Experimental investigation on correlation of corona-induced vibration and audible noise from DC conductor

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Abstract: In this study, the corona-induced vibration and audible noise (AN) on stranded conductor from positive and negative corona discharges were measured and analysed. The experiments were conducted in a semi-anechoic chamber to reduce the inferences from environment. For the measurement of vibration, the conductor was kept in dry condition without water drops on the conductor, which is different from previous investigations and can reveal the contributions of corona-generated space charges on the corona-induced vibration. Besides, the measurement of vibration on the conductor was performed by using a laser vibrometer which was a non-contact measurement device for measuring the vibration velocity. Furthermore, waveforms of corona-induced vibration and AN were measured simultaneously to analyse the correlation between them. The time and frequency domains characteristics of the vibration velocity and AN from negative and positive corona discharge are carefully analysed and no correlated relationship in time and frequency domains can be found in the two corona effects. It can be concluded that disturbance of air molecules caused by the vibration of conductor does not contribute the corona-generated AN.

1 Introduction

Corona discharge around the surface of conductors of high voltage direct current transmission lines may be unavoidable with the increase of operation voltages. Apart from the unwanted electromagnetic effects, i.e. audible noise (AN), ionised fields and radio interface, vibration of conductors may also be induced during the process of corona discharge [1-5]. Experimental and theoretical investigations on corona-induced vibration under rainy condition have been conducted by many researchers [2-18].

In the aspect of experimental investigations, some reports have mentioned that vibration of conductors of transmission lines induced by electrostatic forces under wet weather conditions in the 1970s [3-5]. In 1981, Adachi and Phan conducted experimental investigations in laboratory on the corona-induced vibration under rain using mass-spring configuration [6, 7]. They concluded that corona-induced vibration on the smooth conductor was excited first by electrostatic forces, coulombic repulsive forces and reactive force due to ionic wind, and then the vibration was amplified by the mechanical reactive force due to the ejection of drops or droplets. Besides, Farzaneh et al. carried out a series of experiments on the characteristics of vibration during and after the precipitation in 1984, 1988 and 1992 [8-10], respectively. It has been verified that the corona-induced vibration has close and direct relation to the corona-generated space charges. In their researches, the roles of space charges and ionic wind on the generation of vibration were analysed and discussed, and their researches can be seen as worthwhile thesaurus for further theoretical investigations. In 2001, Derakhshanian carried out a series of experiments on corona-induced vibration from smooth conductor and stranded conductor under rain condition [11]. Their results showed that the vibration characteristics from smooth and stranded conductor were different because of the differences of the water drops on the smooth and stranded conductors. Overall, the previous investigations focused mainly on the characteristics of corona-induced vibration of conductor under rain with water drops suspended on the conductor. Under the rainy conditions, the resultant vibration was directly related to the characteristics water drops and the interactions between the corona-generated space charges and conductor could not be accurately reflected. Besides, previous investigations focused mainly on the natural frequency of the corona-induced vibration, and more detail time and frequency domains characteristics were not given.

For the numerical simulation, Shah and Morgan first developed the numerical model for corona-induced vibration on transmission lines under rain condition in 1978 [4]. Then, Derakhshanian and Brahami also did some numerical analysis of corona-vibration on transmission lines affected by rainfall in 2001 and 2011, respectively [11, 12]. In their simulations, the external forces acting on the conductor consisted of corona force, gravity force and air drag force. In 2015, Zhou et al. also conducted some numerical simulations on the corona-induced vibration under rain [13]. Due to the complexity of the corona discharge and generation mechanism of corona-induced vibration, the corona force varying with time was not accurately considered. Similar with the experimental results, the simulation results may just reflect the characteristics at natural frequency and more detailed characteristics of corona-induced vibration cannot be reflected.

When corona-induced vibration of conductor occurs, the equilibrium of air molecules around the conductor may be disturbed [14-18]. At the same time, the interactions between the space charges and air molecules will also cause the vibration of air molecules and result in the generation of AN in the process of corona discharge [1, 19-22]. The sound pressure is usually used to characterise the disturbance of air pressure and the level of AN. However, whether the disturbance of air caused by vibration of the conductor would contribute the generation of the AN has not been investigated before. Therefore, correlation between the corona-induced vibration and AN should be further analysed in time and frequency domains.

