Numerical Analysis of Narrow Band Ultrasonic Wave Generation with High Repetition Pulse Laser and Laser Scanning

T Hayashi, K Yamaguchi and S Biwa
Graduate School of Engineering, Kyoto University, Kyoto, 615-8540, Japan
E-mail: hayashi@kuaero.kyoto-u.ac.jp

Abstract. Although the easiest way to enhance ultrasonic energy generated with pulse laser is to increase laser output, excessive laser output causes damage of the surface. This study introduced an alternative way to generate burst signals without any damages at the surface using a newly developed high repetition pulse laser controlled by galvano mirrors. The calculation results using two-dimensional elastodynamic finite integration technique coupled with thermoelastic effect proved that burst wave of 1 MHz and its higher harmonics were generated while suppressing excessive temperature rise using this technique. Moreover, significantly large displacements at the frequency range sufficiently lower than laser repetition rate were observed of the same order of displacements generated with one single shot with the same input energy.

1. Introduction
In laser ultrasonics, ultrasonic generation is feasible with pulsed laser emission, while ultrasonic detection requires laser beam reflected or scattered from a surface of the object. Therefore, ultrasonic detection by laser may have some problems when applying it to alfresco civil structures and products in a production line due to their difficult conditions such as roughness, dirt, rust, and paint of surface and large vibration with a low frequency. Thus, authors adopted a scanning laser source technique (SLS) to solve such practical problems and have developed defect-imaging technique using the SLS for the purpose of application to such alfresco structures and in-line inspection.

In the SLS, ultrasonic waves are generated with pulsed laser and detected with ultrasonic transducers fixed on the surface of an object and the laser source is scanned over the surface with galvano mirrors. Authors proved that an amplitude distribution obtained by the SLS corresponds to an image of defects in a thin plate and that clearer images can be obtained using multiple receiving transducers. Moreover, authors showed that we can replace the receiving transducers by non-contact air-coupled transducers when using a low-frequency range.

Although we realized the full non-contact technique, its application is limited due to its low signal to noise ratio. This study, therefore, introduces burst wave generation technique using high repetition pulse laser and investigates the effectiveness of the technique with numerical calculations.

2. Burst wave generation using a high repetition pulse laser controlled by galvano mirrors
The easiest way to enhance ultrasonic energy generated with pulse laser is to increase laser output. However, as excessive laser output causes damage of the surface, it cannot be applied to structures and products whose surfaces should be kept undamaged. We now investigate the burst wave generation
without any damages of a surface using a newly developed high repetition pulse laser, in which laser pulses move at small distance with galvano mirrors to avoid excessive temperature rise.

Hereafter, we evaluate the burst wave generation technique with the numerical calculations of wave propagation and temperature change which is conducted for an aluminium alloy plate of 0.1 mm thickness using a two-dimensional elastodynamic finite integration technique (EFIT) coupled with thermoelastic effect [1]. As optical penetration of laser emission to aluminium is negligibly small compared to the spatial mesh division, heat is supplied at the infinitesimally thin layer of the plate surface $y = 0$ as,

$$Q(x, y, t) = \sum_{n=1}^{N} Q_n(x, y, t)$$

$$Q_n(x, y, t) = \frac{4q_0}{\sqrt{\pi d_0 t_0}} \exp\left(\frac{t - T_n}{t_0}\right) \exp\left(-\frac{4(x - X_n)^2}{d_0^2}\right) \delta(y)$$

where $N$ is the number of laser shots, $Q_n$ is the heat supply for the $n$th shot, $T_n$ and $X_n$ are temporal and spatial shift for the $n$th shot, $d_0$ and $t_0$ are the width of laser source and rise time, $q_0$ is the total heat supply per unit length for a single shot [2], [3]. $T_n$ and $X_n$ in Eq. (1) are described using temporal increment $\Delta t$ and spatial increment $\Delta x$ as,

$$T_n = (n-1)\Delta t, \quad X_n = (n-1)\Delta x.$$  

The area integration of the heat supply expressed by equation (1) in EFIT formalization results in the line integration on the plate surface $y = 0$. All parameters used in the calculation are listed in Table 1.

Figure 1 represents a schematic figure of the burst wave generation with a pulse laser and laser scanning. The A0 mode of Lamb wave generated in the frequency-thickness product range of 1 MHz x 0.1 mm have the phase velocity of about 1000 m/s and the wavelength of about 1 mm. As the spatial interval of scanning $\Delta x$ is sufficiently small compared to the wavelength, from the viewpoint of ultrasonic propagation, ultrasonic wave is generated at approximately the same positions. In general, the product of spatial interval $\Delta x$ and the number of laser shots $N$ should be smaller than half wavelength for effective burst wave generation, where $N$ corresponds to the number of burst cycles to generate. Namely, this relationship determines the effective frequency range in this technique.

