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Experimental Vibration-based Damage Detection in Aluminum Plates and Blocks Using Acoustic Emission Responses

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Abstract

Modal based damage assessment methods are extensively applied to evaluate structural damages since they are cost-effective and comparatively easy to operate. These methods identify defects based on changes in physical properties of the structure such as mass, stiffness and damping. This will result in detectable changes in the dynamic signatures of the Frequency Response Functions (FRFs). This study presents an experimental process for providing modal analysis in order to identify the defects in the isotropic homogeneous aluminum plate and blocks using the impulse excitation signal generated by an impact hammer. Acoustic emission (AE) sensors are employed to measure the vibration responses of the structures due to the impulse. The FRFs are compared to quantify the changes in measurements between the healthy structures versus damaged structures. Based on the features extracted from measured dynamic behavior of the structures in laboratory experiments, an appropriate signal processing method is utilized to identify the damage. The results indicate that the changes in modal parameters due to damage can be successfully used for damage assessment.

Keywords: Modal Analysis, Acoustic Emission, Damage Detection, Impact Hammer

1. Introduction

Reliable damage detection method is vital to the stable and safe operation of structural systems. In other words, detecting damage such as cracks, fatigue, corrosion, and the loosening of bolted joints in the early stage of damage formation is of critical significance in mechanical, civil, aerospace and pipeline structures. Vibration-based damage detection is one of several methods for detecting defects in structures and components. Because of its potential for global monitoring, damage detection from changes in vibration responses of the structure is a popular research topic. This method is independent to the complexities of the test object and has a reasonable calculation weight.

On the other hand, traditional non-destructive test techniques, such as ultrasound, radiography, or magnetic field methods can be useful for detecting local damage [1]. Moreover, these methods usually require that test specimens be isolated from operational conditions so as to enable technicians to carry out the scheduled inspections. Such techniques can be very time consuming and costly, especially if they are applied to target components that are not easily accessible [1].

This study focuses on the vibration-based method for evaluation of structural health. By extending the method to real applications a noticeable enhancement in maintenance costs and operational efficiency is expected. The principles of modal-based damage detection involve monitoring the modal parameters of a structure for changes after damage has been sustained. The most common modal parameters include natural frequency, damping and stiffness.

Given the utility of this method, several modal-based techniques for damage identification exist [2]. Advances in methods to detect, locate and characterize damage in structural and mechanical systems by monitoring for changes in measured vibration response have been summarized in a number of review papers [3–5]. Golubovic [1] presents a correlation approach between structural damage and dynamic response signals in order to detect damage in cantilever beams. Vibration-based damage detection can also be used in combination with other methods, such as the hybrid damage detection method based on the Continuous Wavelet Transform (CWT) and modal parameter identification techniques for a beam-like structure [6]. Alvandi and Cremona [7] have assessed the performance of vibration-based damage detection techniques using a simulated beam excited by a random force with varying noise levels. The application of Genetic Algorithms (GA) in identifying structural damage is carried out by Hao et al. [8] through the minimization of an objective function.

In this paper, damages are defined as a change in the structure that can adversely affect the current or future performance of the structure. Implicit in the definition of damage, the change is identified through a comparison between two different states of the structure, in which we analyze differences of selected features extracted from signals acquired from healthy and damaged states. Almost all vibration-based damage identification studies acquire response signals from accelerometers. However, this study will analyze modal parameters using the Acoustic Emission (AE) response of structures due to elastic stress wave propagation caused by impact hammer excitation.

2. Experiments

An experimental test-bed was designed to provide actuator and sensor signals in the time-domain. A schematic overview of the experimental test-bed is given in Figure 1.