Therefore, more experimental studies should be carried out to obtain characteristics of corona-induced vibration in fair weather to study the contribution of corona-generated space charge on the generation of vibration. In this paper, we set up an experimental
platform in a semi-anechoic chamber to measure the vibration on conductors induced by positive and negative corona discharges. In the experiment, the vibration characteristics were measured by a laser vibrometer which was a non-contact measurement method and did not influence the vibration characteristics. Besides, time-domain waveform of AN was simultaneously measured to investigate correlation between corona-generated AN and vibration on the conductor. The presented work hopefully can lay some experimental foundations for further revealing the generation mechanism of vibration and AN from DC corona discharge.

2 Experimental setup and measurement

In the experiments, a corona cage with a metal mesh was employed. The cross section of the corona cage was square with a dimension of 1 m. The total length of the corona cage was 1.5 m which consisted of a 1 m length measurement part and two 0.25 m length shielding sections for eliminating the end effects. The stranded conductor with a diameter of 4.88 mm was supported in the centre of the corona cage by two insulators. The height of the conductor was 1.2 m above the ground. A high voltage DC source typed as AU-120R10 was connected to conductor. The maximum voltage was ±120 kV with a ripple less than 0.1%. The figure of the experiment arrangement is shown in Fig. 1.

A laser vibrometer (PDV-100) with bandwidths of 0 Hz to 22 kHz was used to measure the corona-induced vibration on conductor. The sensitivity was 5 mm/s/V and the resolution ratio was less than 0.05 μm/s. The laser vibrometer was suited with the same height as the conductor but 2 m away from the conductor and the laser from laser vibrometer irradiated on the conductor through the corona cage. The vibration velocity of the conductor was obtained on the basis of the Doppler frequency shift of the reflection laser. Through this non-contact measurement method, the corona-induced vibration characteristics can be accurately measured when comparing with traditional contact measurement method.

In the experiment, the waveforms of corona-induced vibration and corona-generated AN were recorded simultaneously through B&K pulse with sample rate of 65,536 S/s in order to obtain the correlation between them. The microphone used in experiment was typed as B&K 4189 with typical frequency range of 6 Hz to 20 kHz. The microphone was set 1 m away from the conductor. The experiments were conducted in a semi-anechoic chamber to
reduce the interferences from background noise. Besides, a sound absorbing material was placed under the corona cage to eliminate the effect of reflection sound wave from ground.

The experiments were conducted in dry condition. During the experiment, the temperature was kept within the range of 27°C to 29°C, and the relative humidity was kept within the range of 50 to 55%. Hence the influence of the air conditions on the experiment results can be ignored.

3 Results and analysis

3.1 Time and frequency domain characteristics of vibration

When the applied voltages were −30 and −88 kV, the recorded waveforms of vibration signals are shown in Fig. 2. In the experiment, the onset voltage of the conductor was about −50 kV and the above given voltages are corresponding to the voltages before and after the occurrence of corona discharge. It can be seen from Fig. 2 that due to the corona discharge, the amplitude of vibration velocity increases significantly.

In fact, the source of vibration is the imbalance of forces on the conductor. In order to give some interpretations on the measured results, the force analysis of conductor is given and shown in Fig. 3 where the corona cage is not presented. In Fig. 3, $F_{d1}$ and $F_{d2}$ are the drag forces from both sides of the insulators, $G$ is the gravity of the conductor, $F_{up}$ and $F_{down}$ are the electrostatic forces from top and bottom parts of the corona cage due to the applied voltage, $F_q$ is the coulombic force between the spaces charges and conductor, and $F_v$ is the reactive force due to ionic wind [14–18]. The signals when the voltage is lower than corona inception voltage mainly come from two parts. One is the background interferences from the measurement device, recording device and

![Fig. 2 Time-domain waveforms of vibration velocity at −30 and −88 kV](image)

*a* Applied voltage is −30 kV  
*b* Applied voltage is −88 kV

![Fig. 3 Force analysis of conductor as the corona discharge](image)

