtained minimum attenuation coefficient and maximize signal amplitude.

The frequency selection method as following shown:

1. Determine appropriate frequency range of health monitoring system according to laboratory experience;
2. Determine frequency scanning step obtain signal matrix;
3. Obtain signal distribution of attenuation coefficient and signal;
4. Fit attenuation coefficient distribution with surface fitting ,obtain minimum attenuation coefficient and Minimum attenuation frequency space;
5. Verify frequency selection results, if total amplitude bigger than all of total amplitude of single frequency, is best exciting frequency space.

EXPERIMENT VERIFICATION

The basic principles of Lamb wave viscoelasticity attenuation and frequency selection method were verified through simple laboratory experiments.

Experiment specimen

There were two different specimens for the experiment, aluminum alloy plate and composite tailplane.

Size of the aluminum alloy plane was (50*50*1.4) and location of sensor was shown in Table 1.

Table 1 Sensors location coordinates on aluminum alloy plate

Sensor No.	a	r1	r2	r3
X(mm)	0	300	300	0
Y(mm)	0	0	440	440

Location of sensors on the composite tailplane was shown in Table 2.

Table 2 Sensor location coordinates of composite tailplane structural experiment

Sensor No.	a	r1	r2	r3	r4	r5
X(mm)	0	320	480	640	800	960
Y(mm)	0	0	0	0	0	0

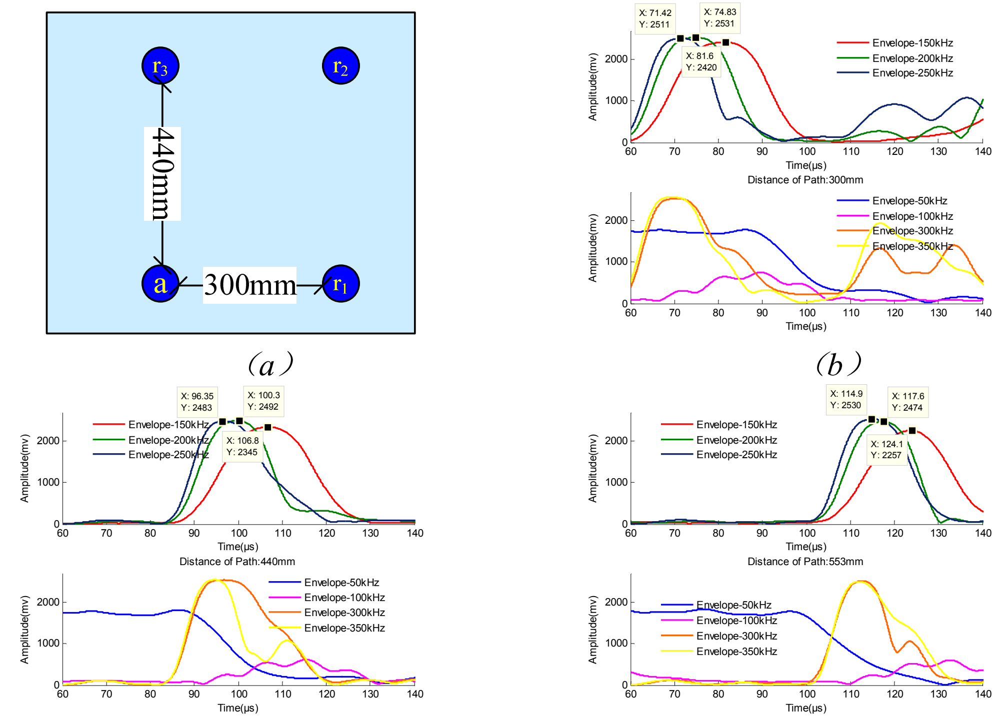
Experiment procedure

Follow minimum attenuation frequency selection method, the experiment is divided into five steps.

A. Determine appropriate frequency range

Before composite tailplane appropriate frequency range of health monitoring system has be determined with help of aluminum alloy plane and 4 piezoelectric sensors was in the Laboratory .Size of the aluminum alloy plane is 50*50*1.4 and location of sensor is shown in Table 1.

In the array, sensor a# is actuator while r1~r3# are sensors. There are three paths a-r1, a-r2, a-r3, signal frequency range is 50-350kHz, step frequency is 50kHz.Hilbert envelope of the signals are shown in Fig.3 (b-c):



(a) (b)

(c) (d)

Fig.3 Aluminum alloy plate test diagram: （a）composite tailplane structural and sensors diagram；（b）signal Hilbert envelope of 300mm path；（c）signal Hilbert envelope of 440mm （d）signal Hilbert envelope of530mm.

