Abstract: Acoustic observation of laboratory simulated lightning discharge can greatly avoid the observation difficulties under natural thunderstorm environment. An acoustic observation experiment based on the impulsive current generation system and a microphone array was carried out and illustrated in this study. A quantitative study on characteristics of response sound pressure initiated from simulated lightning current was performed. The first arrived acoustic N-waves measured at different distances initiated from different discharge amplitudes were compared and analysed. The acoustic amplitude, rise time and duration time defined for N-waves and peak frequencies were found to have an obvious correlation with the discharging amplitudes of simulated lightning currents and the observing distances. The linear change of acoustic amplitude is more obvious than that of the other parameters with the changed discharging amplitude or observing distance. A certain degree of shape change of the simulated lightning current except for the amplitude may not significantly affect the response acoustic characteristics when comparing the first acoustic N-waves from 8/20 μs lighting current and another kind of impulsive current which has a wider shape and two subsequent peaks. The subsequent current peaks in short time delays were proved to successively generate acoustic N-waves independently without overlapping, which meanwhile, indicated a consistent linear relationship of amplitude and time delay between electrical and acoustic pulses.

1 Introduction

Natural lightning is a strong instantaneous discharge process, accompanied by the generation of multiple physical radiations such as sound, light and electromagnetic waves. Thunder is the result of acoustic energy emission associated with lightning discharge which forms shock waves and attenuates into a sound pressure wave during propagation [1, 2]. Through the acoustic detection of thunder radiations, the spatial localisation, inversion of the energy injection and discharge process of the lightning channels can be further studied. Bodhika et al. analysed the peak frequency, sound pressure amplitude, duration and number of time-domain acoustic pulses of audible thunder signals in the tropical region [3, 4]. Qiu et al. and Zhang et al. reported the single station acoustic localisations in Nanjing and Wuhan, China. The inverted geometric characteristics of the main channels were in good agreement with the localisations by electromagnetic or optical observation [5, 6]. Arechiga et al. explained infrasound pulse generation based on the multi-station acoustic, very-high frequency and electrostatic measurements of two intra-cloud flashes in New Mexico, USA [7]. Gallin et al. reported the statistical analysis of 56 thunder events due to a thunderstorm in southern France based on multi-station infrasound research. The distributions describing lightning discharges from different acoustic detection positions were explored and compared with electromagnetic detection [8]. Dayeh et al. obtained the acoustic images of the triggered lightning based on the near-field acoustic array at the International Center for Lightning Research and Testing, Florida, USA [9]. There are few reports on the characteristics of lightning acoustic waveforms and their quantitative correlation analysis of lightning discharge intensity.

The long-distance non-linear radiation propagation of thunder waveforms from the source to the observation site may cause different degrees of waveform distortion while the interference near the ground will cause reflection and superposition. The response of the acoustic sensor itself is vulnerable to thunderstorms and rains. The random location and electrical strength of natural lightning discharge hinder the simultaneous and efficient acquisition of a large number of lightning electrical parameters and thunder signals. It is difficult to carry out quantitative research on characteristics of acoustic waveforms related to lightning discharge processes via natural outdoor observation.

The conditions of simulated lightning strokes in the high-voltage laboratory are relatively mature at present [10]. Laboratory acoustic observation of lightning current discharge can greatly avoid the difficulties faced in the natural environment. Meanwhile, the impulsive lightning current waveforms with different shape and amplitude characteristics can be easily calculated and obtained by the impulsive current generation system, which provides convenience for accurate and efficient research on lightning acoustic waveform characteristics and the correlation between acoustic and electrical parameters. Uman et al. reported the results of laboratory acoustic observations of simulated long gap lightning discharges, but they mainly discussed the acoustic characteristics under given discharge conditions at different observing distances [11]. In order to quantitatively study the acoustic characteristics of lightning current discharge with different intensities and shapes, which provides a valuable reference to outdoor observation of natural or rocket-triggered lightning, an acoustic observation experiment of lightning current discharge based on an impulsive current generation system and a microphone array were carried out in the high-voltage laboratory of Wuhan University by our research group [12]. The acoustic waveforms measured at different distances initiated from 8/20 μs lightning current discharge with different peak values are analysed to research the characteristics of acoustic parameters and the correlation with electrical parameters.

