Research paper

Investigation on the acoustic properties of pyrotechnic whistles

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Abstract

The acoustic properties of pyrotechnic whistle devices with the whistle composition consisting of 30% potassium benzoate and 70% potassium perchlorate have been investigated by advanced measurement technologies in the study. The effects of the loading density and the chimney length on the whistling were examined firstly. The experiment results show that the pyrotechnic whistle composition burns with a loud whistling sound when the loading density is larger than a certain value called critical density and the chimney length is longer than a minimum. The critical density and the minimum chimney length for the whistle composition were obtained. Then the relationship between the whistling and the behaviors of the flame was investigated. It is found that although the flame exited from the tube mouth exhibits the marked difference between non-whistling and whistling, the flame front propagates at a constant rate even when the composition transitions from non-whistling to whistling.

Keywords: whistle, acoustics, pyrotechnics, oscillating burning, combustion

1. Introduction

There are two basic audible effects produced by pyrotechnic devices. One of the audible effects is a loud explosion noise and another is a whistling sound. A unique whistling phenomenon can be produced by firmly pressing certain pyrotechnic composition into a confinement tube closed at one end, open at another end, and igniting the composition. The ingredients in pyrotechnic whistle compositions are the salt of an aromatic acid such as potassium benzoate or sodium salicylate as the fuel and a strong oxidant such as potassium perchlorate. The devices producing a whistle-like effect are widely used in some applications such as fireworks industry.

The acoustic properties of pyrotechnic whistle compositions were studied in detail by W. R. Maxwell[1] in 1952, and a more recent review of the whistle literature has also been published[2]. Further research has continued in efforts to fully understand the whistle phenomenon[3]. Their research results show that the pitch of a whistling sound is related to the length and diameter of the tube filled with a whistle composition. The whistling sound is considered to appear by the resonance of the open tube and its acoustic properties are similar to the sound produced by a musical instrument such as a flute. It is generally agreed that a reaction that produces a whistling effect is burning intermittently from layer to layer in the pressed composition. Although many efforts in understanding pyrotechnic whistles have been made, there is still no firmly established mechanism that accurately describes their operation.

In order to understand pyrotechnic whistling phenomenon, we conducted basic research on the acoustic properties of pyrotechnic whistle devices where new experiment method and modern instrumentation techniques, including precision sound level meter and high -speed camera, were employed to examine the acoustic properties of the whistle composition in the study.

2. Experimental

2.1 Sample preparation

The whistle composition used in the research was a powder mixture prepared by mixing 30% potassium benzoate and 70% potassium perchlorate. The powdered materials had all passed through a 150 μm sieve, so the particle sizes of potassium benzoate and potassium perchlorate were smaller than 150 μm. Two types of whistle device samples (type A and type B) were prepared as follows.

(1) Type A

A steel tube was partially filled with the whistle composition. The sizes of the tube were 10 mm inner diameter, 12 mm outer diameter and 30 mm length. The loading composition length was about one-thirds of the total length of the tube, so there was a chimney above the flame front when burning. The whistle composition samples for different loading densities within 0.9–1.8 g cm^{-3} were prepared by the control of pressing pressure.

The structure of the sample is similar to a whistle device that has been widely used in the fireworks industry.

(2) Type B

An acrylic transparent tube was fully filled with the whistle composition. The sizes of the tube were 12 mm inner diameter, 16 mm outer diameter and 40 mm length. The whistle composition length was the same as the total length of the tube, so there was no space above the composition front. The samples with loading densities about 1.0 g cm^{-3} and 1.8 g cm^{-3} respectively were prepared. For each loading density, the experiment was repeated three times.

Whistle device type B is only used in this study for researching the relationship between the whistling and the behaviors of the flame.

The schematic representations of the whistle device samples are shown in Figure 1.

2.2 Experimental setup

Experimental measurements were conducted with the equipment setup as illustrated in Figure 2. The sample was located vertically over a force transducer which was used for measuring the recoil force of the tube when burned gaseous products exited from the tube. The force transducer was a quartz piezoelectric gauge with 0 to 0.5 kN range, manufactured by Kistler Instrument Corp. (model 9333A). Whistling sound was recorded by a precision sound level meter (model 2250) manufactured by Bruel & Kjaer Corp. and the frequency analysis was carried out by using a data acquisition analytical instrument (model DEWE-41-T-DSA). The sound level meter was installed at a horizontal distance of 1 m from the sample. In addition, the movement of the flame front of the sample in the transparent tube was recorded by a high -speed camera (model Phantom VR-V 4.2). The photographs of the flame of the whistle composition were taken by a video camera (model Sony HDR-XR100S).

