ACOUSTIC EMISSION FOR FATIGUE DAMAGE DETECTION OF STAINLESS STEEL BELLOWS

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Abstract

We utilized acoustic emission technique to monitor crack progression of a formed 300 mm long stainless steel bellows subjected to cyclic axial loading with vibration amplitude of 15 mm. AEs from fatigue cracks in 0.12 mm thick bellow with 10 convolutions were monitored by three resonant type AE sensors mounted on the flange weld to the bellow ends. The bellows failed at 26770 cycles after producing three circumferential cracks near the upper jig and lower flange. First AE was detected at 21782 cycles. This timing was 1500 cycles earlier than the first circumferential crack near the upper jig observed by video camera. AE count increased after 24000 cycles at which large third circumferential cracks were produced near the lower flange. Wavelet analysis of AE signals showed largest amplitude at approximately 180 kHz at which the group velocity is measured as 3100 m/s. Three cracks in the axial direction were correctly located using this group velocity.

Keywords: Bellows, Fatigue crack, Wavelet analysis

1. Introduction

Bellows is a convoluted shell consisting of a series of toroidal shells, usually connected with annular plates called sidewalls [1, 2]. It provides additional flexibility for shell structures such as piping and heat exchanger. For these applications, fatigue fracture is important problem because vibration is inevitable. The critical fatigue damage is a crack initiation which allows fluid leakage. Therefore, fatigue crack initiation must be accurately monitored in the fatigue critical application.

In this study we evaluated fatigue strength of the bellows using AE technique. Crack initiation and propagation were successfully monitored by cylindrical wave AE [3, 4]. Source location estimated by quantitative analysis of cylindrical wave AE agreed well with the fatigue cracks.

2. Wave Propagation Characteristic and Source Location Method

Estimation of AE source location on the bellows is much more difficult due to complex shape of the bellows. We first studied propagation characteristics of elastic wave in the axial direction of the bellows. Shown in Fig. 1 is shape and size of the bellows tested. In the fatigue test, we monitored AEs by four AE sensors mounted on the one-end flange. For the source location in axial direction, we first studied cylindrical wave of the bellows. We exited elastic waves by lead breaking on the crown top of the bellows and monitored by two resonant-type AE sensors (PAC, Type PICO, center frequency 450 kHz) mounted on the crown top in Fig. 1.
Distance of channel 1 and 2 sensors was changed from 5 convolutions (total zigzag propagation distance along 5 convolutions: 96.5 mm) to 10 convolutions (193 mm). Figure 2 shows typical AE signals from ch. 1 and ch. 2 sensors and their time transient of wavelet coefficients at 180 kHz. We utilized the first arrival component for the location analysis.

Group velocity of the first arrive wave was measured by the time differences of first peaks and determined as 3100 m/s. Figure 3 shows overlapping of theoretical velocity dispersion curves of L (0, 1), F (1, 1), F (1, 2) and F (1, 3) of a 52.6-mm diameter pipe of 0.12-mm wall thickness and the wavelet contour map of the wave measured for the bellows. Here the diameter 53 mm corresponds to an average diameter of inner and outer diameters of the bellows. The measured velocity of 3100 m/s at 180 kHz appears to coincide the group velocity.
of F(1,1) mode. Source location in the axial direction was then estimated using the group velocity 3100 m/s and the equivalent diameter of 53 mm.

Next we attempted to determine the source location in the circumferential direction. Figure 4 shows an experimental setup for location determination. We excited elastic wave by breaking a pencil lead at the crown top of several convolutions from the flange. Here the convolution number \( l \) was changed from 1 to 10. AEs were monitored by three AE sensors (ch. 1 to ch. 3) mounted on the flange at 90° interval. Figure 5 shows AE signals from convolution of 1, together with their time transient of wavelet coefficient at 180 kHz. The sensors on the flange detects first packet of the wave with large enough amplitude for the source location. Then we estimated the circumferential locations using the arrival time difference of the first 180 kHz component and the group velocity of 3100 m/s. Figure 6 shows location results for \( l = 1 \sim 10 \). There observed a fairly good agreement between the given and estimated sources.
Fig. 5 Detected AE signals (upper) and their amplitude variations of wavelet coefficient (lower) at 180 kHz for $l = 1$.