Current pulses in natural lightning flashes tend to have different shapes and amplitude characteristics [13], and it is not uncommon for a single current pulse to follow the subsequent impulsive pulses at a very short time delay [14]. Given the above situation, these following problems are currently unclear, namely, whether each discharge pulse in a flash will produce acoustic response waveform with significantly different characteristics, and whether the acoustic response wave has one-to-one correspondence without overlapping. Therefore, another type of impulse lightning current pulse with a shape different from that of the 8/20 μs lightning current was obtained in this study, and their characteristics of acoustic response waveforms under the same discharge amplitude.
were compared. Meanwhile, the latter's main current peaks will be followed by subsequent peaks at a very short time interval to facilitate research on their corresponding acoustic response waveform characteristics. This type of laboratory impulsive lightning discharge further simulates the characteristics of natural or rocket-triggered lightning current and is considered to be of significance for understanding the acoustic characteristics of a natural lightning discharge.

2 Instrument and method

In this study, a series of indoor measurements under high-voltage, as well as powerful electromagnetic radiation, were conducted to research the acoustic characteristics of lightning current. The left half of Fig. 1 shows the circuit of the impulsive current generation system, which generated an impulsive discharge channel between the metal gaps with an acoustic shock wave initiated. The spherical gap, located at 1.8, 2.5, 3.5, and 4.5 m as the distances D from the sound source. Acoustic measurements of impulse lighting current were performed in homogeneous ambient air. Before carrying out the experiment, outdoor environmental noise had been mused via sound insulation measures.

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3 Result and discussion

3.1 Acoustic response of impulsive discharge

As Fig. 3 shows, after an impulsive discharge was generated and the acquisition system was triggered by recording signals, each channel received acoustic signals related to discharges at different time intervals. The first acoustic wave of each channel recorded appeared to be the obvious bipolar wave similar to the N-wave calculated by model [16], consistent with the observed results of laboratory simulated and natural thunder reported by Uman et al. and Depasse [17]. The deviation from ideal results calculated in the ideal environment was due to the limitation of the sensor's fast response and the non-linear propagation of sound waves in atmosphere medium [18, 19]. Since the experiment was arranged indoors, there were several waves with relatively large amplitudes appearing in the sequential waves compared with the average, which was considered to be coming from reflection. The signals before the first acoustic N-wave appear smooth because of a noiseless test environment, and thus the characteristic of the first acoustic waveform which directly correlates with the lightning current discharge was recorded and studied without noise interference and diffraction. Correspondingly, the power spectrogram of each channel under the same time window based on S-transformation is given in turn below the time-domain waveform. The frequency components and power intensities of the responded acoustic pulses varying with time in different distance channels are clearly reflected in the spectrum, and the peak frequency of the first N-type acoustic pressure wave can also be obtained.

It was found that if the metal gap was adjusted to the max length for discharge, the shapes of the first N-waves for all repeated tests with the same current value are extremely similar with a change of acoustic parameters <3%. Each discharge condition has been repeated three times, and Table 1 gives the average electric parameters of totally five discharge conditions. The applied I_{max} is changed from 2.03 to 5.14 kA with a ±0.02 kA error, exceeding the maximum of which the acoustic microphone will exceed the dynamic range.

The measured results focusing on the first acoustic N-waves are shown in Fig. 4. Each chart from Figs 4a-d illustrates the waveforms recorded by microphones located at 1.8, 2.5, 3.5, and 4.5 m, respectively, which is corresponding to arrival times reflected on the X coordinates. The acoustic waveforms in different colours, respectively, generated under different discharge
Table 1  Electric parameters of each discharge condition

| Type | N | \( T_r \), µs | \( \tau_d \), µs | \( I_{\text{max}} \), kA |
|------|---|-------------|-------------|---------------------|
| \( I_1 \) | 3 | 8.0 | 20.2 | 2.03 |
| \( I_2 \) | 3 | 8.1 | 19.9 | 2.64 |
| \( I_3 \) | 3 | 8.0 | 20.1 | 3.53 |
| \( I_4 \) | 3 | 8.0 | 20.0 | 4.34 |
| \( I_5 \) | 3 | 8.0 | 20.1 | 5.14 |

conditions. Each chart from Figs. 4e–i shows the results generated under different discharge conditions, and the waveforms in different colours, respectively, recorded from different distances, while the \( X \)-coordinates just reflect relative times. Through superposition of the waveforms displayed in Fig. 4, it can be found that their typical characteristics are highly similar, with changes only in parameters.