3. Results and discussion

3.1 Acoustic output of a pyrotechnic whistle device

Figure 3 shows a typical example of the complete record of acoustic output of a pyrotechnic whistle device as a function of time and Figure 4 shows a part of the whistling sound pressure output enlarged in the time scale. The whistling sound pressure waveform is very similar to a sine or cosine wave. The result indicates that the sound pressure changes almost periodically, and consequently it can be considered that the sound originates from oscillations in the tube during burning of the whistle composition in an oscillatory manner. Figure 5 shows the frequency spectrogram of the whistling sound. There are some peaks on the spectrogram. The most left peak represents the first harmonic or the fundamental frequency, and the second peak, the third peak represent the higher harmonic, and so on. The frequency 428

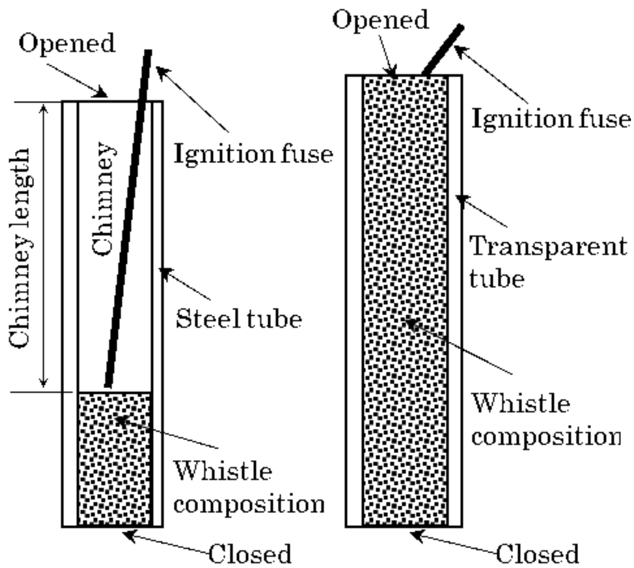

Figure 1 Whistle device samples (left: type A; right: type B).

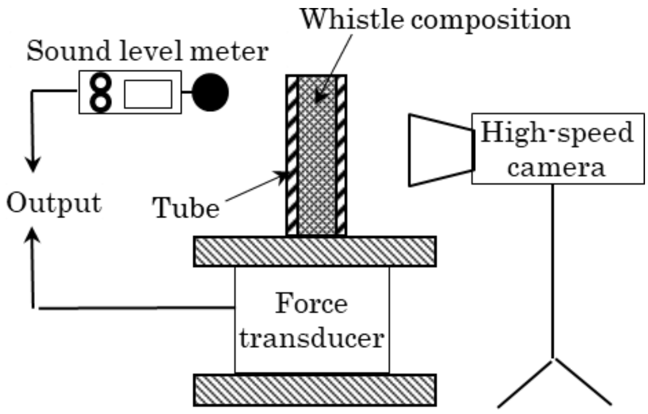

Figure 2 Schematic diagram of experimental setup.

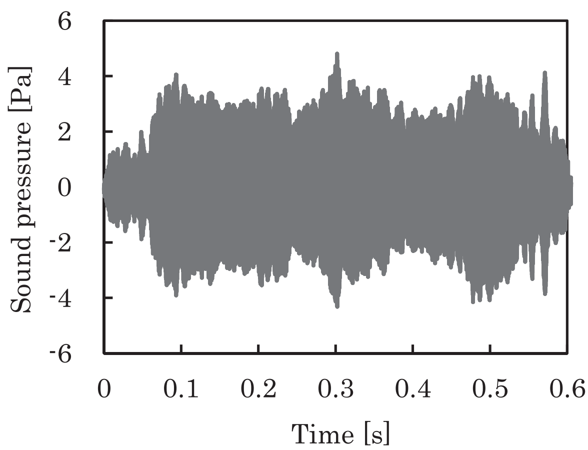

Figure 3 An example of type A whistle device of sound pressure output.

