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ABSTRACT

The analysis of acoustic waves produced during laser materials processing is widely carried out for characterising, monitoring and controlling the process. Traditional methods used in analysing the acoustic data such as RMS signal strength and variation analysis, frequency spectrum analysis are based on signal intensity modulation which offers the advantage of inherent simplicity. However, these basic intensity monitoring systems tend to be sensitive to spurious changes in intensity resulting from variations in the various electrical components within the system and the noise of the industrial environment. In addition, it is known that the acoustic intensity is dependent on the distance and observation angle between its source and acoustic sensor. In this paper, a new type of acoustic analysing method based on chromatic modulation is presented. Chromatic modulation offers not only much more acoustic information, precise distinction of the ambiguous signals and robust monitoring in the laser processing system but it could also make control of the laser process easier by simple chromatic output factors. It is also shown in this paper how a chromatic modulation technique may be utilised as an acoustic analysis method to monitor the laser cleaning process. Consequently, it was found that the chromatic acoustic analysis method could be successfully applied for surface monitoring in the laser cleaning process and could provide correct monitoring information in spite of sensor stand-off variation.

KEY WORDS: chromatic modulation, laser materials processing, intensity modulation, robust monitoring, laser cleaning, chromatic acoustic analysis, surface monitoring

INTRODUCTION

The acoustic emission signals are well suited for real-time or continuous monitoring of the laser process because they are generated while the laser interaction phenomenon is occurring and they give useful information on the current state of the process. The analysis of acoustic waves produced during laser materials processing has been widely studied for characterising, monitoring and controlling the process [1-6].

Most traditional methods used in analysing the acoustic data include RMS signal strength and variation analysis and frequency spectrum analysis etc. All these methods are based on signal intensity modulation which offer the advantage of inherent simplicity. However these basic intensity monitoring system tend to be sensitive to spurious changes in intensity resulting from variations in the sensing conditions or electrical components within the system and the environmental noises. It was known that the acoustic signals generated have normally very low amplitude and high frequency content and need to be amplified close to the signal source using a low noise pre-amplifier to minimise noise contamination as the signal propagates over the transmission cable. In addition, the acoustic intensity is dependent on the distance and observation angle between its source and acoustic sensor.

In this article, a new type of acoustic analysis method based on chromatic modulation is presented. It is also shown how the chromatic modulation technique may be utilised as an acoustic analysis method for monitoring the surface in the laser cleaning process. The results of implementing the chromatic acoustic monitoring technique to monitor the surface during the laser cleaning process as well as brief discussion on the performance is presented in this article.

CHROMATIC MODULATION METHOD

The chromatic modulation method aims to measure changes in the spectral parameters of polychromatic light using carefully configured combinations of broadband detectors [7]. As every colour in colorimetry can be described by three spectral parameters, dominant wavelength (or hue), luminance (or lightness) and purity (or saturation), the process which produces polychromatic light can in principle be specified and identified by these three parameters obtained by chromatic modulation.

A chromatic modulation system consists of polychromatic light for sensing changes during the progress of a physical process and an array of optical detectors with overlapping wavelength dependent responses $R(\lambda)$ for chromatic detection. An example of the form of response from three detectors is shown in Figure 1. When the detectors are used to monitor an optical signal having a spectral power distribution $P(\lambda)$ the output from each detector will

$$V = \int_{\lambda} P(\lambda)\, R(\lambda)\, d\lambda \qquad (1)$$

be

In general, three detectors provide an optimum arrangement for most applications [8]. If we let the responses of the detectors be $R_x(\lambda)$, $R_y(\lambda)$ and $R_z(\lambda)$ respectively, each detector gives an output as follows:

$$\begin{aligned} V_x &= \int_{\lambda} P(\lambda)\, R_x(\lambda)\, d\lambda \\ V_y &= \int_{\lambda} P(\lambda)\, R_y(\lambda)\, d\lambda \\ V_z &= \int_{\lambda} P(\lambda)\, R_z(\lambda)\, d\lambda \qquad (2) \end{aligned}$$

To reduce the chromatic information to two dimensions, each of these responses can be divided by the sum of the three:

$$
\begin{aligned}
x &= \frac{V_x}{V_x + V_y + V_z} \\
y &= \frac{V_y}{V_x + V_y + V_z} \\
z &= \frac{V_z}{V_x + V_y + V_z} \qquad (3)
\end{aligned}
$$

These parameters, x, y and z, are named trichromatic coefficients or chromaticity coordinates which quantify the spectral signatures $P(\lambda)$. Since any two can convey all of the chromatic information from the fact, $x + y + z = 1$, only x and y need to be used. If, for example, x and y are plotted using the three detectors responses shown in Figure 1, the operating chromatic boundary within this two-dimensional space appears as shown in Figure 2. Purely monochromatic signals lie along the curved boundary of Figure 2 while departures from monochromaticity are registered by increasing displacement from the boundary towards the centre of the enclosed space. Figure 2 is called the chromaticity diagram in which a spectral signature may be quantified in terms of two coordinates x, y so that changes in spectral signatures may be traced as a locus in the chromaticity space. In addition, the spectral parameters such as dominant wavelength and purity of the polychromatic source can be determined in the x, y chromaticity diagram. Let the point W(0.3, 0.3) represent the chromaticity of a white illuminant and the chromaticity of a coloured source have coordinates p(x, y) in Figure 2. The dominant wavelength, which is represented as a point 'd', is achieved by connecting the point W and 'p' and extending the line until it intersects the locus of the spectrum. The purity of the source is calculated from the ratio of the distances, pW/dW. If 'p' were coincident with 'd', the purity would be 1.0 or 100%.