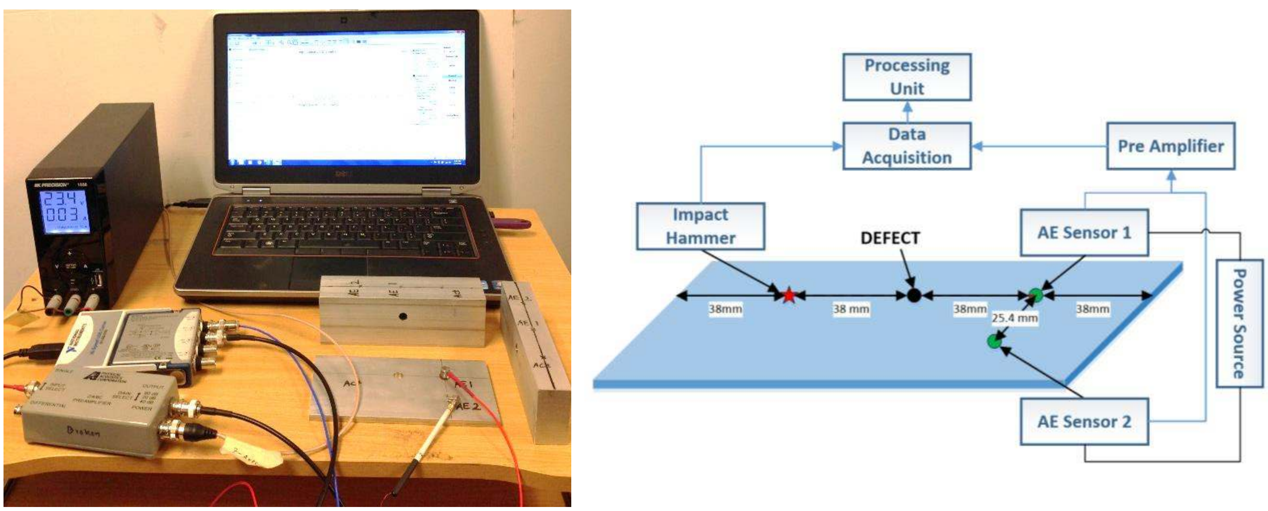
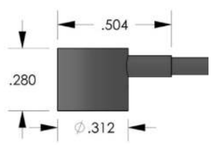


Figure 1. The experimental test-bed used for vibration-based damage detection

The structure under inspection is an aluminum 6061 plate of dimensions 152x76x6.3 mm. In addition, a similar experimental procedure was carried out for damage identification in two aluminum blocks of dimensions 152 × 50.8 × 25.4 mm and 152 × 50.8 × 38.1 mm. Two AE sensors (MISTRAS Nano30) with a peak sensitivity of 62 dB V/(m/s) are mounted to the structure and response is measured in the frequency domain as frequency response functions (FRFs). The specifications of the sensors are summarized in Table 1. We considered that the measured physical quantity of the AE sensors is proportional to velocity, contrary to displacement or acceleration [9]. Therefore, in this study the excitation signal is applied using a hammer equipped with force sensor (PCB 086E80) which has a sensitivity of 23.76 mV/N. The captured FRFs are used to extract changes in the modal parameters of each structure.

The NI 9234 dynamic signal acquisition module was used for providing high accuracy frequency measurement. It was selected since it can digitize signals at the rate of 51.2 kHz per channel, and is equipped with the built-in anti-aliasing filter. During the experiments, 2/4/6 preamplifiers in combination with a voltage supply of 23.4 volts was used to power the AE sensors. The preamplifier was supplied with 40 dB gain. The experiments were conducted on foams (15 cm thickness) to mimic the free boundary conditions.

Table 1. Nano 30 Sensor Specifications

	Peak Sensitivity, Ref V/(m/s)	62 dB
	Peak Sensitivity, Ref V/μbar	-72 dB
	Operating Frequency Range	125-750 kHz
	Resonant Frequency, Ref V/(m/s)	140 kHz
	Resonant Frequency, Ref V/μbar	300 kHz
Dimensions in inches	Weight	2 grams

A through hole is intentionally created in the specimens as a defect in order to study the effects of circular damage on a specific structure in terms of modal parameters. In order to analyze the sensitivity of the technique to more severe damage, we have studied two different levels of damage in the specimens. In the first level, the defect diameter is 8 mm, and in the second level it is 12.5 mm. In the case of the experiment involving the block specimens one of the AE sensors is mounted directly above the defect, as shown in Figure 2.

a. Plate (152x76x6.3 mm)   b. Block 1 (152x50.8x25.4 mm)   c. Block 2 (152x50.8x38.1 mm)