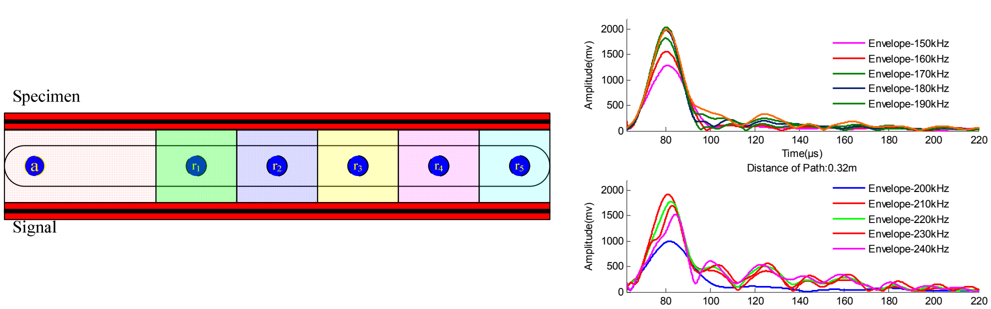
Fig.3(b-c)demonstrate that sensor signal quality was best in 150-250kHz frequency range，signal; Envelope diagram demonstrated that maximum peaks of signal appear in 200-250 kHz frequency range. In next step, frequency range was chosen in 150-250 kHz.

B. Obtain tailplate structural signal matrix

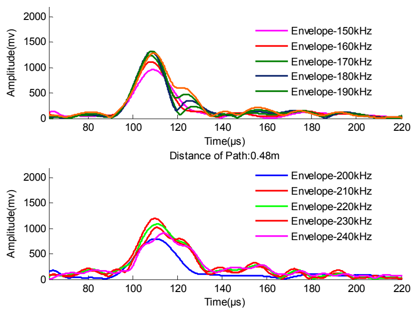
Appropriate frequency range was obtained in step A，therefore in this step, frequency range was chosen in 150-250kHz.In the array, sensor a# is actuator， while r1~r5# are sensors. There are 5 paths：a-r1，a-r2，a-r3，a-r4，a-r5，signal frequency range is 150-250kHz，step of frequency is 10kHz.

Location of sensors on the composite tailplane was shown in Table 2.

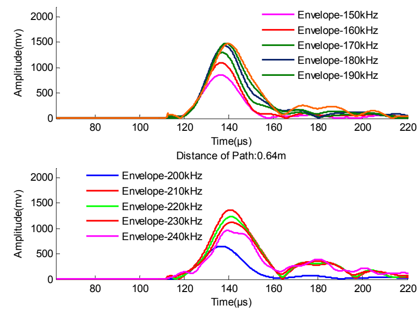
Hilbert envelope of the signals are shown in Fig.4（b-f）:



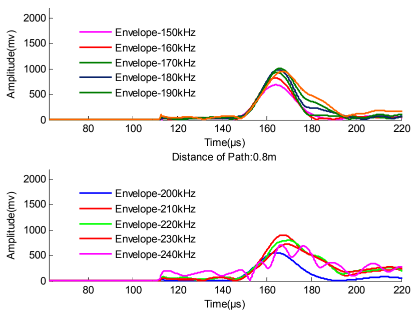
(a) (b)



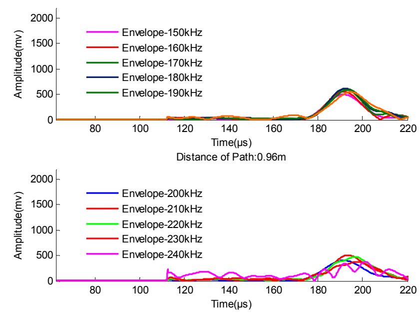
(c)



(d)



(e)



(f)

Fig.4 Composite tailplane structural best exciting frequency selection method diagram: (a) composite tailplane structural and sensors diagram; (b) signal Hilbert envelope of 320mm path; (c) signal Hilbert envelope of 480mm (d) signal Hilbert envelope of 640mm; (e) signal Hilbert envelope of 800mm; (f) signal Hilbert envelope of 960mm.

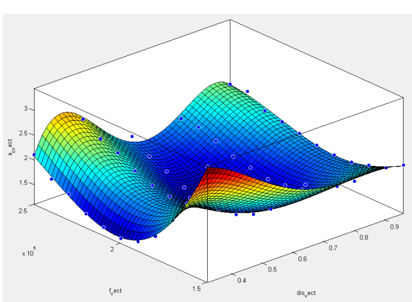
Through actually structure test, signal matrix was obtained.

C. Obtain distribution of attenuation coefficient and signal amplitude

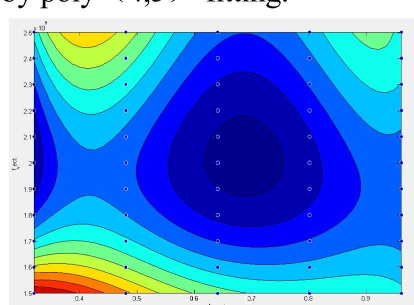
On the basis of attenuation coefficient expression, attenuation coefficient distribution has been obtained. With the help of signal feature extraction method, signal amplitude distribution has been obtained.