If the detector responses $R_x(\lambda)$, $R_y(\lambda)$ and $R_z(\lambda)$ were made to correspond to the detectors in a standard human observer, as laid down by the International Commission on Illumination (CIE) then the resulting x, y plot would be the CIE chromaticity diagram, which is well known in the field of colorimetry [9,10]. In the colour system, hue refers to what would simply be termed colour (i.e. red, yellow, green, blue etc.) and is consequently an indication of dominant wavelength. Saturation is a measure of purity of a colour and varies literally between colourless (i.e. grey) and colourful (e.g. red), while lightness may be considered as a measure of total intensity and it varies between black and white.

The chromaticity diagram which can be used to determine the spectral signatures such as dominant wavelength and purity, which are independent of intensity, is important for optical sensing and monitoring because even complicated spectral signatures can be quantified in terms of only two parameters, x and y. Therefore changes in the spectral signature during the process can be monitored by measuring the chromaticity x, y and clearly quantified at the chromaticity diagram.

This technique has the advantages of being fast, simple, sensitive and cost effective. Successful applications for plasma monitoring in thin film process, electric circuit monitoring in circuit breakers and LPG quality control have been reported [7,11,12].

CHROMATIC ACOUSTIC ANALYSIS

As a conventional acoustic analysis method, the Fourier transformation is performed to obtain the frequency spectra of the acoustic waves where the power spectral density values is shown over the frequency range of interest. This is limited in that the characterisation will reveal only overall information regarding the magnitude of the energy distribution over the frequency domain present in the original signal. It has been known that it is difficult to extract characteristic spectral signatures representing the signal from the spectrum due to its complicated and complex feature so it is not convenient to define the signal yielded by the conventional Fourier transformation in order to monitor the process.

If, however, the chromatic modulation method described in previous section is applied to frequency domain, then the extraction of characteristic spectral signatures or parameters regarding the frequency distribution of energy becomes available [13]. The spectral parameters containing the information on the magnitude and distribution of energy within a signal at a particular time give a unique characterisation of the signal and enables immediate comparison to be made between signals obtained under various conditions and the variation in spectral content with time.

In this article, the chromatic modulation method was applied to the acoustic system in order to obtain spectral information of the signal. Figure 3 shows the acoustic shock wave during laser cleaning (of toner paper) and its frequency spectrum superimposed by three sine-squared filters, which are frequency dependent functions, centred at three different frequencies along the spectrum at suitable positions. The three chromatic filters have a similar role to the three optical detectors having overlapping responses in the wavelength domain, which was shown in Figure 1. A given acoustic signal spectrum may be integrated using the three filters to give three output values which are analogous to V_x, V_y and V_z, in the optical case described in previous section. The acoustic signal spectrum may then be characterised using these values. The sine-squared filter also involves less computation than Gaussian wave because it is a discrete function.

The chromaticity diagram using the acoustic output values through the filters could be used to analyse the acoustic wave quantitatively and then determine the acoustic spectral signatures. The three spectral parameters returned by the chromatic analysis are the dominant frequency (DF), energy level (EL) and excitation purity (EP) of the acoustic signal. These correspond to dominant wavelength (or hue), luminance (or lightness) and purity (or saturation) respectively in the optical system. In addition, it should be noted that any frequency spectrum not only from pulsed acoustic waves during laser cleaning but also from continuous acoustic waves in laser materials processing (e.g. laser welding) can be analysed with the chromatic modulation technique.

SYSTEM AND EXPERIMENTAL DESCRIPTION

The chromatic acoustic monitoring technique is applied to monitor the surface by analysing the acoustic signals derived during a laser cleaning process. Toner paper from a photocopy machine was used in this experiment for cleaning. The laser cleaning of the paper was carried out using a Q-switched Nd:YAG laser (a Paragon 2XL Nd:YAG Laser from Lynton Lasers). It has a pulse length of around 10 nsec. The laser has multi-mode cylindrical cavity optics which produced a non-Gaussian beam with a ‘top-hat’ shape for the surface cleaning. The beam after passing through an articulated arm is focussed by a quartz lens with a 20 cm focal length.

When a very short pulse (5-20 nsec) exceeding the threshold fluence is irradiated onto the contaminated surface a plasma forms whose plume rapidly expands creating acoustic shock waves in the air which are audible as a snapping sound and detectable by a transducer [1-3,14]. A wide band microphone with a frequency response of 10 Hz to 15 kHz was used to detect the acoustic waves during the laser surface cleaning. The distance between the microphone and the laser spot was around 10 cm. The detected acoustic signal was fed into a PC based data acquisition system after passing through a pre-amplifier. The signal was digitised by the signal processor using an analogue-to-digital converter (ADC) with a sampling rate of 50 kHz. The PC monitor showed the digitised acoustic wave. Fast Fourier transform (FFT) analysis was performed after the waveform was read into the computer. The resultant frequency spectrum was investigated by the chromatic modulation method in order to obtain various spectral information of the acoustic wave during the cleaning.

