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# A SENSITIVE APPROACH TO DETERMINE THE HEALTH STATUS OF I-BEAMS BY MEASURING ITS NONLINEARITY THROUGH THE USE OF RAYLEIGH WAVES

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## ABSTRACT

*This study focuses on evaluating the health status of a 1018 steel I-beam using a new nonlinearity parameter defined for Rayleigh waves. This parameter yields a true value of material nonlinearity using the Rayleigh wave harmonics obtained from the experiments carried out at the intact and the impacted state of the I-beam. Accordingly, the evaluated nonlinearity is the inherent and damaged induced nonlinearity. The results show that, for an intact state, the nonlinearity obtained using the new parameter and the experimental results, consist of several peaks and the first peak reaches to the true material nonlinearity. Whereas, in case of damaged state, the nonlinearity parameter at the impacted location shows a sudden increase and reaches a value higher than that of the nonlinearity evaluated at the same location of intact state. Thus, the health status can be easily tracked by comparing the nonlinearity obtained from the current state of the I-beam with that of a physics based nonlinearity parameter obtained at the intact state. In contrast, the velocity and wave attenuation remains unaffected. Thus, by using the new nonlinearity parameter, it has been proven that the inspected I-beam can be easily differentiated whether it is at the intact or impacted state*.

Keywords: Structural health monitoring, I-beam, Rayleigh waves, inherent nonlinearity, damage-induced nonlinearity.

## 1. INTRODUCTION

I-Beams are important part of the construction, civil and mechanical industry. Thus, it is extremely essential to monitor their health status before and after putting them into service. However, the literature regarding the inspection of such complex structural specimens like an I-Beam is very scarce. Most of the proposed approaches are based on the linear theory which rely on the measurement of time of arrival of reflected wave from the defect, wave attenuation, etc. [1]. However, these defects belong to the category of macro-damages which are even visible by naked eye. Thus, it may be difficult to apply these linear approaches to detect micro cracks, impact and fatigue damages. Generally, nonlinear approaches are more suitable for inspecting such micro-damages [2-5]. Thus, if these micro damages are detected and localized at early stage of their life cycles, their further increase in size due to external loading can be avoided, as such increase may result into formation of macro cracks and eventually resulting into catastrophic failure.

The present study is an attempt to fill these potential research gaps and provides a sensitive approach for detecting micro damages that exist in I-beams or Rails using a new nonlinearity parameter proposed for Rayleigh wave propagation.

## 2. MATERIALS AND METHODS

The test specimen used for present study is a 1018 I-section structural steel beam. The material properties of the specimen under investigation are shown in Table.1. The cross-section and dimensions of the specimen are shown in Fig.1.

**TABLE.1** MATERIAL PROPERTIES OF THE 1018 STEEL I-BEAM.

| Modulus of Elasticity (GPa) | Density (kg/m$^3$) | Poisson Ratio (-) | $\lambda$ (GPa) | $\mu$ (GPa) |
|---|---|---|---|---|
| 205 | 7870 | 0.29 | 109.73 | 79.457 |

The nonlinearity at the intact state can also be evaluated using a physics based nonlinearity parameter, which depends on the second and third order elastic constants of the material, and is given as follows [3-5],

$$\gamma_{phy} = \sqrt{\left(\frac{A_3^e}{A_2^e}\right)^2 + \left(\frac{B_3^e}{B_2^e}\right)^2} \tag{1}$$

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where $A_2^e \approx B_2^e = C_{11}$ and $A_3^e \approx B_3^e = 3C_{11} + C_{111}$ for an isotropic material [3-5], $C_{11}$ and $C_{111}$ are the second and third order elastic constants of the material respectively at the intact state. Using the aforementioned relationships and the material properties listed in Table 2 and the elastic constants required in evaluating the physics-based nonlinearity parameter $\gamma_{phy}$ as defined in Eqn.1, the $\gamma_{phy}$ was estimated equal to 12.5, for an 1018 steel I-beam at its intact state.

**TABLE. 2** SECOND AND THIRD ORDER ELASTIC CONSTANTS OF 1018 STEEL [6]

| Material | $C_{11}$(GPa) | $C_{111}$(GPa) | $\gamma_{phy}$(-) |
|---|---|---|---|
| 1018 steel | 229.3 | -2720 | 12.5 |

