A METHOD BASED ON VIRTUAL WAVE FRONT FOR ACOUSTIC EMISSION SOURCE LOCATION IN LAMINATES

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ABSTRACT

The sensor systems to detect impacts on spacecraft promote a demand for acoustic emission (AE) source location method in laminates. Based on the principle of virtual wave front, a new AE source location method for the laminates is derived, a univariate function is used to present the location problem. Experiments have also been carried out on both unidirectional and bidirectional glass fiber reinforced epoxy composites laminates using both lead-break and hypervelocity AE source. The experimental results indicate that: this method can be used in the laminates effectively, when the wave velocity in the plate is lower, the location precision will be higher, and compare with using 3 transducers, 4 transducers can obtain a better result, more accurate results can be obtained for hypervelocity experiments. The results provide a reference for the development of the sensor systems to detect impacts on spacecraft.

1. INTRODUCTION

With the increase of space activities, space debris environment has deteriorated, the threat to active spacecraft from orbital debris is severe [1]. To deal with the threat, a new onboard sensor system based on AE technology for locating the impact position and evaluate the effects of impact in real time has been presented [2]. The composite laminates has been widely applied on spacecrafts due to its excellent material properties [3], this also brings forward demands for AE source location method in composite laminates.

As the basic functions of AE technology, AE source location method has received extensive attention and study [4-5]. However, most are for isotropic material but little for anisotropic material. H. Yamada、Salehia and Jeong .et have investigated the AE source location method in anisotropic laminates. With the help of wavelet, Yamada measured the wave velocity of certain frequency beforehand and determined the arrival time of the selected frequency wave, then a algorithm based on dichotomy was used to calculate the AE source[6]. Salehi and Jeong used triangulation method to locate the source in laminates, they established a nonlinear equations used the angles of the transducers to the AE source as variables. The solution of the angles would be obtained by solving the equations, then the AE source position would be obtained base on the angles too [7].

But singular points were found in the monitoring area in the practical application of Yamada's mated, that the algorithm does not converge at those points, so the location method will fail at those points. Salehia and Jeong's method is not effective, there are too many calculation steps. Therefore, a stable AE source location method in composite laminates should be developed. To locate the AE source position stable and accurately, satisfies the technical requirements of the onboard sensor system, the lead break AE source has been utilized to study the AE source location method in anisotropic laminates, and the hypervelocity impact experiment has also been conducted to validate the location method.

2. Source Location Method

2.1. Velocity Measurement

As the laminates is anisotropic, the wave velocity is a function of the propagation direction in the laminates [8], due to the production process, the real velocity is different from the theoretical velocity, the wave velocity should be calibrated in advance. As the s0 mode wave velocity is faster than other modes wave and it's easier to be identified, it's selected for source location operation.

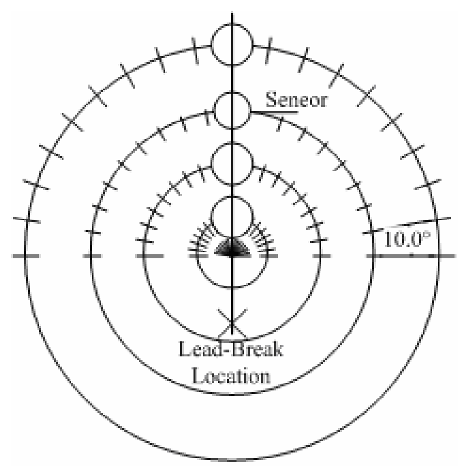

Figure 1. Experimental setup for the measurement of the wave velocities

The wave velocities in 18 directions were measured with 4 transducers, calculated with least square method. Fig. 1 shows the experiment set, 18 directions were selected with 10 degree interval in direction begin from the 0 degree, for velocity measurements, four sensors were placed 100 mm apart along a line from the lead breaking source on the plate, and the arrival times of s0 mode wave were then determined. The distance and arrival times were fitted by the least square method to

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get the velocity. Each direction has been measured 10 times, the mean value would be used as the velocity in the direction, the measured results are shown in the table 1, cubic spline interpolation method was proposed to interpolate the measured velocities to get the velocities in whole direction, the result is shown in fig 2.