Figure 2. The aluminum plate and blocks specimens

3. Theoretical background

The equation of motion in a linear mechanical system, according to the Newton's law or Lagrange's theory, can be expressed by

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)= f(t) \qquad (1)$$

where m is the mass, c is the damping coefficient, k is the stiffness and f is the external force. Performing the Fourier transformation, (1) can be represented by

$$[-mw^2+jcw+k]X(w)=F(w) \qquad (2)$$

Therefore the system transfer function can be inferred as

$$H(w) = \frac{X(w)}{F(w)} = \frac{1}{-mw^2 + jcw + k} \quad (3)$$

In the case of multi-degrees of freedom system, the transfer function becomes as

$$\begin{bmatrix} X_1 \\ X_2 \\ \cdots \\ X_q \end{bmatrix} = \begin{bmatrix} H_{11} & & H_{1q} \\ H_{21} & \cdots & H_{2q} \\ \cdots & & \cdots \\ H_{p1} & & H_{pq} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ \cdots \\ F_q \end{bmatrix} \quad (4)$$

$$H_{pq}(s) = \sum_{i=1}^{N} \frac{(UU)_i}{\left(s^2 + 2\zeta\omega_n s + \omega_n^{\ 2}\right)_i} \quad (5)$$

where U is the mode shape, ζ is the damping ratio, ω_n is the natural frequency, and s is the Laplace operator ($s = j\omega$).

3. Results and Discussions

The FRFs contain information about modal parameters of each structure. The modal parameters can be extracted using an effective curve fitting method. The analysis showed that the plate has eight natural frequencies in the range of 1-12500 Hz while the blocks have two different modes. We have windowed the results to provide better representation of the signals in the frequency domain. As each mode shows distinct sensitivity to the changes in the material, Figure 3-5 show the dynamic behavior of structures regarding modal characteristics in the most sensitive modes. The most sensitive mode is the mode in which the natural frequency has the highest change. Natural frequency, damping ratio and κ have been summarized in Table 2-4. It should be noted that κ refers to the similar quantity corresponding to the modal stiffness.

3.1 Aluminum Plate (152x76x6.3 mm)

Although the plate specimen has eight different modes of vibration, the analysis is focused on the first two modes because the higher amplitude in the excitation signal makes it more reliable. The first natural frequency in each sensor show less than 0.4 percent changes in natural frequency. Therefore, it is preferred to focus on the 2nd mode for evaluation of the specimen. Moreover, sensor 1, which is located along the path from actuation point to the defect, shows the most variation in modal parameters, because the propagating wave directly interact with the defect in the plate.

Table 2. Modal parameters for plate specimen.

			Healthy			Damage 1			Damage 2		
			fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ
Plate	Sensor 1	Mode 1	3778	2.85E-01	-4.33E+08	3777	2.46E-01	-3.92E+08	3771	1.88E-01	-2.29E+08
		Mode 2	5754	5.29E-01	-4.01E+09	5726	4.17E-01	-4.71E+09	5644	5.00E-01	1.40E+09
	Sensor 2	Mode 1	3786	2.29E-02	-2.25E+09	3782	1.60E-01	-3.57E+08	3773	1.39E-01	-3.60E+08
		Mode 2	5760	5.97E-01	6.65E+08	5699	4.78E-01	7.52E+08	5658	1.86E-01	8.42E+08