3. Damage Detection on the Bellows

3.1 Experimental Setup

Experimental setup of fatigue test was shown in Fig. 7. A 300 mm long bellows was attached to jigs of fatigue machine as shown in Fig. 8. Lower jig was fixed and upper one was actuated at 1 cycle/s with a maximum displacement of 20 mm. Fatigue of upper 10 convolutions was, however, eliminated by attaching a special jig to give the lower ten convolutions large vibration displacement.

AEs from fatigue cracks in lower 10 convolutions were monitored by PICO sensors mounted on the lower 10-mm

Fig. 6 Estimated source location.

Fig. 7 Setup for AE monitoring during fatigue test of type-A (left), type-B (right).
thick flange as shown in Fig. 8. The bellows was welded to the flange. We utilized two-types of AE monitoring method shown in Fig. 7. One of four sensors (A) and five sensors (B) was used as a trigger signal to stop the fatigue test. Thus, AE signals were monitored by three (ch. 1, 2, 3) and four (ch. 1, 2, 3, 4) sensors in type-A and -B system, respectively. Sensor outputs were pre-amplified 40 dB, digitized at 200 ns interval, and fed to a computer. The trigger sensor signals were digitalized at 1 µs interval. Type-A and -B systems were used for fatigue tests with 25 mm and 30 mm displacement, respectively.

![Fig. 8 Figure of specimens with jig.](image)

3.2 Results of Fatigue Tests

Figure 9 shows that load, $P_{\text{max}}$, changes with the number of cycles, $N$. Figure 9(a) represents $P_{\text{max}}$ change and AE timing over entire cycles up to 38586, and Fig. 9(b) in expanded cycle number from 37500 to 38586. This bellows sustained cracks at the root of convolution near the lower flange between ch. 2 and ch. 3 sensors as shown in Fig. 10. Figure 9(b) shows that the first AE was detected at around 37630 cycles, 1000 cycles before the test finished at 38586 cycles. We detected 7 events before 38586 cycles. Figure 11 shows AE signals and their amplitude variations of wavelet coefficient at 180 kHz. We detected AEs with high S/N ratio and large $S_0$ component that are adequate for source location. In Fig. 12, damage areas are indicated by gray tone, and AE sources of 7 events were located close to the observed crack location.

![Fig. 9 Relationships between load $P_{\text{max}}$ and AE timing at number of cycle $N$.](image)

![Fig. 10 Observation of fatigue crack.](image)
In the type-B test with 30 mm vibration displacement, we monitored crack initiation by one video camera. Figure 13 presents load and cumulative AE counts with $N$. We monitored the first AE at 21782 cycles, but no load reduction at this moment. AE increased continuously from 21782 to 2400 cycles and rapidly increased from 2400 cycles. Figure 14(a) shows the first circumferential fatigue crack near the upper jig at 22486 cycles. After this timing the load slowly decreased. Fatigue crack progressed in the circumferential direction and second crack started at around 22800 cycles when load decreased rapidly. This second crack could not be captured by the CCD camera since the crack occurred on the opposite side. At 24000 cycles at which sudden load drop and large event rate were observed, third circumferential crack was produced near the bottom flange, as shown in Fig. 14(b). Figure 15 shows the location result of type-B test, with damage areas indicated by gray tone. Source locations estimated after 24000 cycles were designated by open triangles. Location results agreed well with observed crack zone. Some of sources after 24000 cycles were located in upper gray tone. This is supposed to be due to noises by contacts of crack surface.
Fig. 13 Relationship between load $P_{\text{max}}$ and AE count at number of cycle $N$.

Fig. 14 Picture of video monitoring at 22486 cycles (a) and 24000 cycles (b), circled point is crack initiation.

4. Conclusion

We utilized AE technique to monitor the fatigue damage of formed bellows made of stainless steel. We monitored AE signals by sensors mounted on the weld flange, and utilized them for detecting the initiation and location of fatigue cracks.

(1) Fatigue crack initiation of the bellows at vibration amplitude of 25 mm and 30 mm were correctly detected by AE at early time. AE technique was useful for detecting the fatigue crack initiation of complicated components such as formed bellows with weld flange. The flange can be successfully utilized for detecting the anti-symmetric-mode cylindrical AEs.

(2) Source location of fatigue cracks were successfully performed utilizing the first arrival wave components. Locations of AE source, estimated by the group velocity of 3100 m/s at 180 kHz, agreed well with the fatigue cracks.
References