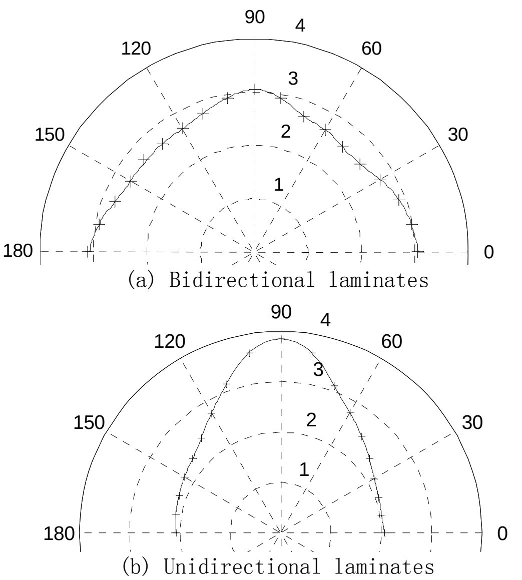

Figure 2 . Experimentally measured group velocity curve for the laminates

Table 1 Measured Velocity in Laminates

Direction Deg	Unidirectional Velocity Km/s	Bidirectional Velocity Km/s
0	2.03	3.05
10	2.03	2.98
20	2.07	2.88
30	2.15	2.72
40	2.30	2.58
50	2.50	2.58
60	2.76	2.65
70	3.11	2.71
80	3.62	2.93
90	3.85	3.05
90	3.85	3.05
90	3.85	3.05
100	3.63	2.93
110	3.15	2.77
120	2.75	2.68
130	2.45	2.66
140	2.29	2.69
150	2.21	2.67
160	2.15	2.77
170	2.11	2.94

2.2. Location Algorithm

After the arrival times of every channel signals determined and the wave velocity calibrated, the source location problem turns to be a mathematical problem. The problem can be described as follows: the system contains N transducers(N>2), the transducers are placed at different points $(x_i,y_i)(i=1\cdots N)$ and receive the signal produced by the AE source at time t0 propagating with velocity $v_i(\theta)$ at time t_i.

This paper supposes that t'_0 is the zero time, and then the propagation time of the AE signal should be t'_0+t_i. If there generated an AE signal at time t_0 at the position of a transducer, the wave front could be determined with Eq. 1 easily

$$l'_i(\theta)=(t'_0+t_i)\times v_i(\theta) \quad (1)$$

As the wave front is fictitious, it’s called virtual wave front. Based on the virtual wave front, every potential position of the AE source can be determined by Eq. 2

$$\begin{aligned} x'_0 &= x_i + l'_i(\theta)\times\cos(\theta) \\ y'_0 &= y_i + l'_i(\theta)\times\sin(\theta) \end{aligned} \quad (2)$$

Eq. 2 shows the calculation method of the virtual wave front. If t'0=t0, the virtual wave fronts would intersect just at the point of the AE source (fig 3), otherwise they would intersect at some other place. When $t'_0\neq t_0$, every two virtual wave fronts will determine one or two (include one false point) intersections. If there exists two intersections, the false point can be identified with the third virtual wave front. There will be at most C_N^2 intersections, the coordinate points of the intersections are (x_{ij},y_{ij}), the points are all the function of t'_0 and t_i

$$\begin{aligned} x_{ij} &= f_1(t'_0,t_i,t_j) \\ y_{ij} &= f_2(t'_0,t_i,t_j) \end{aligned} \quad (3)$$

As t'_0 and each t_i determine the distance between the transducers and the virtual wave fronts, the distance will change with t'_0. With the value of t'_0 approaches to the real zero time t_0, all the intersections will go to the real position of the AE source.

$$\begin{aligned} x_{ij}-x_0 &= 0 \\ y_{ij}-y_0 &= 0 \end{aligned} \quad (4)$$

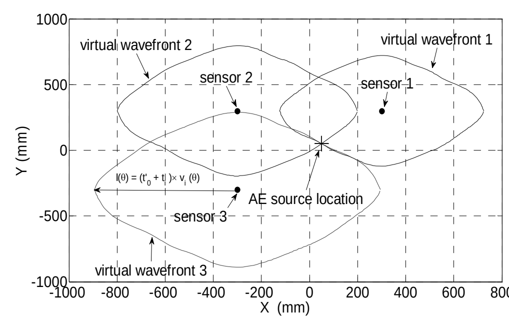

Fig. 3 Illustration of virtual wave fronts in the laminates

The real zero time can be calculated out with Eq. 4, furthermore, the position of the AE source can be calculated out with Eq. 3. Since the arrival time t_i of each channel signals contains some error, it’s not suited to solve Eq. 4 directly. The error of t_i can be measured by the sum of the variance of x coordinate and y coordinate of the intersections

$$f(t_0') = \sigma(x) + \sigma(y) = \sum_{i=1}^{N}(x_{ij} - \overline{x}_{ij})^2 + \sum_{i=1}^{N}(y_{ij} - \overline{y}_{ij})^2 \quad (5)$$