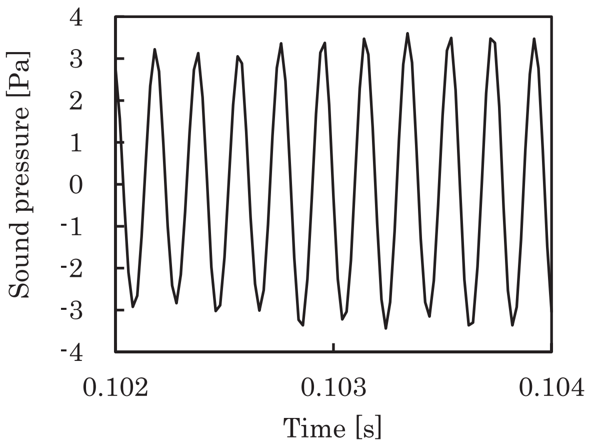

Figure 4 Whistling sound pressure output enlarged in the time scale.

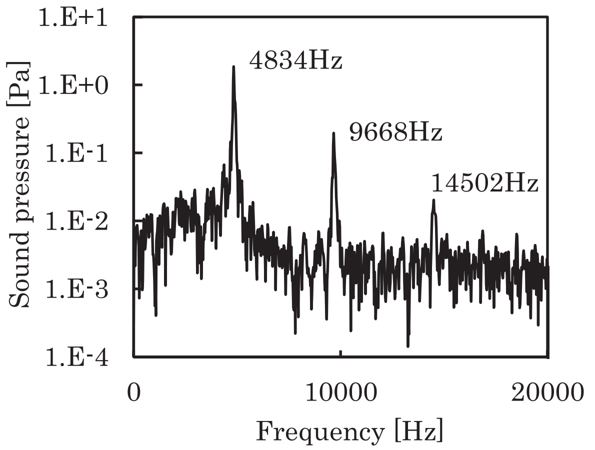

Figure 5 Frequency spectrogram of the whistling sound.

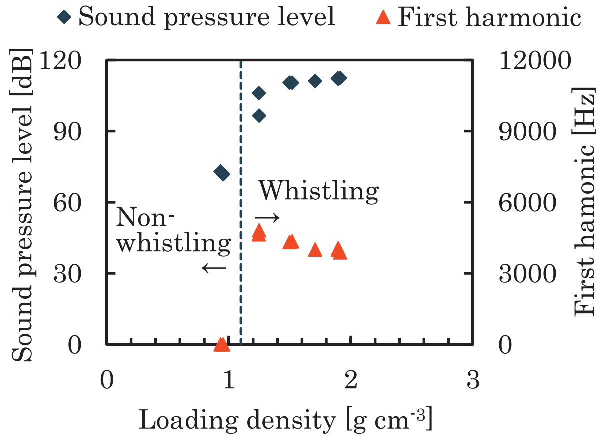

Figure 6 Effect of loading density on whistling sound pressure and first harmonic frequency.

Figure 7 Photograph of the flame of whistle device type B (loading density is below critical density).

corresponding to the first peak is about 4834 Hz, the ratio of the frequencies of the higher harmonics and the first harmonic follows an integral multiple 1, 2, 3, ⋯ relationship.

3.2 Effect of loading density on whistling sounds

The determinations of the outputs of the whistling sounds produced by different loading density samples with same chimney length were carried out. The sound pressures levels of whistle outputs and the first harmonic frequencies are shown in Figure 6. If the loading density is larger than 1.2 g cm^{-3}, the composition produces a loud whistling sound. As the loading density increase, the sound pressure level increases but the first harmonic frequency decreases. On the other hand, when the loading density is lower than 1.0 g cm^{-3}, there are no peaks on the frequency spectrogram. Therefore, the first harmonic frequency marked in Figure 6 is zero. This means that the whistle composition does not produce any whistle-like effect but only produces a weak noise with low sound pressure due to the flow of burned gas. The experiment results indicate that the pyrotechnic whistle composition does not produce a loud whistling sound during burning if the loading density is lower than a certain value. Here, the loading density is called critical density as shown by a broken line in Figure 6. For the whistle composition consisting of 30% potassium benzoate and 70% potassium perchlorate, the critical density obtained from the experimental data is about 1.1 g cm^{-3}.

3.3 Effect of chimney length on whistling sounds

For the whistle composition that is filled throughout a transparent tube, the flame propagates downward and the chimney length above burning front in the tube increases with time as the whistle composition is consumed during burning. Figure 7 is a photograph showing the burning of a whistle composition that had a loading density of 1.0 g cm^{-3} below the critical density. Broken line and red arrow in the figure refer to positions of the tube mouth and the flame front, respectively. The observed flame above the tube mouth was always long, but no whistling phenomenon occurred during burning.