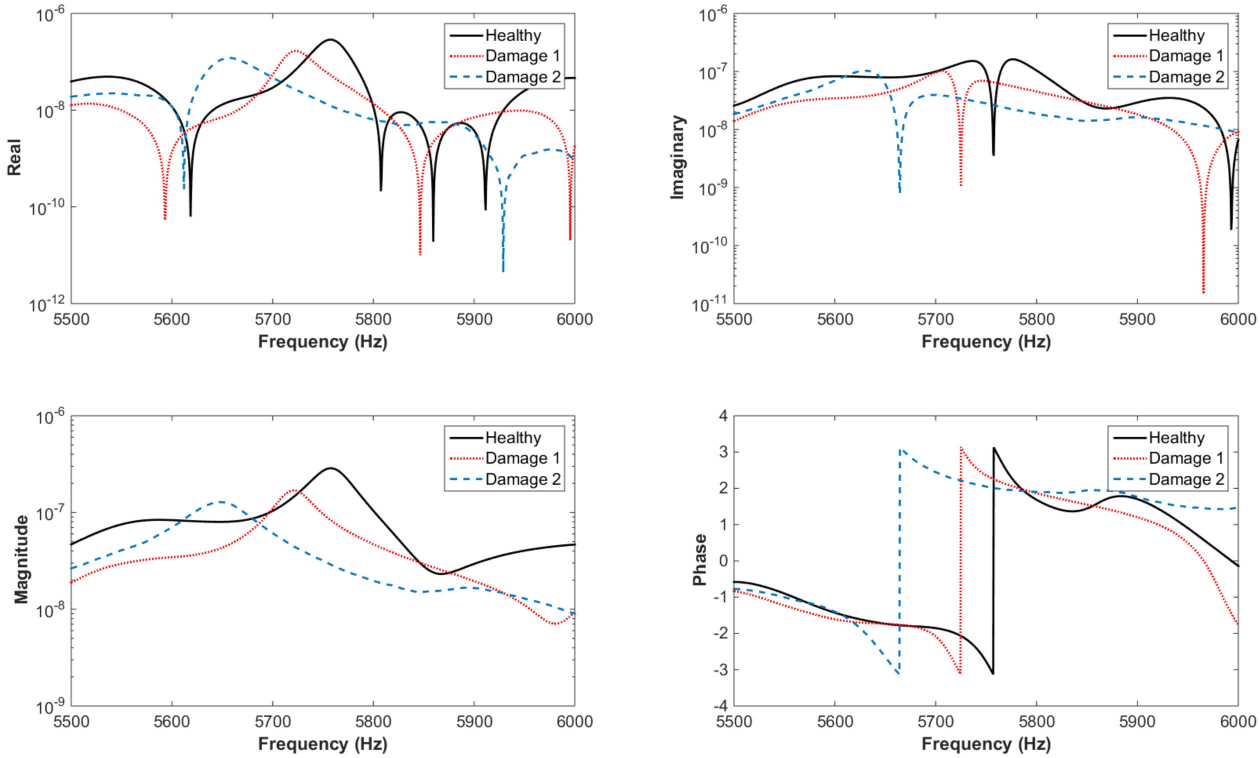


Figure 3. Frequency domain response of the aluminum plate based on sensor 1 data.

3.2 Aluminum Block 1 (152x50.8x25.4 mm)

This specimen has a different dynamic behavior. There is a single mode of vibration detected from sensor 1, and the other sensor represent a lower and more sensitive natural frequency as well. Additionally, sensor 2 receives a stronger reflection of wave from the defect, since sensor 2 and actuation point are opposite each other with respect to the defect. This clearly illustrates the importance of the sensor location in vibration-based damage detection. The 1st mode natural frequency in sensor 2 shows 1.84% and 4.39% variation due to the existence of two damage cases, as is shown in Figure 4.

Table 3. Modal parameters extracted for block 1

			Healthy			Damage 1			Damage 2		
			fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ
Block 1	Sensor 1	Mode 1	8554	4.67E-02	1.83E+09	8557	3.86E-02	6.15E+09	8533	3.83E-02	8.33E+09
		Mode 2	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Sensor 2	Mode 1	7810	7.49E-01	9.65E+09	7666	1.09E+00	7.25E+09	7467	7.20E-01	2.55E+10
		Mode 2	8592	1.71E-01	-2.68E+10	8599	3.51E-01	1.13E+10	8568	1.78E-01	2.29E+10

