High-voltage transmission tower-line system subjected to disaster loads

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Abstract The high-voltage power transmission system is an important lifeline structure. It is significant for wide researches on the features and ability of the system subjected to earthquake and environmental loads. The promising prosperity of the system has been demonstrated around the world. The corresponding advances of the system with respect to the mechanism of loading action, analytical methods, experimental research measurements, structural vibration control, fatigue damage, lifetime prediction, and design methods are comprehensively discussed herein. Finally, further research work on dynamic response characteristics of high-voltage transmission tower-line system in the near future is predicted.

Keywords: high-voltage power transmission tower-line system, loading effects, dynamic analysis, experimental researches, design theories.

The increasing demand for electrical energy of national economy and people’s daily life has recently brought significant changes of the formation of electrical energy and the technology of electrical power transmission. Largely for the growing scale of electrical power plant and power transmission network, advances in modern construction technology have resulted in increasing application of high-rise transmission towers, large-diameter and long-span conductors in the power transmission system. It is very obvious that the application of high-voltage (HV) or ultra-high voltage (UHV) technology for developing power transmission networks in the majority of countries in the world will be an inevitable trend.

HV or UHV power transmission system is not only a body with high-capacity electrical energy, but also an important lifeline engineering structure. This structural system is compatible with both high-rise and large-span structural features, such as high-rise tower, large-span conductors, distinct flexibility and geometrical nonlinearity. Generally, this structure is sensitive to earthquakes and certain environmental loads (e.g. wind, rain, and ice accretion). Hence, it is very likely that these environmental dynamic effects may bring fatigue damage or dynamic collapse events to them.

Once fatigue damage or collapse of the tower occurs, the direct or subsequent economic loss will be huge, and the corresponding reconstruction expenditure should not be underestimated either. The recent cases of damage during earthquakes and extreme meteorological conditions below may clarify this problem well. During the Northridge earthquake in 1994, 85 cables were damaged when two transmission towers collapsed due to high ground motion. The Landers earthquake in 1992 caused the burning down of 100 lines in the city of Los Angeles\(^{[1]}\). The strong vibration of ground motion overturned a main transmission tower during the Ji-Li earthquake of 1999 in Taiwan, which caused the reduction of electricity supply for more than six weeks\(^{[2]}\). In contrast, the damage caused by environmental wind loads is not in the shade at all. According to recent reports, it is a common event in Japan and in the south-east regions of China that a typhoon or a thunderstorm strikes power transmission line system. The list of the destruction events with respect to transmission line system has been growing successively. From the disaster-preventing viewpoint, it is very imperative for electric and structural communities to deeply exploit and further understand the dynamic mechanisms.

The orientation and advance of dynamic response of transmission tower have shown that further deeply

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investigating its response characteristics can meet the requirements of this structural construction, protect them from natural disasters, and provide precise technical parameters for design procedure. It can be seen that comprehensively solving the problem of dynamic response analysis by means of experimental test, theoretical analysis, and computer simulation has become an imperious issue. Therefore, the contribution of further investigation will rebound to the improvement of the anti-seismic and wind-resistant capacities and structural design methodology, and realize the objective of preventing disasters and damage eventually.

1 Recent progress

The power transmission system is conventionally attributed to a cable-tower tension structural system, which consists of high-rise towers and continuous long-span conductors hanged with insulators. This typical structure is subjected to earthquakes and environmental loads (such as wind and rain) once in a while. Due to apparent geometrical and material non-linearity as well as frequent damage events of this type of structures, previous studies have focused on devoted deeply revealing their dynamic response mechanism and performance failure causation. Here, it is necessary to make a state-of-art review on the continuous investigation.

1.1 Loadings

A transmission line system is always regarded as a wind sensitive structure in design. In most countries, the wind load and ice accretion are conventionally treated as principal governed external loads by corresponding codes and standards. In turn, an earthquake is viewed as an incidental load. Other types of loads, such as rain, are neglected. However, taking into account the manifold areas where the system is located, there exists a limitation to such methods for introducing loads.

In civil engineering, an earthquake may cause a stochastic ground motion with huge energy included in various amplitude waves introducing inertia force on structures. The effect of an earthquake sometimes may lead to serious destruction for power transmission system, such as foundation liquefaction, collapse, and deformation without load lasting capacity. The damage degree not only depends on specific earthquake intensity where the structure is located, but also is related to the geological structural features and anti-seismic characteristics. However, since the occurrence of an earthquake is seldom in comparison with the strong wind action, the earthquake load is often treated as an incidental load in design procedure.

As for wind action, it is very complex that its action not only depends on wind characteristics, but also relates to structural features. If only wind characteristics are considered, wind loads can be classified into two components\(^3\); One is called mean wind load, which is well known and accepted in various design standards of wind engineering. The other is called fluctuating wind load. It is referred to as when the wind velocity propagates with high frequency close to the natural frequency of transmission tower-line system, the resonant response may occur, and then the amplitude must be amplified. Namely, fluctuating wind load is regarded as dynamic component that can cause the responses of inertia force, moving displacement and acceleration. Therefore, the effects of wind action on structures strongly depend on mean wind velocity profile, turbulence scale, turbulence intensity and the function of power spectral density.