Figure 8 shows a set of flame photographs of the whistle composition at three different burning moments. The loading density of the sample is about 1.8 g cm^{-3} above the critical density. At the beginning of the burning, the sample only produced noise due to the flow of burned gaseous products and did not produce any whistling sound, and the observed flame above the tube mouth was long as shown in photo (a). As the flame propagated downward along the tube, the chimney length above the flame front increased little by little. When the chimney length exceeded a certain value, the whistle oscillations built up and the flame became smaller as shown in photo

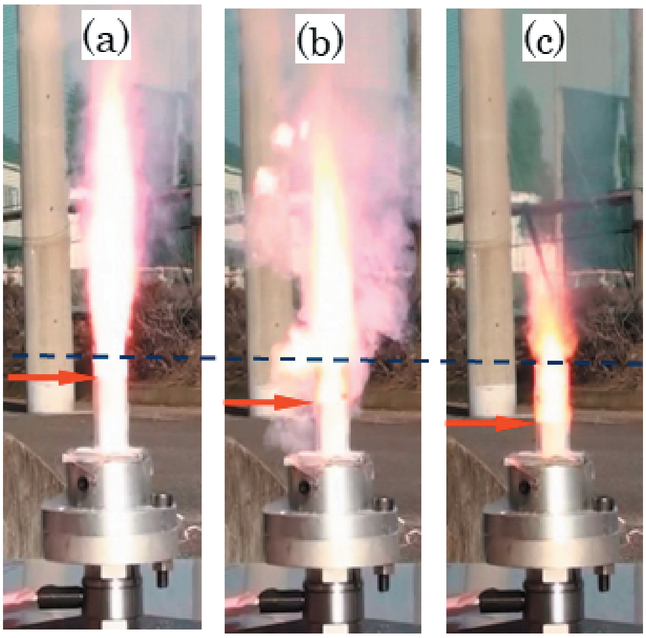

Figure 8 Photographs of the flame of whistle device type B (loading density is above critical density) at three different burning moments. (a) Non-whistling, (b) Start to whistling, (c) Whistling

(b). After that, the flame further became smaller as shown in photo (c) and a loud whistling sound was generated. As the composition was further consumed and the chimney length increased, the harmonic frequency of the whistling sound decreased gradually. The experimental results indicate that there is a minimum chimney length for whistling. If the chimney length falls below the minimum length, the whistling oscillations cannot build up and the composition cannot produce any whistling sound. The minimum chimney length with different inner diameter of the tube was also investigated. For potassium benzoate/potassium perchlorate (=30/70) composition, the minimum chimney length is about 15 mm and is not related to the diameter of the tube.

3.4 Propagation of the flame front

In this study, the propagation of the flame front in an acrylic transparent tube was recorded finely by a high-speed camera with frame speed 800 frame s^{-1}. The experiment was conducted three times with the same conditions for each whistle device sample. The experimental results shown in Figure 9 indicate that there is a linear relationship between the displacement of the flame front and the burning time for each whistle device. It suggests that the flame front uniformly spreads at a constant rate. From the slopes of the straight lines shown in Figure 9, the flame front spread rates for the compositions with loading density 1.0 g cm^{-3} and 1.8 g cm^{-3} were determined to be about 12.2 mm s^{-1} and 7.5 mm s^{-1}, respectively. The higher the loading density is, the slower the flame spread rate is. The reason is that since the spaces among the particles of the composition with low loading density are large, the hot combustion gaseous products are easily to enter the unburned composition and the propagation of the flame front becomes faster. The

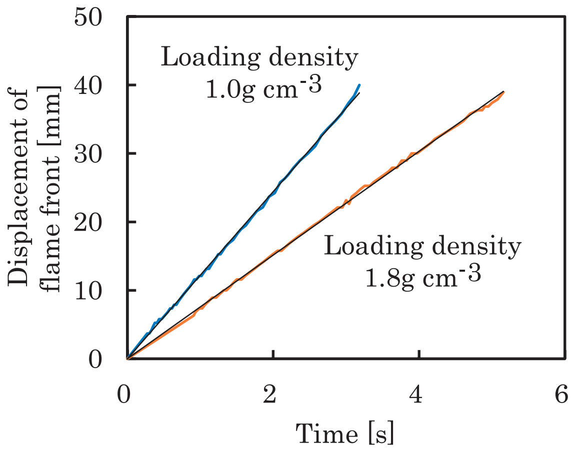

Figure 9 Relationship between the displacement of the flame front and the burning time.

result indicates that the burned products of whistle composition contain a lot of gaseous products.

