Detection of Contact-type Failure Based on Non-linear Wave Modulation Utilizing Self-Excited Ultrasonic Vibration: Evaluation of Failure Development Focusing on Frequency Modulation

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Abstract
This research concerns the detection method of contact-type failure based on non-linear wave modulation utilizing ultrasonic vibration driven by self-excitation. When the structure is vibrating by environmental force or forced excitation, the contact area is fluctuated by vibration. In this condition, the vibration transfer characteristics of ultrasonic vibration have fluctuated in synchronization with vibration (non-linear wave modulation). The detection method based on non-linear wave modulation can detect contact-type failure. In this paper, the novel detection method based on non-linear wave modulation is presented. Firstly, the self-excitation method using local feedback control is introduced. Local feedback control can oscillate at the natural frequency automatically. Secondly, the concept of a novel detection method is introduced. When the structure with contact-type failure is vibrating, the frequency of the ultrasonic vibration excited by local feedback control will fluctuate in synchronization with natural frequency fluctuation. To explain the detection method, non-linear wave modulation is expressed 1 degree of freedom model. In this model, the local stiffness fluctuation is modelled by the spring element of which spring coefficient is fluctuated in synchronization with structural vibration. We regard the transfer function of this model as a linear time-varying system. The amplitude of the fluctuation of natural frequency caused by stiffness fluctuation can be the novel index of failure level. Lastly, the result of the experiment using the uniform beam specimen is shown. From the relationship between forcing pressure of the contact-type failure and the amplitude of the frequency modulation, it is proved that the novel index is associated with failure level.

Keyword: Detection, Contact-type Failure, Ultrasonic, Non-linear Wave Modulation, Self-excited Vibration.
1. Introduction
Ultrasonic nondestructive testing is effective to detect a small failure. However, the contact-type failure such as fatigue crack, delamination of composite material, bolt loosening and adhesive failure is difficult to detect by ultrasonic testing because of high transmissivity of an ultrasonic wave in the vicinity of failure. The non-linear ultrasonic method was proposed to solve this problem [1-3]. This method is difficult to use for structural health monitoring because of the necessity of large-scale equipment.

The authors study the detection method based on non-linear wave modulation (NWM) [4, 5]. While the structure with contact-type failure is vibrating by the low frequency vibration, e.g. environmental disturbance or vibration generated by force excitation, the contact condition is fluctuated by vibration. Under this condition, the ultrasonic vibration is modulated caused by fluctuation of contact-type failure. The method based on NWM can detect contact-type failure using ultrasonic vibration of small amplitude. In this method, the resonance of the structure in the frequency range of ultrasonic is used. One of the problems of this method is the necessity of the measurement of natural frequencies. Another one of the problems is the independence of the failure index based on a demodulation component of the amplitude and phase.

In this paper, the novel detection method of contact-type failure utilizing self-excited ultrasonic vibration to solve these problems is presented. The authors proposed the self-excitation method at the natural frequency automatically using local feedback control [6]. The frequency modulation of the excitation signal will be generated when the NWM can express as the linear and time-varying system.

In this paper, the experimental verification is done. Firstly, the self-excitation circuit is designed. Secondly, the excitation experiment of ultrasonic natural vibration of the uniform beam structure is examined. The result is confirmed that the frequency of the self-excited ultrasonic vibration corresponds to the natural frequency. Finally, the detection experiment of contact-type failure is examined. The generation of frequency modulation of the excitation signal and the increase of the amplitude of frequency modulation in synchronization with the amplitude of vibration is confirmed.

2. Non-linear wave modulation (NWM) utilizing self-excited ultrasonic vibration
In this section, the overview of NWM and the self-excited ultrasonic vibration is introduced. First, the phenomenon theory of NWM based on the linear and time-varying model is expressed. From this model, the fluctuation of natural frequency is the essence of NWM. Secondarily, the mechanism of self-excitation method using local feedback control and the characteristics of the vibration excited by local feedback control is introduced. It is explained that the frequency modulation generates to the frequency of the self-excited ultrasonic vibration from these models.

2.1 Non-linear wave modulation
The NWM is the phenomenon caused by fluctuation of the contact condition. Figure 1 shows the illustration of NWM. When the structure with healthy condition is vibrating at a low frequency and an ultrasonic frequency, the amplitude and phase of the ultrasonic frequency component of the observation signal are constant. On the other hand, when the structure with contact-type failure is vibrating, the contact condition of the failure fluctuates in synchronization with a vibration frequency. In this case, the amplitude and phase of the ultrasonic wave through the vicinity of the failure is oscillated by the fluctuation of the contact condition. This inconsistency of the contact condition can be expressed as the fluctuation of local stiffness.

In the case of ultrasonic vibration excited at a natural frequency, the NWM can model with stiffness fluctuation. If there is a great difference between the frequency of the low frequency vibration and the ultrasonic vibration, this model can be regarded as the linear and time-varying model. The transfer characteristics of the time varying model are shown in Figure 2 (a). The natural frequency vibrates in synchronization with the stiffness fluctuation. As a result, the fluctuation of amplitude and
Phase occurs. Figure 2 (b) shows the characteristics with large damping. The peak of the gain becomes smaller caused by damping. The gradient of the phase delay is gentle. Therefore, the fluctuation width of the amplitude and phase is smaller than Figure 2 (a).

From these discussions, the failure index using the fluctuation width of the amplitude and phase is independent of damping.

The authors focus on the fluctuation of natural frequency, which is the essence of NWM. The natural frequency decides only the stiffness and the mass. Therefore, frequency modulation caused by NWM depends only on the fluctuation of the stiffness. The failure index using fluctuation of natural frequency will become the independent index of damping.