Figure 2 shows the temperature change at the laser spots: (a) is for a single shot ($N = 1$), (b) is for 10 shots at the same position ($N = 10, \Delta x = 0$), and (c) is temperature change at the fifth laser spot for 10 shots with scanning ($N = 10, \Delta x = 40 \mu m$). As the temperature change is linearly proportional to the total energy input $q_0$, the vertical axis in figure 2 is represented by the temperature divided by $q_0$. In order to compare (a), (b) and (c) under the same input energy, the temperature change for the input

| Table 1. Parameters used in the calculations. |
|-----------------------------------------------|
| Material                                      |
| (Aluminium plate)                             |
| Cross-section size  | Density  | Longitudinal wave velocity | Transverse wave velocity |
| 10 mm x 0.1 mm   | $7800 \, \text{kg/m}^3$ | 6400 m/s | 3200 m/s |
| Specific heat   | Thermoelastic coupling constant  | Thermal conductivity | Base temperature |
| 900 J/kg/K      | $5.6 \times 10^{-3} \, \text{K}^{-1}$ | 160 W/mK | 300 K     |
| Temporal and spatial mesh division            |
| Temporal division  | Spatial division  | Number of divisions | Number of temporal iteration |
| 1 ns            | 0.01 mm (both directions) | $10000 \times 10$ | ($10000$ (up to 10 ms)) |
| Single line source parameters                  |
| Width of line source ($d_0$)                  | Rise time ($t_0$) | Total energy input ($q_0$) |
| 200 $\mu$m | 10 ns | $q_0$ J/m |
| Firing repetition parameters                   |
| Repetition frequency (=1/$\Delta t$) | Repetition time interval ( $\Delta t$ ) | Spatial interval ( $\Delta x$ ) |
| 1 MHz          | 1 $\mu$s | 40 $\mu$m |
energy of $10q_0$ is shown in (a). Comparing the maximum value of (c) with those of (a) and (b), we can find that the temperature rise could be suppressed about 1/6 of that for the single shot (a) and about 2/3 of that for 10 shots with no scanning (b) by the use of a high repetition laser and scanning. The temperature rise in (c) is approximately determined by the number of times laser is incident on the measurement point of temperature. Therefore, when the spatial interval of laser scanning $\Delta x$ is larger than the width of line source $d_0$, the maximum temperature of the surface becomes about 1/10 of that for the single shot.

Next, temporal displacements at 20 mm from the first laser source ($n=1$) and their frequency spectra are shown in figure 3. In (a), significantly large chirp-like waveform was observed as a natural vibration of A0 mode of Lamb wave generated in the aluminium thin plate with the thickness of 0.1 mm. As the group velocity of the A0 mode monotonically increases with frequency in the range of frequency-thickness product, the signal period gradually increase with time. In (b) and (c), waveforms between about 8 $\mu$s and 20 $\mu$s are signals controlled by the multiple laser emission having components mainly about 1 MHz. The waveforms of (b) and (c) are very similar, which proves that the laser scanning does not affect significantly the temporal displacements. In the frequency spectra of (b) and (c), main peaks were obtained about at 1 MHz as well as the higher harmonics. Comparing the peak positions of (b) and (c), (c) provided frequency peaks at slightly higher frequency than (b), which is due to the Doppler shift occurred by moving laser spots in $\Delta x$.

Since large displacements with low frequency components were observed in figure 3 (a) as well as (b) and (c) after 20 $\mu$s, figure 4 shows extended waveforms of figures 3 (a) - (c) until 100 $\mu$s and their frequency spectra. These three waveforms after 60 $\mu$s are similar except for small vibration with high frequency in (a) after 70 $\mu$s which is the reflected waves from the plate end. These results represent that waveforms in low frequency range were not affected by the number of laser shots because the repetition rate is sufficiently high compared to the low frequency oscillation.

3. Visualization of temperature change and wave propagation

Figure 5 is the visualization results of the region of $2.0 \times 0.1 \text{ mm}^2$ around laser spots: (a) is temperature change, and (b) and (c) are wave propagations showing displacement data magnified appropriately. Since the generated wave is dominated by the low frequency components as shown in (b), in order to visualize the targeting burst wave of 1 MHz, (c) is obtained by filtering with the high-pass filter of 0.6 MHz cut-off frequency. We can recognize that the laser shots deform the thin plate in (b) and that ultrasonic burst wave is generated in (c).

4. Conclusions

This study presented the results of numerical calculation for the burst wave generation technique with the combination of high repetition laser emission and laser scanning. The calculation results proved that burst wave of 1 MHz and its higher harmonics can be generated while suppressing excessive
temperature rise using this technique. Moreover, significantly large displacements at the frequency range sufficiently lower than laser repetition rate were observed of the same order of displacements generated with one single shot with the same input energy.

Figure 3. Displacements in the thickness direction and their frequency spectra for \( q_0 = 1 \) at 20 mm from the first laser spot.

Figure 4. Extended waveforms of figure 3 and their frequency spectra

Figure 5. Visualization of calculation results for \( N=10 \) with scanning.

5. References
[1] Yamaguchi K, Biwa S and Hayashi T 2013 Proc. of ICU 2013 518 - 9
[2] Arias I and Achenbach J D 2003 Int. J. Solids Struct. 40 6917 - 35
[3] Sun H and Zhang S 2010 J. Appl. Phys. 108 123101