For loading density 1.0 g cm^{-3} below the critical density, the composition does not produce any whistling sound and the flame spread rate is a constant. On the other hand, for the sample (1.8 g cm^{-3}) whose loading density is above the critical density, the observed flame becomes smaller during whistling, but the flame spread rate does not change even if the audible effect changes from non-whistling to the whistling.

3.5 Whistling oscillation

If a whistle device was ignited, a recoil force at the bottom of the tube should be produced due to the pressure of out-streaming gas. The sound pressure and the recoil force produced by a whistle device during burning were measured. The whistle device was an acrylic transparent tube fully filled with the whistle composition and the loading density was 1.8 g cm^{-3}. Figure 10 shows the complete record of the sound pressure and the recoil force.

Figure 11 show a part of the outputs of the sound pressure and the recoil force enlarged in the time scale at the beginning of the burning. Because of without chimney or enough chimney length above the flame front, the pyrotechnic burn generates its own random noise produced by the flow of burned gaseous products and the sound pressure is very low. The tube due to the out-streaming gas also generates a weak random vibration. The frequencies of the sound pressure and the recoil force are shown in Figure 12 and the sound is very similar to a noise, and therefore the frequency spectrogram does not show any peak.

According to M. Podlesak[3], the acoustic behavior of a whistle device can be modelled on the classic quarter-wave resonator, where the flame front in the tube provides both a high acoustic impedance boundary and an acoustic energy source, and the open end provides a low impedance boundary. Our experiment results show that when the chimney length becomes larger than the minimum chimney length as the flame front propagates, the chimney above the flame front becomes a resonator and a resonating standing wave is created, and therefore a

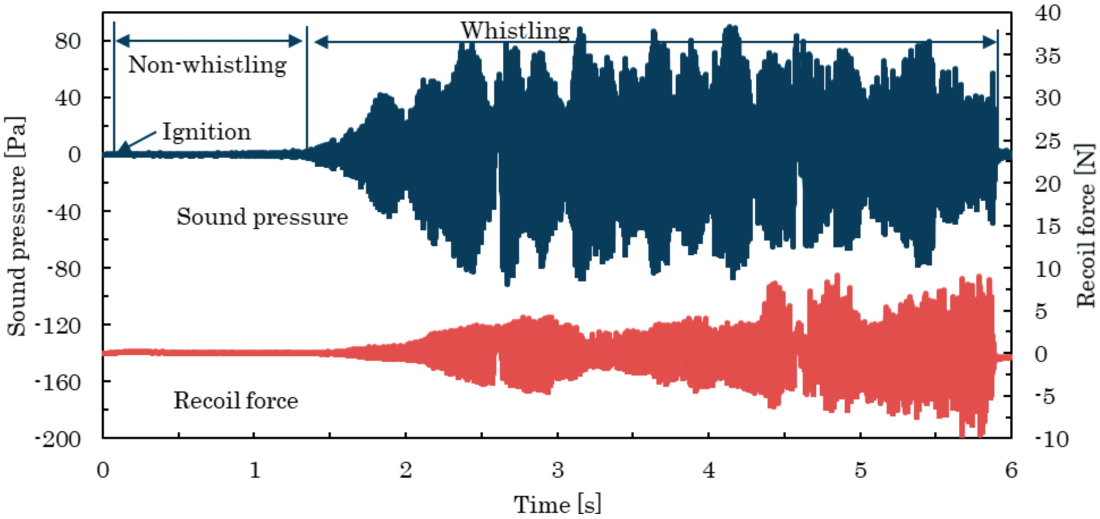

Figure10 The sound pressure and the recoil force during whistle composition burning.

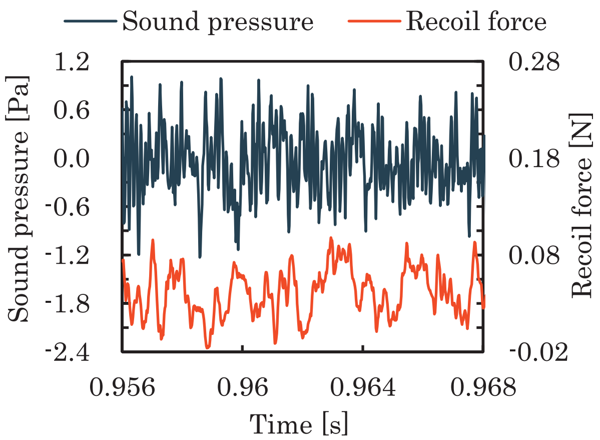

Figure11 A part of the outputs of the sound pressure and the recoil force during non-whistling.