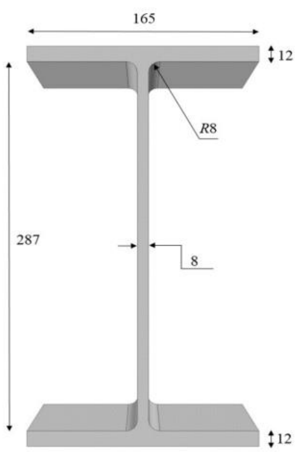



**Fig.1** THE CROSS-SECTION OF THE STEEL I-BEAM (ALL DIMENSIONS ARE IN MM).

### 2.1 Theoretical fundamentals

When a Rayleigh wave with a single excitation frequency is launched into a nonlinear medium, additional waves with frequencies multiple of the excitation frequency, are generated. This nonlinearity in the propagating medium comes from the lattice anharmonicity at the intact state and from the formation of dislocations at the impacted, fatigued, and elastoplastically loaded state. Thus, a nonlinearity parameter depending on the amplitudes of the fundamental and second harmonic waves, can be used to quantify the nonlinearity of the medium. This nonlinearity parameter yielding a true value of material nonlinearity using the Rayleigh waves is primarily proposed by the authors and is given as follows,

$$\delta^R = \left[\frac{A_2}{A_1^2}\right]\left\{\frac{2}{\sqrt{(\zeta_2^R)^2-(\zeta_1^R)^2}}\right\} \quad (2)$$

where, $\zeta_1^R = \left\{\frac{\lambda+2\mu}{\xi^x}\right\}\left[2qk - \frac{k(k^2+s^2)}{s}\right]$ (3)

$$\zeta_2^R = \left\{\frac{\lambda+2\mu}{\xi^y}\right\}[2k^2 - (k^2+s^2)] \quad (4)$$

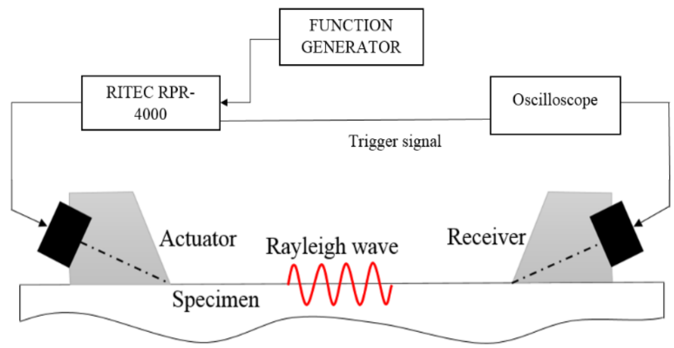
$$\xi^x = 4\mu qk^2 - \frac{(k^2+s^2)}{s}[(\lambda+2\mu)q^2 - \lambda k^2] \quad (5)$$

$$\xi^y = 4\mu sk^2 - \frac{(k^2+s^2)}{q}[(\lambda+2\mu)q^2 - \lambda k^2] \quad (6)$$

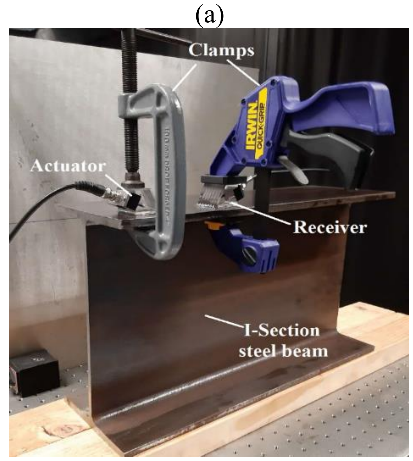
The symbols $A_1$ and $A_2$ are the amplitudes of the fundamental and second harmonics respectively, $\zeta_1^R$ and $\zeta_2^R$ are the terms arising from the longitudinal and shear wave contributions, $\lambda$ and $\mu$ are the Lames' constants, $q = k\sqrt{1-\left(\frac{V}{V_L}\right)^2}$, $s = k\sqrt{1-\left(\frac{V}{V_T}\right)^2}$, and $k$ is the wavenumber. Furthermore $V_L$, $V_T$, and $V_R$ are the longitudinal, transverse, and Rayleigh wave velocity respectively. Eqn. 2 is used to evaluate the true value of material nonlinearity using the amplitudes of Rayleigh wave's harmonics, $A_1$ and $A_2$, measured at different propagation distances.

### 2.2 Experimental Setup

The schematic of experimental setup is shown in Fig.2 (a). The actual view of the specimen and the transducers mounted on it are shown in Fig.2 (b).




(a)




(b)

**FIG.2** EXPERIMENTAL SET UP (A) SECHEMATIC VIEW (B) ACTUAL VIEW OF SPECIMEN

A tone burst waveform was produced by a function generator and amplified by the RITEC RPR-4000 system. This amplified signal having high-voltage was allowed to pass through a RITEC RT-150 ohm load to compensate for the electrical impedance mismatch between the transducer mounted on a $90^0$ steel wedge, which was designed exclusively for exciting Rayleigh surface waves in steel specimens. These propagating Rayleigh waves were sensed using another transducer mounted on another $90^0$ steel wedge and recorded by an oscilloscope, which has a maximum sampling rate of 2.5 GS/s. The collected signals were then stored in a computer for further data analysis and signal processing. Measurements were taken with an increment of 10 mm from the exciter's location.