Figure 4 shows the block diagram of the experimental procedure for the chromatic acoustic monitoring in the laser cleaning process. The spectral responses (R_{High}, R_{Medium} and R_{Low}) of three sine squared filters with centre frequencies of 5 kHz, 7 kHz and 9 kHz and base width of 6 kHz are shown in Figure 3 (b) superimposed on the frequency range of interest. As the spectral responses of the chromatic filters can be adjusted easily by modifying the software it is convenient to control the spectral range of interest in the frequency domain. The spectral outputs from the chromatic analysis can be used for in-process surface monitoring and control in the laser cleaning process.

EXPERIMENTAL RESULTS AND DISCUSSION

Laser Cleaning of Paper

The removal of toner from the surface of photocopied paper was conducted using Q-witched Nd:YAG laser irradiation with the wavelength of 1064 nm. Figure 5 shows the magnified laser craters on toner paper surface with the sequence of the number of laser pulses with the fluence of 1.2 J/cm^2. The first spot at the right end is the crater made by the first laser pulse and the number of laser pulses increases one by one toward the left direction up to the ninth crater. It is shown that the bright white paper surface is gradually revealed with each pulse since the black toner on the surface has been removed. In the end, a well-cleaned paper surface was achieved after the irradiation of the seventh laser pulse.

Figure 6 shows the acoustic waves emitted from the toner paper surface during laser irradiation of the first (a), the third (b), the fifth (c) and the seventh (d) laser pulse respectively at the fluence of 1.2 J/cm^2. When the first laser pulse is irradiated on the paper surface, a very strong acoustic wave is observed. This strong acoustic wave implies that the surface was contaminated and the laser pulse interacted strongly with the toner. Due to the short laser pulse length (around 10 nsec), the acoustic wave emission is especially strong in the initial time period and decays rapidly with time. The overall signal strength decreases significantly in the third and the fifth laser pulse. When the seventh laser pulse is irradiated on the surface, the acoustic wave becomes quite small and does not change obviously with further laser pulses. This very weak wave implies that there is little toner to interact with the laser pulse on the paper surface. A well-cleaned paper surface is then achieved by the irradiation of the seventh laser pulse.

Chromatic Analysis

In order to obtain characteristic spectral information during the laser cleaning of paper, chromatic analysis is carried out in the frequency spectrum domain which is obtained from the fast Fourier transformation of the acoustic waves shown in Figure 6.

Figure 7 (a) shows the output patterns as a function of the number of laser pulses irradiated on the same spot which was obtained through three chromatic filters of different responses R_{High}, R_{Medium} and R_{Low} covering the frequency range up to 12 kHz shown in Figure 3. The variation of the resulting chromaticities x, y and z, which was achieved by equation (3), is also shown in Figure 7 (b). It is seen that the x and z chromatic coefficients change as the number of laser pulses increases. Clear change is shown between the fourth laser pulse and seventh laser pulse and then the value does not change with further laser pulses. This implies that the transition of surface condition happened during the laser cleaning i.e. the surface toner has been removed in the seventh laser pulse so well cleaned paper surface was obtained. These results agree with those of the optical microscopic analysis shown in Figure 5.

In order to quantify the change of the acoustic spectral signature during the cleaning, translating these chromaticities into the chromaticity diagram was conducted as shown in Figure 7 (c). The monochromatic locus was achieved by the chromaticity equation (3) using the original tristimulus values (R_{High}, R_{Medium} and R_{Low}) of the three chromatic filters. Each point on the chromaticity diagram can be mapped on to the number of laser pulses. It is shown graphically that clear changes in spectral signature are apparent with the number of laser pulses. If we suppose the point W(1/3, 1/3) represent a white point it is possible to obtain the dominant frequency by extending the line between the white point W and the chromaticity point of acoustic source until it intersects the locus of the monochromatic spectrum. It is seen in this diagram that the dominant frequency of the acoustic wave is around 5 kHz and the value does not change obviously with the increase of the number of laser pulses. This result can be understood from the frequency spectrum of the acoustic waves where the largest peak in the spectrum was found at around 5 kHz (which is shown in Figure 3 (b)) and the peak value did not change significantly with the increase of the number of laser pulses. Meanwhile, the excitation purity of the acoustic wave (which was defined as the ratio of the distances, pW/dW, in Figure 2) changes significantly with the number of laser pulses. The value of excitation purity (EP) was changed from 0.6 at the first laser pulse to 0.4 at the ninth laser pulse. This implies that the spectral bandwidth of the acoustic spectrum increases with the increase of the number of laser pulses. That is to say that acoustic spectral signature changes with the variation in the surface cleanliness during the laser cleaning.

From these results, it is possible to say that the acoustic chromaticity is able to give much spectral information about the acoustic waves as well as a clear indication of surface changes during the laser cleaning process.