![Fig. 4 Frequency spectrums of vibration velocity at −30 and −88 kV](image)

*a* Applied voltage is −30 kV  
*b* Applied voltage is −88 kV
surrounding environment. The other is the vibration caused by the unbalance of forces on the conductor in the process of adjusting the applied voltage, which is the main source of the signals. With no voltage applied on conductor, only $F_{d1}$, $F_{d2}$ and $G$ exist and the resultant total force is equal to zero. When a certain voltage (below the onset voltage) is kept on the conductor, electrostatic forces $F_{up}$ and $F_{down}$ will emerge and total force on the conductor will also be equal to zero. Under the two cases, the conductor will keep still. However, during the adjustment of the applied voltage, the change of electrostatic force induces the vibration of conductor and the amplitude of the resultant vibration is relatively small. When a constant voltage is kept on the conductor for a while, the vibration will be damped and the conductor will return to be still eventually.

Once the corona discharge occurs, two more forces because of the interactions between the corona-generated space charges and conductor are applied on the conductor, i.e. $F_q$ and $F_v$. The removal and creation of space charges exist in the process of corona discharge, and thus $F_q$ and $F_v$ are time-variant and usually have pulse characteristics resulting in the imbalance of forces on conductor. Therefore, the interactions between the space charges and conductor are the source of the corona-induced vibration and with the increase of voltage the amplitude of vibration will increase.

The frequency spectrums of the measured vibration signals in Fig. 2 are shown in Fig. 4. It can be found that the corona discharge induces many frequency components of the vibration. The frequencies at which the vibration increases significantly are 9, 14, 46, 48, 57, 102, 168, 272, 350, 483, 548 and 617 Hz. Besides, the amplitudes of high frequency components are relatively small which may be accounted for the inertia of the conductor.

As for the positive corona discharge, the measured waveforms of vibration velocity when the applied voltages were 30 and 88 kV are shown in Figs. 5a and b, respectively. The corresponding frequency spectrums calculated through fast Fourier transform (FFT) are shown in Fig. 6. Similar with the results in negative corona discharge, the amplitude of vibration velocity in time-domain increases a lot when the corona discharge occurs. The positive corona discharge also induces significant increase of vibration at some frequencies, i.e. 9, 14, 46, 49, 57, 98, 168, 287, 331 and 400 Hz. Most of these frequencies are not identical with those induced by negative corona discharge. Besides, the vibration induced by negative corona discharge has more and higher frequency components than that generated positive corona discharge. The differences for the vibration frequency may be due to the difference of mobility of the corona-generated charges under negative and positive corona discharges. For the positive corona discharge, the remaining
charges around the electrode are positive charges. While the remaining charges around the electrode are mainly electrons for negative corona discharge whose mobility is higher than that of positive charge. Thus repulsive forces caused by interactions between space charges and conductor for negative corona discharge are more frequent than those for positive corona discharge [23–25]. Therefore, more and higher frequency components can be identified in the vibration induced by negative corona discharge.

The maximum amplitudes of the vibration velocity varying with electric field on the surface of the conductor are shown in Fig. 7. The electric field is the free of charge electric field and calculated by charge simulation method. It can be seen that after the corona discharge the amplitude increase significantly with the increase of the applied voltage. At the voltages which are a little higher than the onset voltage, the amplitude of vibration velocity induced by negative corona discharge is a little higher than that induced by positive corona discharge. As the applied voltages are further increased, the amplitude of vibration velocity from positive corona discharge turns to be higher than that from negative corona discharge.

Some qualitative explanations can be given about the difference. In negative corona discharge, the positive space charges around the conductor may shield the development of the electronic avalanche and hinder the increment of ionisation zone. The ionisation zone is limited to small area around the conductor, resulting in small scale of electron avalanches. While for the positive corona discharge, the positive corona discharge may promote the development of electronic avalanches outside the ionisation zone and result in large scale of electron avalanches [25]. Therefore, the interactions and forces between the space charges and conductor in positive corona discharge may be higher than those in negative corona discharge, which results in higher amplitude of the vibration velocity induced by positive corona discharge.