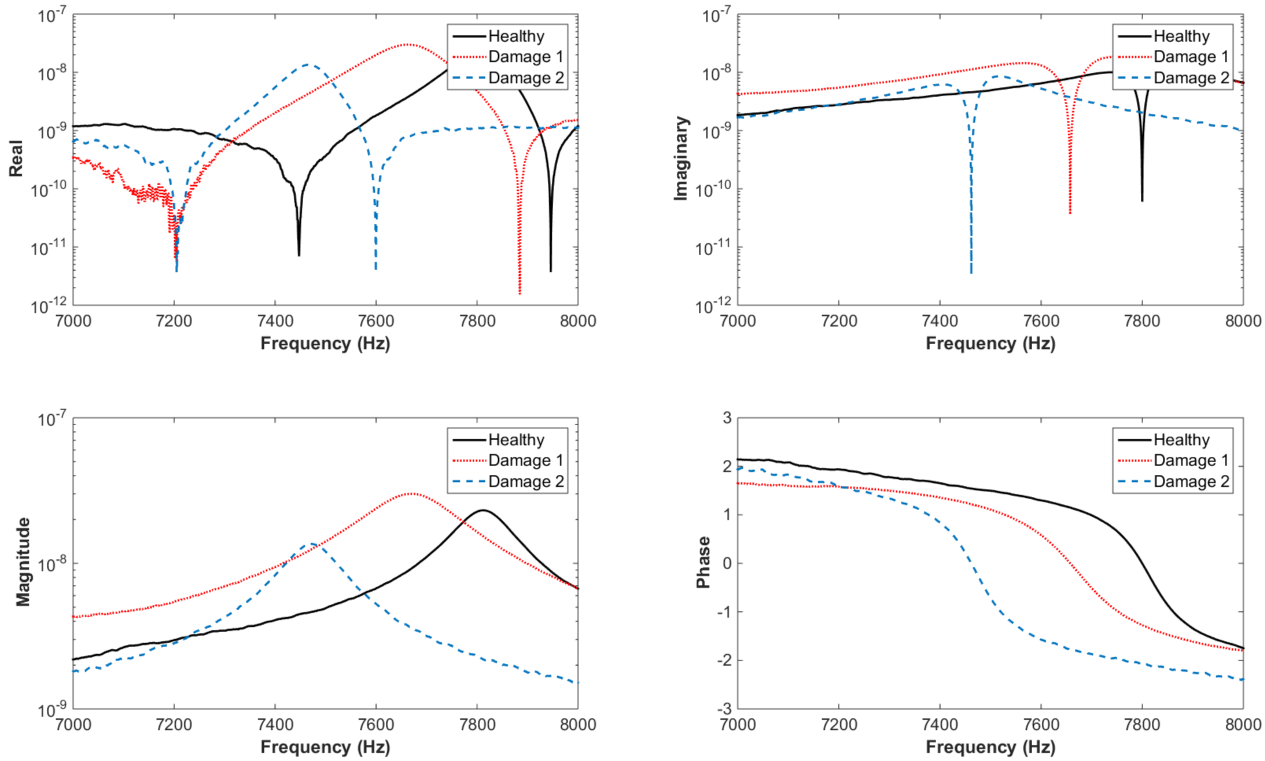


Figure 4. Frequency domain response of the aluminum block 1 based on sensor 2 data.

3.3 Aluminum Block 2 (152x50.8x38.1 mm)

While processing the result of block 2, we found two very close but different modes when analyzing the responses of sensor 1 for block 2. However, the results for the same specimen under previous conditions showed a single mode. This is considered to be a result of slight inaccuracy in the actuation point. The test results for block 2 at damage level 2 seem to represent a single mode, because the first and second modes have been shifted such that they are coincident.

Table 4. Modal parameters for block 2

			Healthy			Damage 1			Damage 2		
			fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ	fn (Hz)	Damping Ratio (%)	κ
Block 2	Sensor 1	Mode 1	8674	4.17E-02	4.63E+09	8687	4.47E-02	4.33E+09	8680	3.77E-02	2.76E+10
		Mode 2	NA	NA	NA	NA	NA	NA	8723	4.72E-02	4.67E+10
	Sensor 2	Mode 1	8702	1.86E-01	-2.55E+10	8710	1.04E-01	1.60E+10	8748	3.55E-01	8.70E+09
		Mode 2	9125	2.46E-01	-7.84E+10	8972	1.67E-01	2.70E+10	8748	3.55E-01	8.70E+09

Extracting the modal parameters reveal that a material discontinuity in the structure could make specific changes to the dynamic behavior of the specimen. In addition, some of these parameters, particularly the natural frequencies, do not show same trend which means that they either decrease or increase.