Although the subsequent waves after the first wave have complex shapes and processes due to reflection and superposition, the first acoustic \( N \)-wave recorded appears to have roughly the same shape and characteristics when compared at a different distance or amplitude of the impulsive current. Meanwhile, the appearance of the first obvious \( N \)-wave is also reflected in thunder signals of natural lightning or rocket-triggered lightning flash. Thus, the characteristics of the first \( N \)-wave acoustic waveform were selected to study the correlation with the impulsive lightning current. In order to characterise the first \( N \)-wave in time-domain, three acoustic parameters are defined and shown in Fig. 5. \( P_{\text{max}} \) is the peak pressure amplitude, \( T_r \) is the rise time of the first positive phase, \( \tau_d \) is the total wave duration time of \( N \)-wave. The secondary positive peak of the first \( N \)-wave is not defined and discussed in this study because it is susceptible to diffraction from the sensor installation location [20].

3.2 Characteristics of acoustic parameters

The peak pressure amplitude \( (P_{\text{max}}) \) versus the peak value of current impulse \( (I_{\text{max}}) \) is shown in Fig. 6a. It appears that \( P_{\text{max}} \) varies significantly linearly proportional to \( I_{\text{max}} \), changing from 0.22 to 1.95 Pa. It is worth mentioning that with the measurement distance changing from far to near, there is a shift from linear growth to slight exponential growth. Figs. 6b and c show the linear change of acoustic rise time \( (T_r) \) and duration time \( (\tau_d) \), respectively, from 15.5 to 19.4 µs and 97 to 146 µs. When comparing the variation of acoustic parameters with the \( I_{\text{max}} \), it was found that the \( I_{\text{max}} \) increased the fastest by nearly three times at each observing distance, while the ratios of increase for \( T_r \) and \( \tau_d \) are small, about 15 and 40%, respectively. The little fluctuation of all parameters at a given condition proves the steady repeatability of acoustic responses of simulated lightning impulsive discharges. Similar relative ratios of variation occurred at different measuring distances with little change when comparing the scatters of different colours.

The latter two parameters \( T_r \) and \( \tau_d \) are related to the frequency characteristics of the sound pressure pulses and the response of the acoustic sensor. Since the selected sensor has a high response quality in the frequency range reflected by the power spectrum of the acoustic signals from impulsive discharge, the factor of the acoustic sensor was ignored in frequency domain analysis. The peak frequency \( f_{\text{max}} \) of the first \( N \)-wave obtained based on the power spectrum versus electrical \( I_{\text{max}} \) is shown in Fig. 6d. It was found that the \( f_{\text{max}} \) is close to an exponential decay with \( I_{\text{max}} \) increasing. Few et al. had proposed the calculation model which reflects the exponential attenuation relationship between peak frequency of thunder signals and injected energy of lightning channel in 1969, which may well explain the attenuation law of \( f_{\text{max}} \) with \( I_{\text{max}} \) mentioned in this study. Meanwhile, a series of quantitative experimental results obtained in laboratory simulated lightning discharge prove that \( f_{\text{max}} \), an important and intuitive parameter for characterising the discharge intensity, can directly reflect the correlation with the \( f_{\text{max}} \) of response acoustic pulses. The analysis of thunder signals initiated from simulated lighting discharge illustrated that the waveform characteristics of response acoustic pulses are significantly linearly correlated with the peak value of discharge current. The obvious correlation provides certain ideas and possibilities for inversion of lightning electrical processes through thunder signals, although the \( I_{\text{max}} \) of lightning return strokes changes from hundreds to tens of thousands of amps. In the latter study, which will not be mentioned in this study, we can further compare the correlation of acoustic and electrical parameters by quantitative acoustic observation experiments of a rocket-triggered lightning flash, which contains natural current.
pulses with a larger range of magnitude than that of laboratory impulsive current pulses in this study.

The values of acoustic parameters versus observing distances are shown in Fig. 7. The $P_{\text{max}}$ of acoustic N-wave shows a significant attenuation trend under the change of distance, reduced to about one-half relative to that of the nearest distance. This attenuation trend was basically consistent with the calculated numerical exponential decay trend reported in [21]. As for $T_p$ and $T_d$, both of them gradually increased in given discharge conditions with the increase of distance, respectively, by 10 and 8%, and the degree of change is much smaller than that of $P_{\text{max}}$. Acoustic $I_{\text{max}}$ also exhibits a certain degree of attenuation. The attenuation of the amplitude and frequency of thunder signals are mainly related to the propagation effect for finite amplitude sound pressure wave in the atmospheric medium and the dielectric absorption [22, 23].