2.2 Self-excited ultrasonic vibration by local feedback control

The authors study the self-excitation method at the resonance point [6]. In this section, the mechanism of self-excitation method using local feedback is explained.

Firstly, the characteristics of the linear vibration system are introduced. Figure 3 shows the three degrees of freedom system model as an example and transfer characteristics when the actuator and sensor is the same location as this model. \( \omega \) is the excitation force and \( h \) is the relative displacement. Under this condition, the phase of all-natural frequencies equals a 90-degree delay in the transfer function.
Local feedback control is the control method using a 90-degree delay at the natural frequency. The condition of the oscillation of the self-excited vibration is a 180-degree delay on the open-loop transfer function. Thus, the self-excited vibration oscillates at the resonance point automatically when the phase of the feedback controller that the sensor and the actuator collocate designed a 90-degree delay at all frequencies.

In this paper, the integral negative feedback control is used as the control that has the phase delayed by 90-degree. Figure 4 shows the block diagram of the local feedback control using the integral negative control. The saturation element 1 is the protection circuit for protecting the operational amplifier. The all saturation voltage of this self-excitation controller is -3V to 3V.

3. Detection of contact-type failure based on non-linear wave modulation utilizing self-excited ultrasonic vibration

In this section, the verification of excitation of self-excited ultrasonic vibration and detection of the contact-type failure are described. Firstly, the setup of the excitation experiment using the beam structure is expressed. Next, the self-excited vibration generated by the local feedback control is observed. Lastly, forced entrainment is done to change the oscillation frequency to the other natural frequencies.

3.1 Experimental setup

In this subsection, the experimental setup is described in detail. Figure 5 shows the experimental apparatus and setup. The beam structure whose length is 3000 mm, with a width of 50 mm and a height of 6 mm. The boundary conditions of the heads of the specimen are fixed by vises. The piezo-electric patches for the actuator and the sensor are attached on both sides of the specimen of 600 mm from the left edge. The additional piezo-electric patches are attached to confirm the vibration mode. The size of the piezo-electric patch is 30 mm×20 mm. The bipolar power amplifier to drive the piezo-
electric patch amplifies the circuit output 10 times. The max voltage of circuit output is $30V_{pp}$. The exciter is used to excite the specimen at low frequency. The oscilloscope is used to measure time response. The sampling frequency of measurement is 1 MHz. The measurement time is 1 s.

The open-loop transfer function is shown in Figure 6. The open loop transfer function is measured from the input signal the filtered integral controller to the output signal of the saturation element 1.

It was confirmed that the phase delay at the natural frequencies is 180-degree. From this result, the self-excitation can only be generated at the natural frequencies.

3.2 Excitation of self-excited ultrasonic vibration by local feedback control

The result of the excitation experiment of self-excited ultrasonic vibration by local feedback control is described. Firstly, the self-excited ultrasonic vibration generated automatically is shown in Figure 7. Figure 7 (a) illustrates the feedback signal. Figure 7 (b) displays open-circuit voltages of the piezoelectric patch for measurement. The blue line and the red line are the output signals of the piezoelectric patch over and under the beam structure. The period is 0.0791 ms (12.64 kHz) that is the natural frequency of the black line of Figure 6. It can be seen that this natural vibration is the bending mode from Figure 7 (b).

Next, the generation of the self-excited ultrasonic vibration using forced entrainment attempts to use the various natural vibration for the proposed method. The result is shown in Figure 8. The period of Figure 8 (a) is 0.0639 ms (14.435 kHz) that is the natural frequency of the red line of Figure 6. It can be seen that this natural vibration is also the bending mode from Figure 8 (b).
3.3 Detection of contact-type failure using self-excited ultrasonic vibration

The detection experiment of the contact-type failure is described. Firstly, the frequency modulation of the feedback signal in the case of self-excitation automatically will be confirmed. In this experiment, the location of the contact-type failure is 2200 mm from the left edge. The frequency of feedback signals are calculated by short-time Fourier transform when the voltage and frequency of exciter are 3.0 V\text{p-p} and 8.5 Hz (see Figure 9). Figure 9 (a) shows the feedback signal which is vibrating at 12.64 kHz. Figure 9 (b) displays the result of the short-time Fourier transform of feedback signal (Figure 9 (a)). From Figure 9 (b), the frequency modulation in synchronization with the low-frequency vibration is confirmed.

Finally, the variation of the amplitude of the frequency modulation to the failure development is investigated. The relationship between the amplitude of the frequency modulation and low frequency vibration is shown in Figure 10. The amplitude increases in synchronization with the voltage of the low frequency vibration which describes the failure level. This index is associated with failure level.

![Figure 7](image1.jpg)  
(a) Feedback signal  
(b) Output signal of the piezo-electric patch for measurement

**Figure 7.** Self-excited ultrasonic vibration generated automatically

![Figure 8](image2.jpg)  
(a) Feedback signal  
(b) Output signal of the piezo-electric patch for measurement

**Figure 8.** Self-excited ultrasonic vibration generated by forced entrainment
4. Conclusion
This paper presented the detection method of the contact-type failure based on NWM using self-excited ultrasonic vibration. Especially, the verification experiment of the proposed method is done. As a result, the self-excited ultrasonic vibration can be generated at a natural frequency. Thus, the frequency of the self-excited ultrasonic vibration can change the other natural frequencies by forced entrainment. Therefore, the frequency fluctuation of the feedback signal occurs by the NWM. The amplitude of the frequency fluctuation increases in synchronization with the failure development. From this result, the amplitude of the frequency fluctuation is the novel failure index.

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