Effect of variation in experimental conditions

In order to see the effect of the variation of experimental conditions, acoustic emission was detected at two positions with different distance between an acoustic sensor and its source. The two distances 10 cm, 3 cm were used respectively. Figure 8 shows the average acoustic intensity, which was obtained by averaging the spectrum in the whole frequency range (~15 kHz) with the two positions. It is seen that acoustic intensity is strongly dependent on the distance i.e. the shorter distance the stronger acoustic wave was detected. This is an example of problems at using the intensity modulation method for process monitoring since a re-calibration procedure should be conducted every time when the experimental conditions are changed.

Figure 9 shows the excitation purity (EP) and energy level (EL) changes with the two different positions. EP changes are very similar with the two positions (Figure 9 (a)). However, EL shows the dependency on the distance, which is apparent in the intensity results of Figure 8. This implies that the chromatic acoustic analysis method is not only able to monitor the surface without the effect of the variation in experimental conditions such as detection distance but also it can recognise the current experimental condition using the EL spectral parameter. These results are produced by the unique characteristics of the chromatic modulation method, which depends on the spectral signature of the signal by analysing the distribution of the acoustic energy.

CONCLUSIONS

The chromatic modulation method based on the principles of colour theory was used to analyse acoustic waves and then was applied for surface monitoring in the laser cleaning process. The gross potential and versatility of the approach derives from the possibility of controlling the system range easily by suitable choice of the relative responses of the chromatic filters and from the intensity independent nature of the method. In addition, the chromatic modulation provides a convenient method for quantifying the difference accurately between the acoustic spectra in terms of chromaticity coordinates.

It has been shown that the spectral parameters (dominant frequency, energy level and excitation purity) from the chromatic acoustic analysis provide a clear indication of the surface cleanliness as well as much acoustic spectral information during the process. These parameters may be used as monitoring factors for the acoustic monitoring of laser materials processes.

In addition, it is shown that the chromatic acoustic analysis method offers a robust system for monitoring the surface without the effect of the variation in experimental conditions such as detection distance due to its inherent immunity to extraneous influences.

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CAPTIONS OF THE FIGURES

Figure 1. Relative wavelength responses of three optical detectors for the chromatic detection

Figure 2. Chromaticity diagram using the three detectors shown in Figure 1

Figure 3. Typical acoustic shock wave (a) (during laser cleaning of toner paper) and its frequency spectrum superimposed by three sine-squared filters (b) centred at three different frequencies along the spectrum

Figure 4. Block diagram of the experimental procedure for the chromatic acoustic monitoring in the laser cleaning process

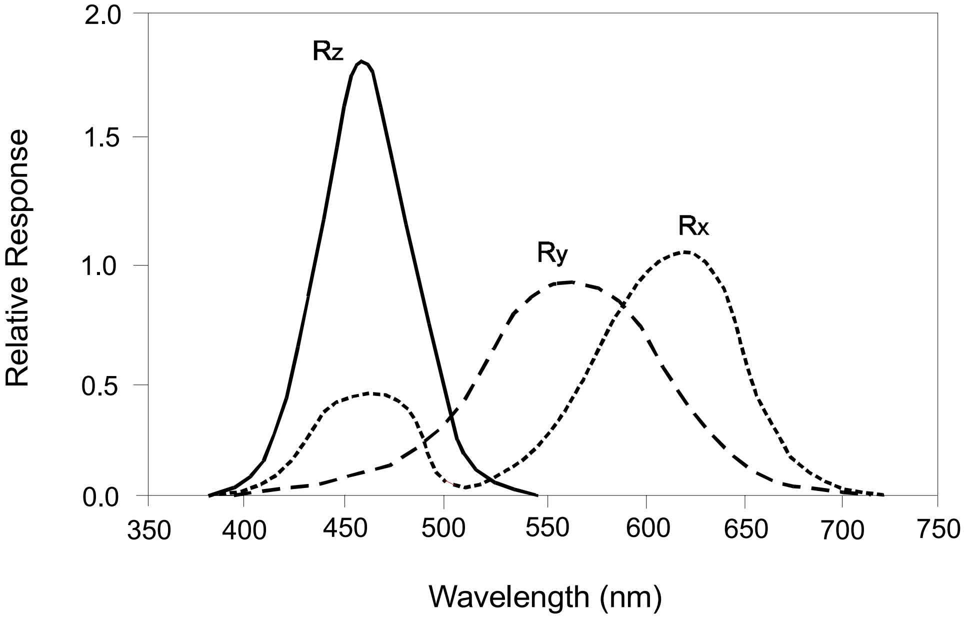
Figure 5. Laser craters on toner paper surface with the sequence of the number of laser pulses with the fluence of 1.2 J/cm^2

Figure 6. Acoustic waves emitted from a toner paper surface under Q-switched Nd:YAG laser irradiation of (a) the first, (b) the third, (c) the fifth and (d) the seventh laser pulse respectively

Figure 7. Outputs from the chromatic analysis during the laser cleaning of paper: (a) outputs from the three chromatic filters, (b) chromatic coefficients (x, y, z) variation with the number of laser pulses and (c) chromaticity variation in the chromaticity diagram