### 2.3 Near-field distance calculations

The near field distance for a transducer is dependent on the excitation frequency, transducer element size, the velocity of the propagating wave, and can be obtained by using Eq.7 as:

$$N = \frac{kL^2 f}{4V_R} \quad (7)$$

where $k$ is the aspect ratio constant, $L$ is the length of transducer element, $f$ is the excitation frequency, $V_R$ is the Rayleigh wave velocity. Complying with [7], for a ratio of 0.5 (small side over longer side i.e. 13/25), the value of $k$ is 1.01. Accordingly, the near field distances were computed for the inspection frequency of 1.5 MHz considered in this study. The near field distance was calculated as 21.75 mm and 43.5 mm for the fundamental and second harmonic respectively. Thus, the experiments were carried out from the location until the second harmonic wave has propagated through the near field distance which was 43.5 mm, as obtained theoretically. This is because, there are amplitude variations in the near field zone of the transducer, due to which the second harmonic wave is unstable. Noting this, the measurements were carried out starting from 40 mm with respect to the actuator location, and then with an increment of 10 mm.

## 3 RESULTS AND DISCUSSION

One of the signal recorded at a propagation distance of 90 mm from the actuator is shown in Fig. 3. The Rayleigh wave velocity calculated theoretically is 2943 m/s, whereas, using the experimental measurement is 2961.17 m/s. Furthermore, there is a strong agreement between the calculation of near field distance using theoretical calculations and experimental measurements. The incident part of the temporal signal was then converted to its frequency component via the application of Fast Fourier Transform (FFT) algorithm. The amplitudes of the harmonics, i.e. $A_1$ and $A_2$ were then extracted, and used to evaluate the value of $\delta^R$ by using Equation 2. The above process was repeated at different wave propagation distances to examine the change in $\delta^R$, and is shown in Fig. 4. The results in Fig.4 shows that only the first peak in $\delta^R$ reaches close to the true material nonlinearity, which is 12.5, for an intact 1018 steel specimen as evaluated using $\gamma_{phy}$. It is also observed that the remaining peaks do not reach close to $\gamma_{phy}$, and the relationship between these two parameters is illustrated in Fig.4. This is primarily due to the fact that the fundamental wave attenuates, and loses its energy in driving the second harmonic wave, to fulfil the cumulative effect. Ideally, it is expected that all the peaks should reach the value of $\gamma_{phy}$. However, in practical scenario, this is limited by the attenuation of wave in the test specimen. Thus, the nonlinearity obtained using $\delta^R$ at its first peak, shall be compared with $\gamma_{phy}$ to identify the health state of the specimen.

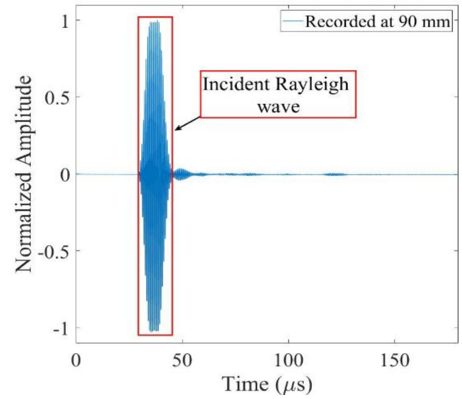



**Fig.3** THE RAYLEIGH WAVE RECORDED AT A DISTANCE OF 90 MM FROM THE ACTUATOR.

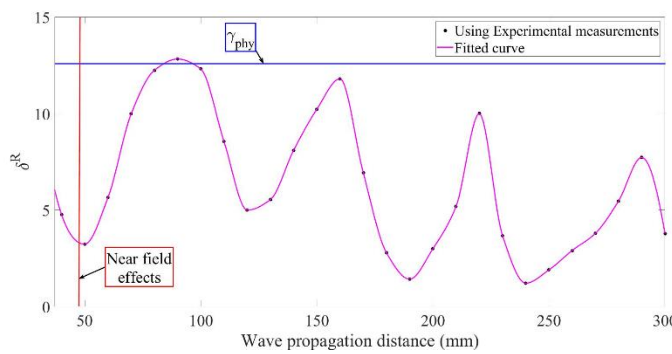



**Fig.4** EVALUATION OF $\delta^R$ USING EXPERIMENTS CARRIED OUT AT 1.5 MHZ FOR AN INTACT STATE OF THE SPECIMEN.

## 4. CONCLUSIONS

In this study, an effective inspection method for monitoring the health status of a 1018 steel I-beam is presented. The method introduces the use of nonlinear features of the Rayleigh surface waves and a new nonlinear parameter for identifying the state of specimen. The results obtained from an I-beam at intact state shows that the material nonlinearity evaluated using the Rayleigh wave nonlinear parameter at its first peak reaches to the true value of material nonlinearity evaluated by using the second and third order elastic constants of the material. Thus, it can be said that the specimen is at its intact state. In contrast, if the evaluated nonlinearity value is higher than this original nonlinearity value, it should have been caused by the action of external loading or degradation. Hence, the presented method has significant potential in differentiating the intact and damaged states of tested specimens.

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