Based on the results illustrated above, it is easily recognised that $I_{\text{max}}$, an important parameter for characterising the discharge intensity, has different degrees of nearly linear correlation effects on the parameters of the response acoustic pulses. The acoustic $P_{\text{max}}$ is more sensitive to the change of electrical $I_{\text{max}}$ than to the change of the other parameters. For the acoustic response pulses of the impulsive discharge measured at different distances, the results showed that the propagation effect from 1.8 to 4.5 m was reflected in different degrees of acoustic characteristics, which is smaller than the relative change in acoustic characteristic parameters caused by electrical $I_{\text{max}}$ obtained in this work. It is worth mentioning that the influence mechanism of the propagation effect and the lightning discharge intensity on the acoustic response waveforms are different, and the given experimental results are only a certain range of quantitative measurements and analysis, thus the characteristic correlation between the two factors and the acoustic pulse needs to be understood separately.

3.3 Acoustic response of current discharge with subsequent peaks

The previous Sections 3.1 and 3.2 mainly indicate the characteristics of response acoustic pulses from 8/20 μs impulsive lightning current discharge. By changing the capacitance value of the impulse discharge circuit [24], a simulated lightning current pulse with subsequent oscillation waves was obtained, the first
arrived peak $t_r$ and $t_d$ of which are measured to be about 50 and 110 μs, much wider than those of the 8/20 μs current pulse. Although

the occurrence of the negative second peak of the current in laboratory discharge is contrary to the current polarity characteristic of a natural lightning flash, it causes no difference in

**Fig. 6** Acoustic parameters (a) Peak pressure amplitude $P_{\text{max}}$. (b) Rise time $T_r$. (c) Duration time $T_d$. (d) Peak frequency $f_{\text{max}}$ versus peak values of lightning current $I_{\text{max}}$ from 2.03 to 5.14 kA

**Fig. 7** Acoustic parameters (a) Peak pressure amplitude $P_{\text{max}}$. (b) Rise time $T_r$. (c) Duration time $T_d$. (d) Peak frequency $f_{\text{max}}$ versus observing distances $D$ from 1.8 to 4.5 m
Fig. 8 Another kind of impulsive current and acoustic response
(a) Impulsive lightning current with two obvious subsequent peaks, (b) Corresponding acoustic response measured at 1.8 m.

Fig. 9 Amplitude ($P_{\text{max}}$) versus $I_{\text{max}}$ correlation between acoustic $N$-waves and corresponding current peaks

The characteristics for the generation of acoustic radiation and optical radiation [25]. Therefore, the amplitude of the negative polarity peak was inverted to positive polarity, and the first three obvious peaks of the current were marked with different colours in Fig. 8a, where $I_{\text{max}}$ is about 2.03 kA.

The first measured acoustic $N$-wave initiated from the impulsive current with subsequent oscillation peaks was similar to that of the previously discussed 8/20 μs current. Comparing the acoustic first $N$-waves with different discharge amplitudes and observing distances from two kinds of impulsive current pulses, no significant difference was found in the four parameters of the previous analysis. The acoustic response $N$-wave corresponding to current pulse in Fig. 8a measured at 1.8 m is shown in Fig. 8b. The acoustic waveforms with different colour markers indicated that the first $N$-wave is followed by two $N$-waves with relatively low amplitudes. Also, each subsequent $N$-wave appears after the end of the second peak of the preceding $N$-wave regarded as the ‘tail’ of the acoustic $N$-wave in this study. That is to say, the three consecutive $N$-waves reached the microphone sensor with no superimposition on each other.

The appearance of the latter two acoustic $N$-waves was obviously related to the subsequent oscillation peaks of the impulse discharge current, which was not found in the acoustic response of 8/20 μs current. Comparing Figs. 8a and 8b, where the time size and peak position are adjusted to be consistently presented, the peaks of the acoustic $N$-waves can be found to roughly match the oscillating current pulse in arrival time. To further confirm their one-to-one correspondence, the $I_{\text{max}}$ of the main current peak, the inverted inverse peak, and the third peak versus the $P_{\text{max}}$ of the corresponding first, second and third acoustic $N$-waves was drawn on the same scatter plot with different colours labelled in Fig. 9. As can be seen, the amplitude correlation of the three sets of parameters basically conforms to the same linear law with a high degree of fitting. Meanwhile, the time delay of the subsequent peaks relative to the main peak was compared between electrical and acoustic pulses in Fig. 10. The time delay is represented by $T_d$, subtracted from the time corresponding to the maximum value of each peak. It can be found that the acoustic and electrical time delay parameters are almost the same. The above two scatter plots comparing acoustic and electrical parameters came from repeated discharges at different amplitudes and the acoustic responses were measured at 1.8 m. Based on the correlation of the above two groups of parameters, it can be clearly considered that the subsequent acoustic $N$-waves are independently generated by the subsequent peaks of the impulsive current without superposition.