Figure 8. Average acoustic intensity with the variation of detection distance between an acoustic sensor and its source (10 cm and 3 cm)

Figure 9. Energy Level (a) and Excitation Purity (a) change as a function of laser pulses with the two different positions, 10 cm and 3 cm



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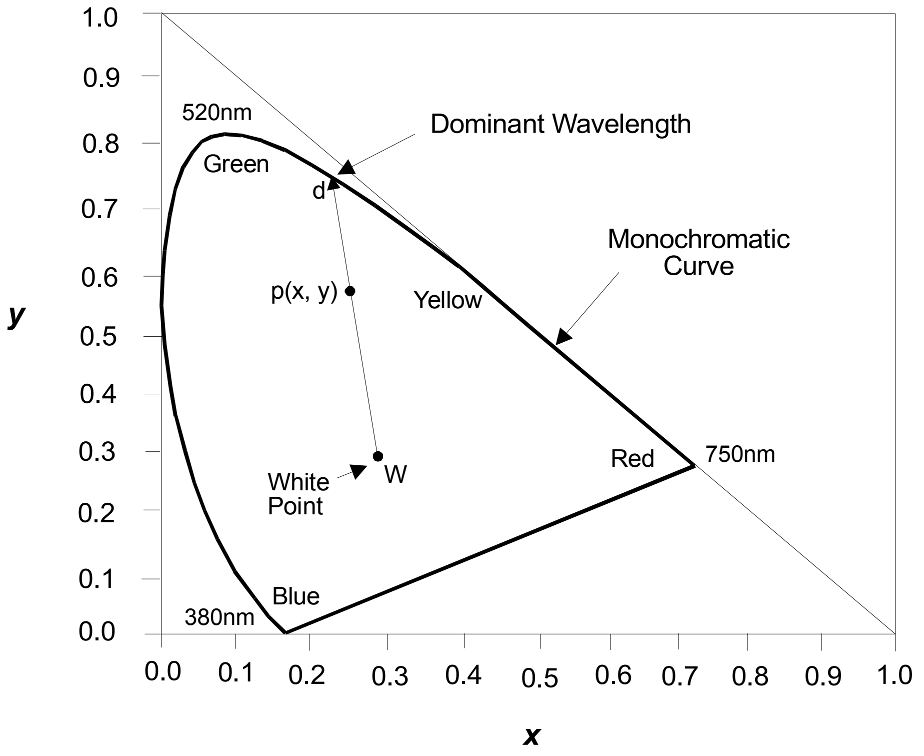
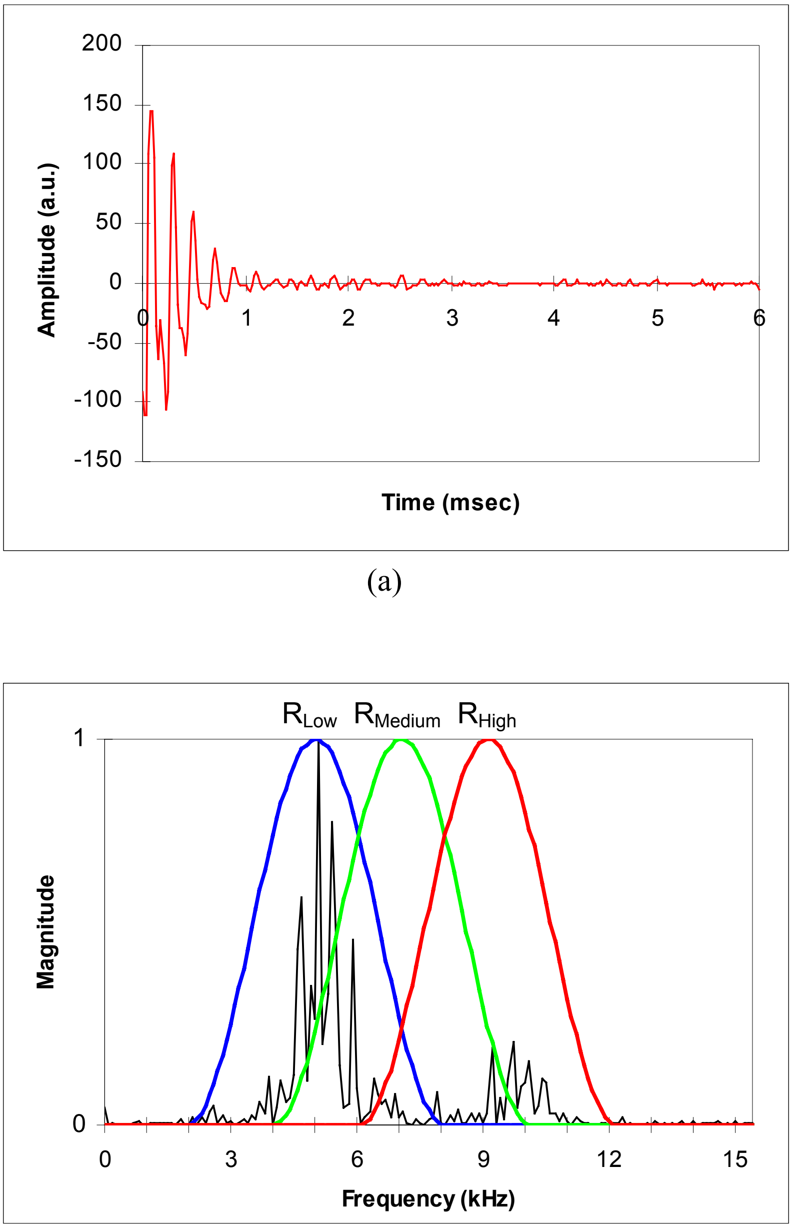