3.2 Correlation between corona-induced vibration and AN

The waveform and frequency spectrum of background noise in 1 s when the applied voltage was 10 kV without corona discharge is shown in Figs. 8a and 8b, respectively. The measured waveforms of the corona-generated AN when the applied voltages are +88 and −88 kV are shown in Figs. 9a and 9b, respectively. In Fig. 9 a

![Fig. 8 Waveform and frequency spectrum of the background noise](attachment:image1)

*a Time domain waveform of the background noise
*b Frequency spectrum of the background noise

![Fig. 9 Time-domain waveforms of the AN at 88 and −88 kV](attachment:image2)

*a Applied voltage is 88 kV
*b Applied voltage is −88 kV

![Fig. 10 A-weighted SPL at different voltages](attachment:image3)
we just give the waveforms in 0.05 s to distinguish the sound pressure pulses.

The anechoic chamber provides such good sound environment that the background noise is very small compared with the corona-generated AN. In the experiment, background noise mainly comes from the high voltage source and internal noise from devices. The background noise contains mainly low frequency components as shown in Fig. 8b.

The corona-generated waveforms are consisted of a series of random sound pressure pulses with bipolar characteristics which are different from the waveforms of vibration as shown in Figs. 2 and 5. Each sound pressure pulse corresponds to one corona discharge and is induced by the interactions between the space charges and air molecules. Besides, the pulse amplitudes of sound pressure caused by positive corona discharge are higher than those from negative corona discharge. However, the pulse repetition rate of sound pressure pulse from positive corona discharge is lower than that from negative corona discharge. Furthermore, it can be seen from the measured A-weighted sound pressure levels (SPL) at different electric fields as shown in Fig. 10 that the SPL from positive corona discharge are higher than those from negative corona discharge. These differences can contribute to the differences of space charges in the positive and negative corona discharges. As it is stated in Section 3.1, more avalanches can be generated in positive corona discharge, which means the interactions between spaces charges and air molecules for positive corona discharge may be higher. Thus, the pulse amplitude of sound pressure and resultant SPL for positive corona discharge are higher than those generated by negative corona discharge.

The frequency spectrums of the AN calculated by FFT when the applied voltages are 88 and \(-88\) kV are shown in Figs. 11a and 11b, respectively. The low frequency components in Fig. 11 (below 100 Hz) are mainly due to the background noise as shown in Fig. 8. Corona-generated AN covers mainly the high frequency components above 1 kHz [26–29]. When comparing with the spectrums of vibration velocity in Figs. 4 and 6, the frequency components of vibration velocity are mainly located below 1 kHz and no correlated frequency components could be found in the spectrums of the AN and vibration of conductor. That means the correlation of corona-induced vibration and AN is small. Thus, we can conclude that corona-generated AN is mainly generated by the interactions between the space charges and air molecules, and the imbalance of air caused by vibration may not contribute the generation of AN.

### 4 Conclusions

This paper presents experimental investigations on the time and frequency domains of corona-induced vibration on the conductor in dry condition for negative and positive corona discharges. Besides, through simultaneous measurement of corona-generated AN and vibration, the correlation between vibration and AN is presented. The main conclusions can be listed as follows.

The waveforms of corona-induced vibration may not have obvious characteristics. The amplitude increases significantly with the increase of the applied voltage after the occurrence of corona discharge. The amplitude of vibration induced by positive corona discharge is higher than that induced by negative corona discharge. The frequency components of corona induced vibration are all lower than 1 kHz. The vibration induced by negative corona discharge has more and higher frequency components than that induced by positive corona discharge.

Different from the waveform of corona-induced vibration, waveform of corona-generated AN is consisted of random sound pressure pulse trains. High frequency components above 1 kHz are notable for the corona-generated AN. No correlated frequency components could be found in the spectrums of the AN and vibration of conductor. The characteristics of corona-induced vibration and AN are determined by the space charges generated in the process of corona discharge. However, disturbance of air molecules caused by the vibration of conductor does not contribute the generation of corona-generated AN.

The presented work hopefully can be used to lay some experimental foundations for further revealing the generation mechanism of vibration and AN from DC corona discharge. More experimental and theoretical work should be done to get the intrinsic characteristic and generation mechanism.

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### 6 References

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