$\overline{x}_{ij}, \overline{y}_{ij}$ are arithmetic mean values of x_{ij}, y_{ij}

$$\overline{x}_{ij} = \frac{1}{N}\sum_{i=1}^{n} x_{ij}$$

$$\overline{y}_{ij} = \frac{1}{N}\sum_{i=1}^{n} y_{ij}$$

The range of the distance between the transducers and the virtual wave fronts can be determined according to the monitoring area: $l \in [l_{\min}, l_{\max}]$, considering the wave velocity, the range of the zero time can be derived, shown in Eq. 6

$$t_0 \in [\frac{l_{\min}}{\max(v_i(\theta))}, \frac{l_{\max}}{\min(v_i(\theta))}] \quad (6)$$

The unique zero of Eq. 5 is corresponding to the unique real position of AE source. The source location problem now has been converted into a mathematical problem obtaining the minimal value of a one-dimensional function. The golden section method is select to solve the function [9]. The basic idea of the method is insert two points into a section containing only one peak properly to divide the section into 3 new sections, then comparing the value of the 2 points and determine which section should be deleted.

Repeat this process, the left section will decreased gradually. The technique derives its name from the fact that the algorithm maintains the function values for triples of points whose distances form a golden ratio. The method is simple, effective and stable.

But the boundary of unknown solution needs to be given first. After the value range and the arrival times of each channel signal has been determined, the minimal value of the function can be derived by Eq. 5, namely, the position of the AE source.

3. Source Location Experiments on Unidirectional and Bidirectional GFRP Laminates

3.1. Experimental Scheme and Results

To validate the source location method, source location experiments were carried out on both unidirectional and bidirectional glass fiber reinforced epoxy composites laminates. The standards of the two specimens were shown in table 2. Although 3 transducers are enough for the location operation, more transducers are deployed to gather more information to improve the location precision, 4 transducers have been used during the experiment. The results derived from 3 transducers and 4 transducers of the location experiments on the bidirectional laminates have been compared, the result shows that use 4 transducers can improve the location precision.

The location test has been carried out on the two specimens using lead break AE source. fig 6 shows the experiment set, 4 transducers are placed on the four corner of the plate, 300 mm apart from both the x and y axis, three circles (radius are 50, 100 and 150 mm) are drawn on the plate, a test point will be set every 90 degree on the 50 mm circle, every 40 degree on the 150 mm circle and every 20 degree on the 250 mm circle begin from the x axis. Signals were generated by fracturing a 0.7 mm diameter HB pencil lead on the surface of the plate, ten times at each test point. The distance between the real position of the AE source and the calculated position was set as location error. The test results show the location error is less than 15 mm and there is no singular point in the monitoring area. Table 5 shows some typical location results.

Table 2 Manufactured Composite plate specifications

	Stacking sequence	Plate size (mm)	material
Unidirectional laminates	$[90_{10}]$	1000×1000×3	glass fiber and epoxy composite
Bidirectional laminates	$[0_3/90_3]_S$	1000×1000×4	

Table 3 Comparison on location error of using 3 transducers and using 4 transducers

test points coordinate	distance(mm)	250									
	direction(deg)	0	100	140	200	220	240	260	280	300	340
mean error mm	3 transducers	13.22	12.95	13.12	25.07	20.31	14.19	19.99	26.67	18.26	15.86
	4 transducers	10.84	7.13	10.40	8.91	9.03	8.83	8.87	13.76	9.03	11.32

3.2. Influence of the Velocity on The Location Result

Table 5 shows the location results of the unidirectional laminates is better than the bidirectional laminates, this is due to the wave velocity in most directions in the unidirectional laminates is lower than the bidirectional laminates. According to equation 1, the wave velocity is directly proportional to the error of the virtual wave front introduced by the error of the arrival times, and so does the location error. Table 4 presents detailed test information of two test points, the wave velocity in same direction in the unidirectional laminate is lower than the bidirectional laminates, so the location error is lower.

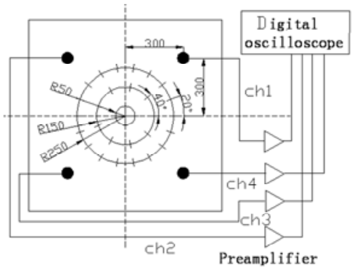

Fig. 4 Lead break source location experiment set

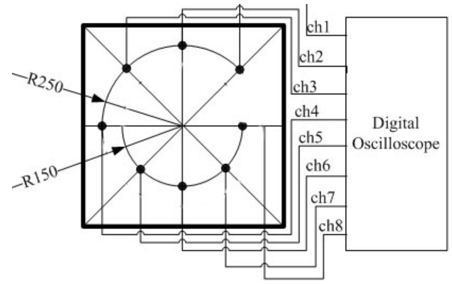

Fig. 5 Hypervelocity impact source location experiment set

Table 4 influence of the velocity on the location result

test points coordinate	Distance (mm)	50		50	
	Direction (deg)	0		90	
Wave velocity	channel	ply sequences		ply sequences	
		bidirectional	unidirectional	bidirectional	unidirectional
	1	2.58	2.51	2.58	2.51
	2	2.65	2.30	2.65	2.30
	3	2.57	2.31	2.56	2.31
	4	2.66	2.46	2.65	2.46
mean error （mm）		11.32	7.86	10.63	4.85