Figure 2. Chromaticity diagram using the three detectors shown in Figure 1



(a)

(b)

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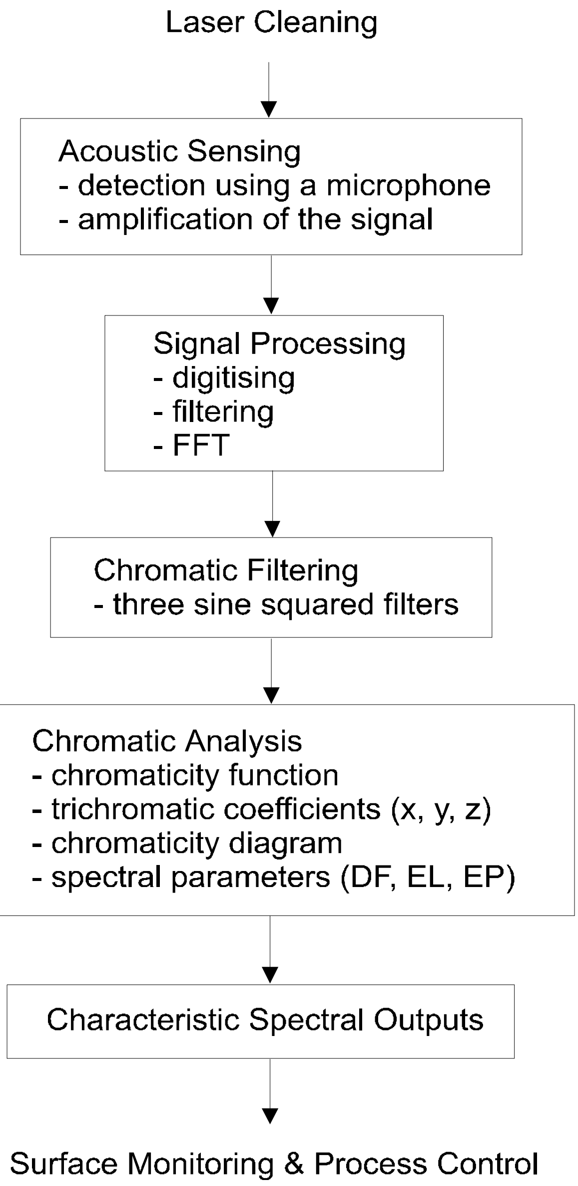

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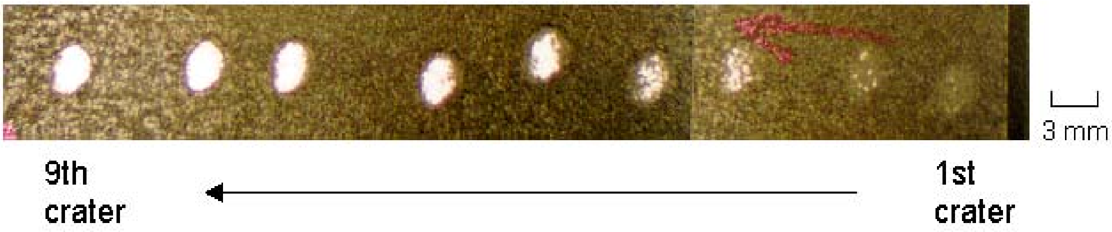