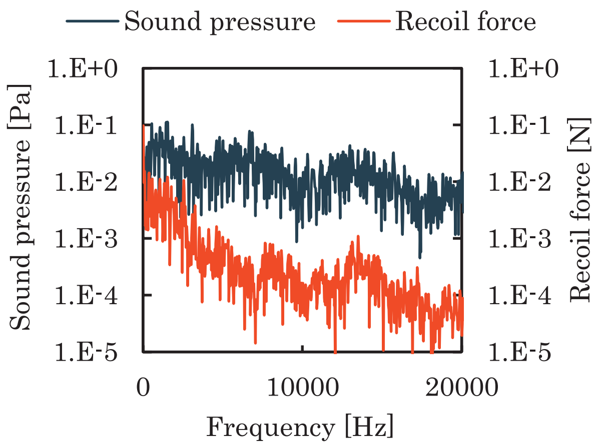

Figure12 Spectrogram of the sound pressure and the recoil force during non-whistling.

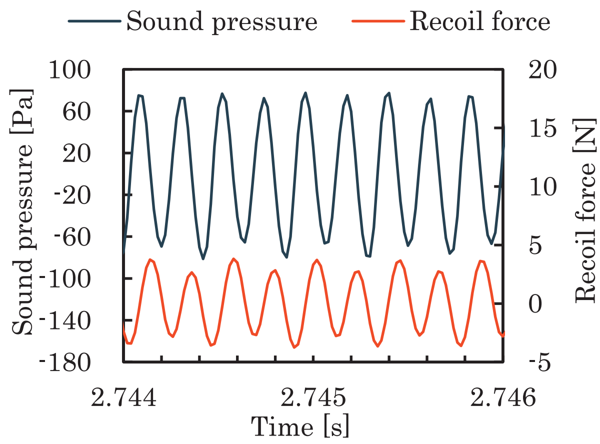

Figure13 A part of the outputs of the sound pressure and the recoil force during whistling.

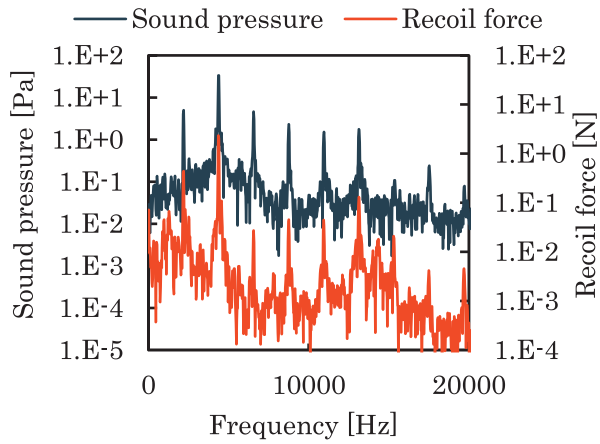

Figure14 Spectrogram of the sound pressure and the recoil force during whistling.

periodic sound pressure waveform with large amplitude and a loud whistling are also established. Figure 13 show a part of the outputs of the sound pressure and the recoil force enlarged in the time scale when whistling. The recoil force of the whistle device changes periodically and the recoil force profile has the similar shape as the sound pressure profile. The results of the frequency analyses for the sound pressure and the recoil force during whistling are shown in Figure 14. On the sound spectrogram, there are some peaks because of whistling. The recoil force spectrogram is approximately same as the whistling sound spectrogram. The intermittent combustion on the surface of the pressed composition results in an oscillation of the burned gas above the burning surface in the tube, and therefore the tube vibrates with the same manner as the burned gas oscillation.

Based on the above experimental results, it can be seen that the flame spread rate does not seem to be affected by the intermittent combustion because the flame propagates at a constant rate.

4. Conclusions

The acoustic properties of pyrotechnic whistle devices with the whistle composition consisting of 30% potassium benzoate and 70% potassium perchlorate have been investigated in the paper. The main conclusions are obtained as follows.

(1) To produce a whistling sound, the loading density of the whistle composition must be large than critical density. The critical density for the whistle composition is about 1.1 g cm^{-3}.

(2) If the chimney length is too short, the whistling sound does not be produced. The minimum chimney length for the whistle composition is about 15 mm.

(3) Although the flame exited from the tube mouth exhibits the marked difference between non-whistling and whistling, the flame propagates at a constant rate even when the composition transitions from non-whistling to whistling.

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