Although the main and subsequent peaks of the current have different shapes in terms of $t_r$ and $t_d$, the amplitude relationship between the $P_{\text{max}}$ and $I_{\text{max}}$ is highly consistent, which is not affected by the current characteristics. As for the relationship between electrical and acoustic time delays, although the acoustic parameters $T_d$ and $t_d$ will change with electrical $I_{\text{max}}$, which causes interference for $T_d$ statistics, the linear coefficient of 1.02 and the $R^2$ of 0.967 obviously conclude that they are highly correlated.

Two phenomena have been demonstrated and discussed in this section. Firstly, the impulsive current with subsequent waves was obtained, which is different from the 8/20 μs current. The characteristics of their first acoustic $N$-waves are similar, i.e. a certain degree of shape change of the simulated lightning current except for the discharge amplitude may not significantly affect the acoustic characteristics. This conclusion obtained through laboratory simulated lightning discharge has a certain value for researching on acoustic characteristics of natural or rocket-triggered lightning flashes, which may contain individual current pulses with different shape characteristics in addition to the difference in amplitude. Secondly, if the impulsive current pulse is followed by peaks in short time delays without overlapping, the subsequent current peaks can continue generating acoustic $N$-waves independently, time delays of which are consistent with the corresponding current peaks. Meanwhile, the amplitude characteristics of the main and subsequent pulses also indicate a highly consistent linear fit relationship. The obtained one-to-one correspondence acoustic response feature can also promote understanding of the corresponding relationship of the thunder waveforms from natural lightning channels. With regard to the superposition of acoustic waves generated by natural lightning
discharge, the main analysis and reports in the literature so far are focusing on the superposition of thunder waves initiated from different spatial locations but arriving at the same time [26, 27]. Those acoustic waves generated by lightning have short time delays from the bottom of the lightning channel, similar to the laboratory experiment in this study.

4 Conclusion

In this study, an acoustic observation experiment of simulated lightning current discharge was carried out in the high-voltage laboratory. The experiment not only calibrated the array acoustic observation system built by our group applied to the observation of natural or rocket-triggered lightning flash but also quantitatively studied the variation of characteristic parameters of the response acoustic waves initiated by the impulse discharge.

The first arrived acoustic N-waves measured at the different distances initiated from 8/20 μs standard lightning current discharges with different peak values were monitored. The parameters of acoustic characteristics were significantly correlated with the peak values of discharging current I_{max}. When the I_{max} changed from 2.03 to 5.14 kA, the sound pressure peak value P_{max} showed a linear increase of nearly three times. Meanwhile, the rise time T_{r}, duration time T_{d} and peak frequency f_{max} of the acoustic N-wave all had certain degrees of linear variation with 15% increase, 40% increase and 35% reduction, respectively. The observation distance change from near to far, the P_{max} of response acoustic N-wave is obviously attenuated, and the other parameters have different degrees of proportional changes as well. Regardless of whether or not considering the influence of observed distances or discharge amplitudes of lightning current, the linear change of acoustic P_{max} is more obvious than that of the other parameters. This conclusion, obtained from acoustic characteristics versus discharge amplitude and observing distance based on indoor simulated lightning impulse discharge, can facilitate understanding of the characteristics of response acoustic signals from natural lightning discharge, which features randomness in terms of discharge intensity and location.

The acoustic response characteristics of an impulse current discharge, which has a longer rise time than a half-wave duration T_{d} compared with 8/20 μs current and followed by two subsequent current peaks were analysed and compared. It was found that a discharge of a certain degree of shape change of the simulated lightning current except the discharge amplitude might not significantly affect the response acoustic characteristics. As for the subsequent peaks in short time delays without overlapping, they can continue generating acoustic N-waves independently, whose time delays are consistent with corresponding current peaks, and the amplitude characteristics are also highly consistent. Meanwhile, the subsequent current peaks in short time delays without overlapping can continue generating acoustic N-waves independently. Time delays of acoustic and electrical pulses are consistent with corresponding subsequent current peaks, and the amplitude characteristics of the main and subsequent pulses indicate a highly consistent linear fit relationship. Based on the results of the laboratory experiment, it is useful to understand the acoustic response characteristics of natural lightning current pulses with different characteristics in pulse shapes and short time delays.

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