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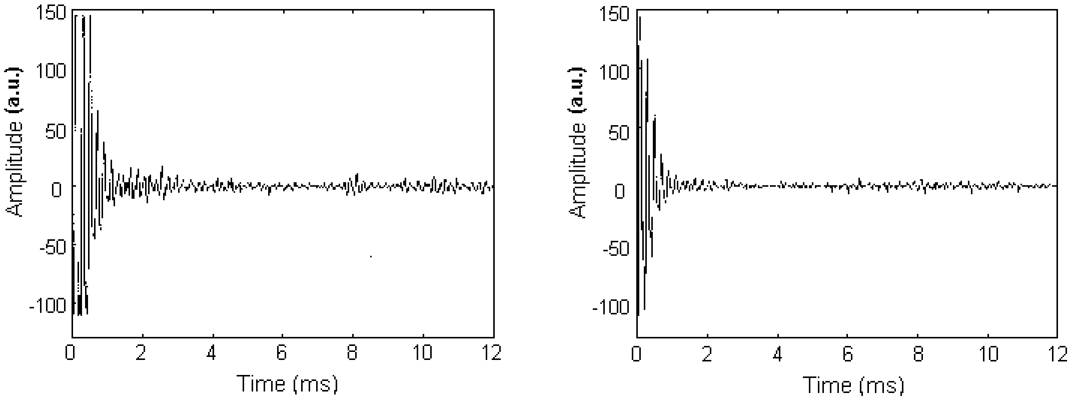
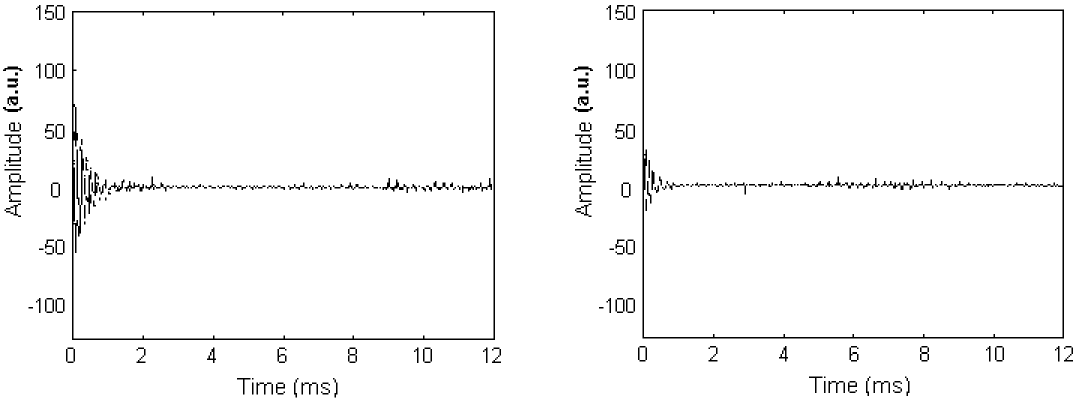


(a) 1st acoustic wave

(b) 3rd acoustic wave



(c) 5th acoustic wave

(d) 7th acoustic wave

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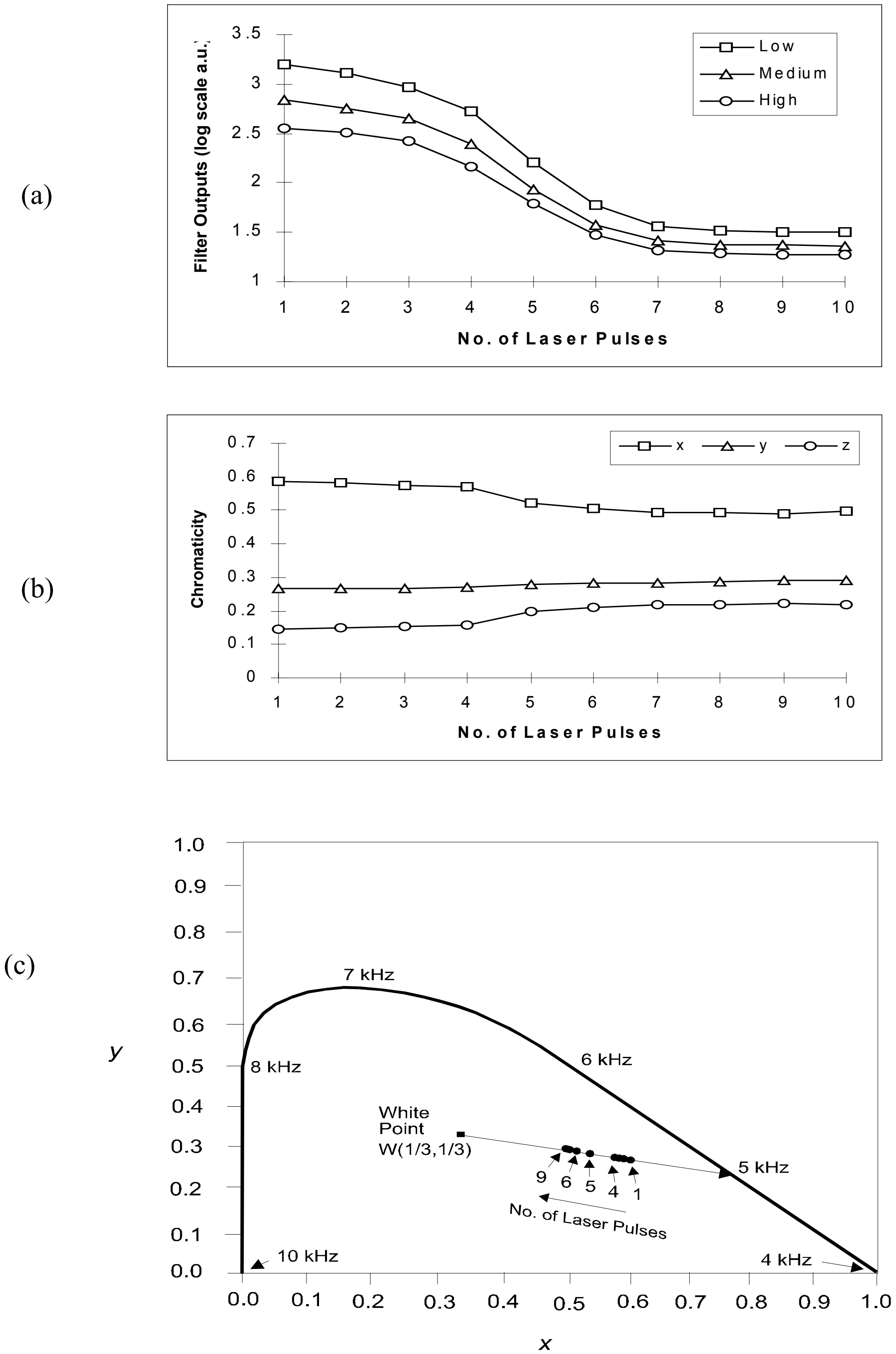