Table 5 Comparison on location error of two different laminates

test points coordinate	distance(mm)	0	50				150				
	direction(deg)	0	0	90	180	270	0	80	160	240	320
mean error mm	Unidirectional	7.60	7.86	4.85	6.30	8.29	8.75	6.95	5.01	7.83	7.3
	bidirectional	7.98	11.32	10.63	11.22	14.09	13.22	10.55	9.12	12.39	12.32

Table 5 (continued) Comparison on location error of two different laminates

test points coordinate	distance(mm)	250									
	direction(deg)	0	100	140	200	220	240	260	280	300	340
mean error mm	Unidirectional	8.17	7.92	9.00	11.74	9.87	7.92	11.84	9.31	10.98	12.09
	bidirectional	10.84	7.13	10.40	8.91	9.03	8.83	8.87	13.76	9.03	11.32

4. Hypervelocity impact source location experiment

A two-stage light-gas gun was used to accelerate the spherical aluminum projectile, the projectile will impact the laminates with a very high velocity, which more closely simulate the impact event caused by hyper-velocity impact of space debris. The two different laminates mentioned above were used in this experiment, the specimens were all cut to 500×500 mm. 8 ultrasonic transducers were deployed to receive the signals from the hypervelocity impact AE source, as the signals are strong enough, the transducers were linked directly to the digital oscilloscope. The transducers were placed on the laminates as shown in figure 5, transducers 1 to 4 are 200 mm apart from the origin while transducers 5 to 8 are 150 mm apart from the origin. three different experiments were conducted on the specimen, 2 times on the bidirectional laminates and one time on the unidirectional laminates. The experiment parameters and results are shown in table 6, these location results are better than the lead break source location experiment results, this is due to its s0 mode wave is much stronger than the lead break AE source location experiment. . Fig 6 shows a comparison of the signals from the two different AE sources, s0 mode wave in the signal produced by hypervelocity impact is much stronger than the signal generated by lead the break. So, more accurate arrival times will be obtained.

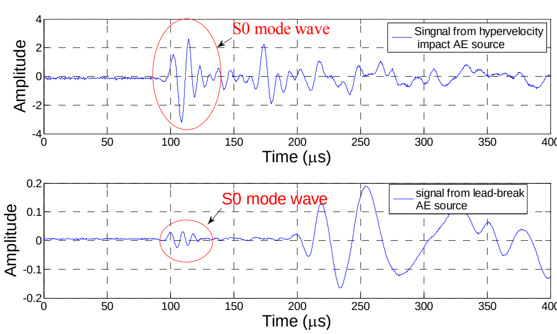

Fig. 6 Comparison of the signals generated by two different AE sources

Table 6 Hypervelocity impact source location experiments results

Experiment number	Velocity Km/s	Damage mode	Laminates type	Location error (mm)	
				4 transducers	8 transducers
2008072401	1.67	penetration	bidirectional	1.0083	1.9872
2008072501	2.10	penetration	bidirectional	7.9345	6.1261
2008072601	1.97	penetration	unidirectional	2.7204	2.1108

5. Conclusion

In order to locate the AE source in laminates accurately, meet the technical requirement of the onboard sensor system, a new source location method in composite laminates has been developed, and the new method provides a reference for the development of the sensor systems to detect impacts on spacecraft. The location problem is simplified to be a univariate function based on the concept of virtual wave front, the new location method needs at least 3 or more transducers. The lead break source and impact source location experiment were carried out both on unidirectional and bidirectional laminates to confirm the location method, the experiments' results indicate that:

(1) The location error of the method is less than 15 mm, which can satisfy the engineering accuracy requirements. As the wave velocity was measured and irregular, it's expected that the location method can be expanded to other anisotropic laminates.

(2) The positioning precision and the wave velocity have an inverse proportion relation.

(3) Compare with using 3 transducers, using 4 transducers can obtain a better result, it means that the multi-sensors scheme can improve the positioning precision to a certain extent.

(4) The impact experiments show the location method is still feasible for hypervelocity impact AE source location, the precision also increased significantly due to the s0 mode wave is stronger.

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