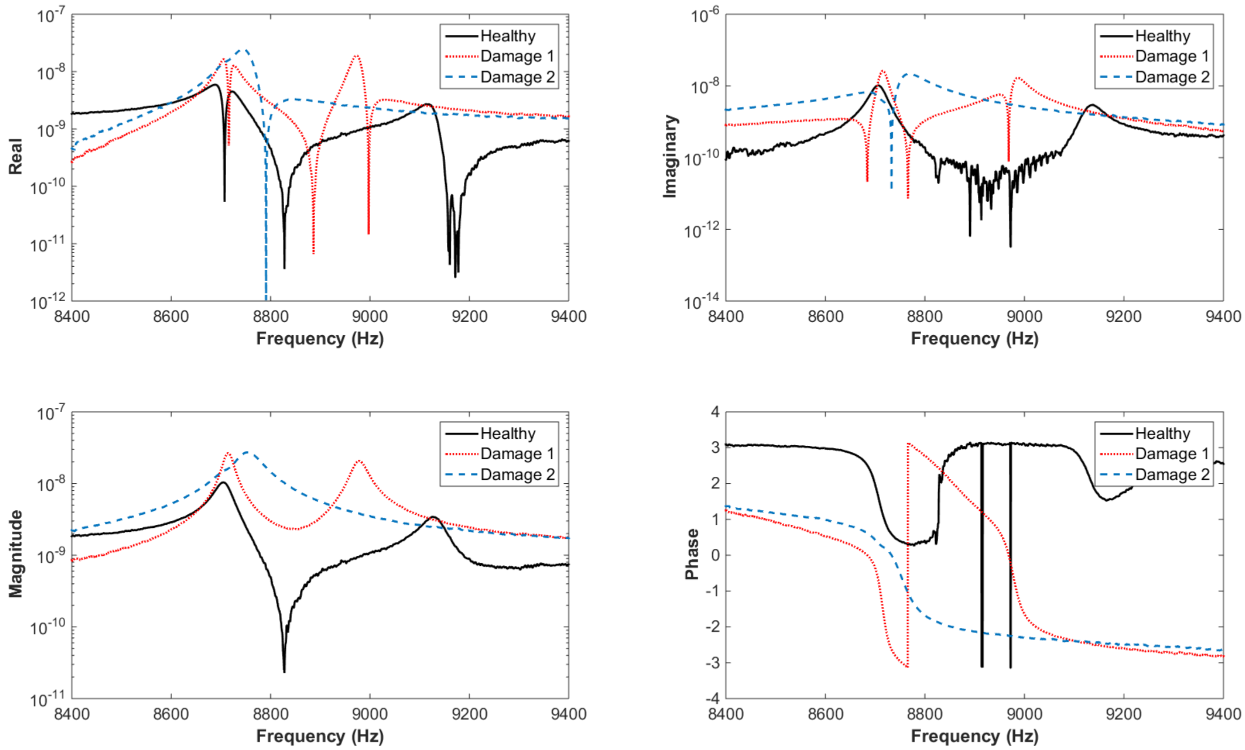


Figure 5. Frequency domain response of the aluminum block 2 based on sensor 2 data

There are also sources of limitations which cause challenges in measurements and comparisons. Since the suggested operating frequency range of sensors was higher than the actuation impulse signal, utilizing a system for higher frequency excitation would have resulted in more accurate analysis. It was also assumed that a foam can properly provide the free condition for the specimen. Applying advanced hybrid methods for signal processing and optimization is suggested to reduce noise level and unwanted spikes.

4. Summary

This paper presented vibration-based damage detection, as an efficient and global tool for evaluating the state of the structure. The experiments were designed based on an impulse actuation signal generated by the impact hammer, and the responses were recorded using acoustic emission sensors. We studied the dynamic behavior of specimens as well as changes in the modal parameters of the aluminum plate and blocks to assess the structural health. Our experimental results suggest sensitivity to damage can be can be shown by analyzing different modes of vibration. In addition, the location of the sensors is a significant factor which can result in reliable vibration based damage detection.

5. References

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