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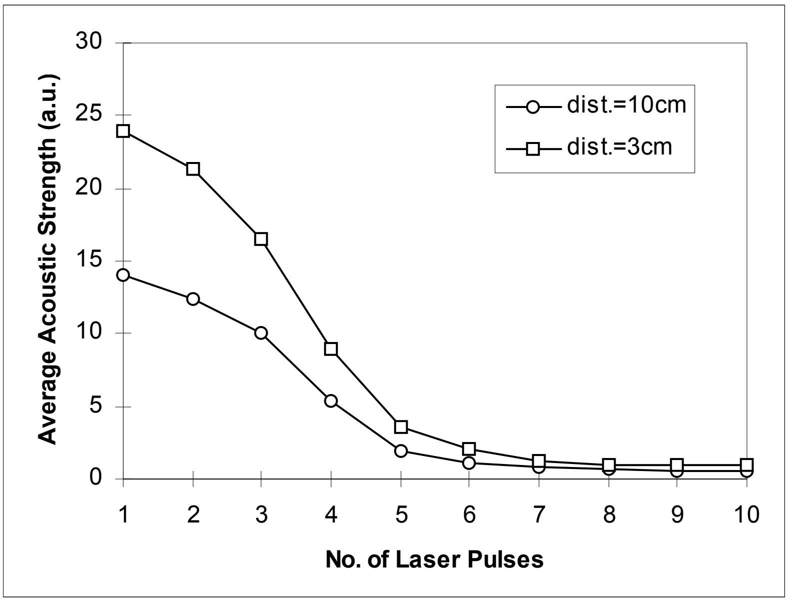

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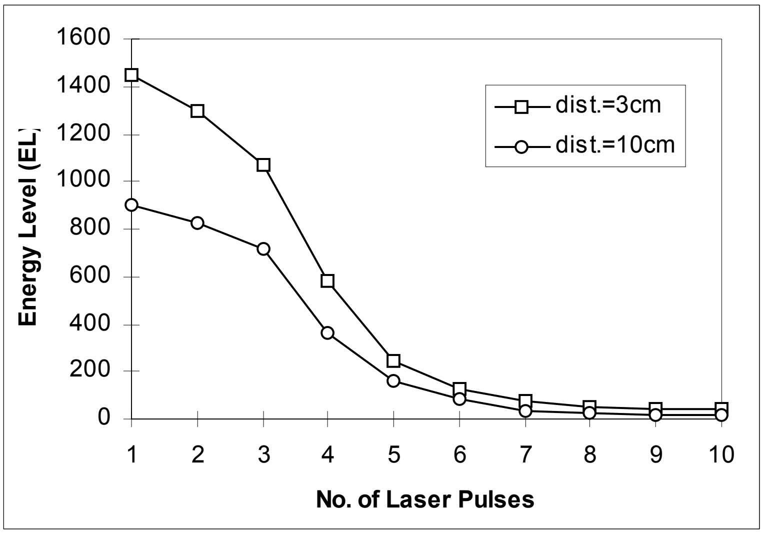
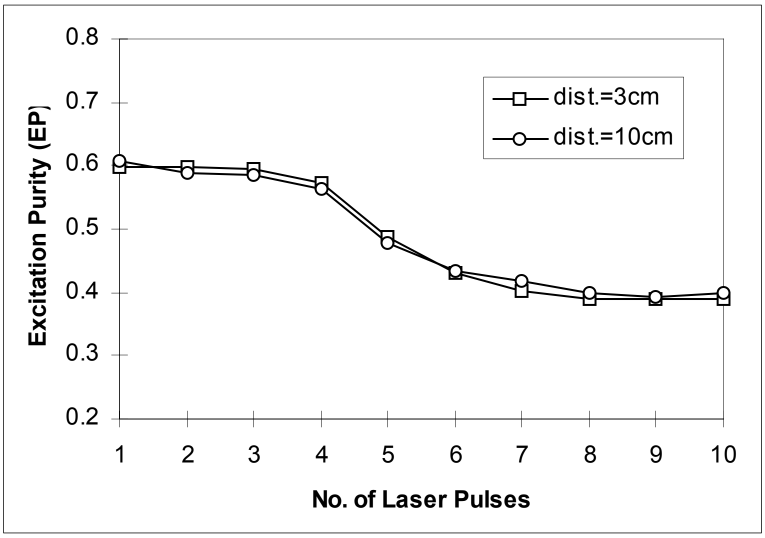


(a)



(b)

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