D. Attenuation coefficient distribution fitting

Attenuation coefficient distribution was obtained by disposing signal matrix, polynomial surface fitting has been apply for obtain the tendency. Variation trend of attenuation coefficient with (ω, x) was presented by poly（4,5） fitting.



(a)



(b)

Fig.5 Attenuation coefficient surface fitting results diagram : (a) Attenuation coefficient surface fitting diagram , (b) Attenuation coefficient isohyets line diagram

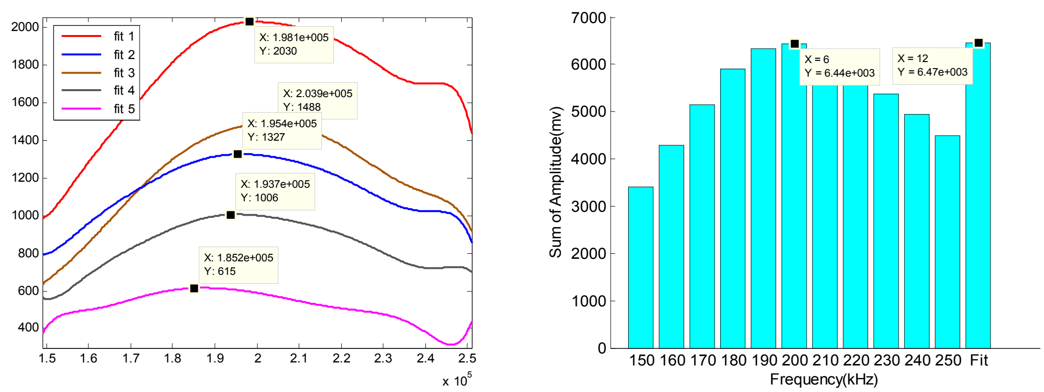
Fig.5 demonstrated that attenuation coefficient in low frequency range bigger than high frequency range it's generally consistent with experience， but on the basis of assume by Rose and Cawley attenuation coefficient should be linear correlation with frequency,but as shown in Fig.5 attenuation coefficients were no longer linear correlation with frequency. Minimum attenuation coefficient space was shown in Table5 .

Table 5 minimum attenuation coefficient

Path No.	a-r1	a-r2	a-r3	a-r4	a-r5
length of path(mm)	320	480	640	800	960
Minimum attenuation frequency (kHz)	198	204	195	194	185
Minimum attenuation coefficient space (Np/m)	1.237	1.725	1.167	1.293	1.65

E. Results verify

Amplitude distribution of every signal were fit with the help of 4 order Fourier fitting respectively and obtain signal amplitude space which corresponding minimum attenuation frequency space. Fig.6 demonstrate that amplitude of every path has been maximized, it means Minimum attenuation frequency selection method obtain best exciting frequency space.



(a) (b)

Fig.6 Frequency selection method results : （a）signal amplitude—frequency curve, （b）frequency signal total amplitude

RESULTS AND DISCUSSION

As shown in Fig.3, signal amplitude attenuation of paths 300mm-530mm is very weak, it means that viscous damping of aluminum alloy plate is weak and it can be defaulted as elastic material.

From Fig.5, it could be seen that different from laboratory experiments and Kelvin-Voight viscoelasticity model assume, the attenuation coefficients present frequency domain nonlinear distribution because of composite tailplane structural different regional fiber content， so elastic wave attenuation characteristics present regional.

Average signal amplitude of difference paths signal is shown as Table3. As shown in Table 3，signal in composite tailplane attenuation very seriously，signal into the original half pass 0.48m,signal into a third of the original pass 0.64m.Fig.4(b-f) demonstrate that signal quality has been began to fall when frequency exceed 240kHz, it means composite tailplane structural damping to seriously high frequency signal; in addition, biggest signal amplitude of every paths appear in 190kHz weren't expected in 250kHz, it means because of structural features of composite tailplane its structural health monitoring can't completely reference laboratory experience.

Table 3 Average signal amplitude of difference paths signal

Material of specimen	Aluminum alloy plate			Composite tailplane				
Length of path(mm)	300	440	533	320	480	640	800	960
Signal amplitude(mV)	2298	2315	2271	1691	1114	1179	827	505

CONCLUSION

In this paper, a frequency selection method base on minimum attenuation coefficient for Lamb waves has been presented for damage detection on a stiffened composite structure with attached PZT sensors. It consisted of a combination of the signal feature extraction method, which employed Hilbert transform, and the surface fitting method, which enabled the computation of the minimum attenuation coefficient of the guilded wave on a certain path. In the study the PZT sensors were installed on a stiffened panel and the paths parallel to stiffeners have been studied. Experimental results showed it was feasible to find the optimal frequencies for the guided waves used for damage detection using the proposed minimum attenuation frequency selection method. For further investigation, additional testing of the method in various configurations is envisaged, such as arbitrary path that may cross stiffeners and greater frequency range.

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