On the other hand, due to the fluid-solid effects between transmission line system and wind load, under certain conditions, there are several other types of excitations acting on transmission line system. The first one\(^4\) is the vortex shedding phenomenon; it is well known that it produces forces that originate in the wake of the structure and mainly act in the across-wind direction. The resultant oscillation is resonant in character and the frequency of the shedding depends on the shape of ice-accreted conductors, the velocity of the flow, the surface roughness and the Reynolds number. The second one\(^4\) is the wake effect between bundled conductors, which is also possible with large amplitudes of vibration. This is essentially an aerelastic vibration relevant to the interaction between the elastic system and the wind flow. The third one\(^5\) is called ice shedding, which is still a dynamic phenomenon. Namely, in cold regions, this phenomenon happens when glaze formed on conductors suddenly drops off at certain temperature and in certain wind conditions. The dynamic effects of ice-shedding on transmission line system include the impact of suspension strings on tower, which may lead to broken insulators, excessive tensions generated in conductors, and large unbalanced loads on towers.

Apart from the above-mentioned excitations,
there exist high intensity winds associated with tornado and downbursts\textsuperscript{[6,7]} in some regions, especially in America, Australia and South Africa. Both meteorological phenomena are localized and unpredictable, so that their structure, scale and intensity cannot be easily measured in the field. However, according to current literatures\textsuperscript{[8]}, a tornado is small, but extremely intense whirlwind formed by a severe thunderstorm. It descends as a funnel or tube-shaped extension from a cumulonimbus cloud. If the tornado reaches the ground, its high winds and sudden drop in air pressure as it passes cause almost complete destruction of everything in its patch. A downburst is an intensive downdraft and gust front system which can induce an outburst of damaging winds near the ground, with near surface velocity in excess of 50 m/s. The strong wind tends to flow outward radially from where the descending current strikes the earth. The typical physical size of damaging storm is 6—8 km across. 

At a point beneath the thunderstorm strong winds may sustain for up to 30 min. Hence, even though the two events may be similar in intensity and have the potential to cause failure in the transmission tower, the actual failure modes would probably be different. Tornados that extend to the ground are characterized by strong vertical motion in the horizontal plane, perhaps with secondary suction vortices, and the local environmental wind field convects these motions laterally. In contrast, a “wall jet”, which rapidly spreads radially by the ambient wind field characterized downbursts of different scales, including microbursts. Savory and his coworkers cited two simplified models for the wind field associated with downburst, namely the “ring vortex” model and the impinging jet model, and elementally revealed the mechanism of the damage types of transmission towers under different thunderstorms. The two models are illustrated schematically in Fig. 1\textsuperscript{[6]}.

Lastly, several typical collapse events of transmission line systems under the combined actions of severe wind and rainfall conditions have drawn the attention of structural researchers. The occurrence of such failures essentially depends on the characteristics i.e. wind intensity, precipitations, incidences of wind and rain, and structural aerodynamic properties. Till now, except for the experimental study of aerodynamic drag of new-design electric power wire under a heavy rain and wind condition by Kikuchi and his coworkers\textsuperscript{[9,10]}, there are no reports about this phenomenon. Unfortunately, Kikuchi’s wind tunnel test only investigated the cross-sectional aerodynamic property rather than expanded into transmission line system. Therefore, it is anticipated that the combined action with severe wind and rainfall will be continuously disclosed in the course of further investigations.

All actions mentioned above indicate that investigation of dynamic response of transmission line system subjected to extreme meteorology has progressively become a fresh research field.

1.2 Mechanical modelling and dynamic response analysis

The importance of dynamic response analysis for transmission line system results in the key to clarifying its inherent structural characteristics and to improving the levels of corresponding code and standard. Structurally, the complexity of dynamic response mainly concentrates on the tower vibration coupled with conductors. It is necessary to investigate the dynamic vibrations of transmission line system.

For electrical engineers, in order to prevent power transmission line from disruption events such as short circuit, failure of an insulator or hardware, break-up of one or more conductors, they are conventionally concerned about the dynamic responses related to transmission lines, including turbulence induced oscillations, galloping in ice-accreted cables, subspan galloping in bundled conductors and ice-shedding vibration. Among these phenomena, firstly, turbulence
induced oscillation is a forced vibration occurring under the combined action of the steady wind and fluctuating turbulence. Secondly\textsuperscript{[11-13]}, galloping is a low frequency and large amplitude wind-induced vibration of ice-accreted transmission lines, which usually occurs in moderately strong and steady wind conditions and is well regarded as one of the main wind-induced failure causations. Meanwhile, it is also revealed that galloping is a rare and unpredictable event, namely, if either ice or wind is absent, galloping cannot occur, but even if both are present, galloping does not always be result in. From kinematical and dynamic theories, galloping can be further divided into Den-Hartog galloping and flutter galloping. The former is an aerodynamic instability because the main factor at the origin of this problem is the aerodynamic properties of the ice deposit. The latter is an aerelastic problem to which the structural properties of the line are also important and there is a coupling effect between at least two degrees of freedom. Thirdly\textsuperscript{[14]}, subspan galloping is related to wake effect in conductor bundles. Essentially, it is a flutter-type instability caused by the interaction between elastic system and wind flow, but not a forced excitation. Previous investigations have revealed that: the frequencies of subspan galloping are around 1–2 Hz; the motion is harmonic in time and with sinusoidal shape along the span; moreover, when observing the cross-section of the bundle, the motion of conductors in the wake has an elliptical shape circle. Fourthly, ice-shedding vibration has been interpreted in Section 1.1.

Subsequently, the other primary problem for dynamic response analysis is to build mechanical analysis model. However, transmission tower and conductor are attributable to frame-type and cable structures, respectively. In theory, they should be modeled as both appropriate spatial truss elements and cable elements. For engineering applications, such modeling seems to be cumbersome for transmission tower. Therefore, based on specific structural conditions, previous investigators have developed various effective simplified models to investigate dynamic response of transmission line system. A comprehensive theory of linear oscillations was developed by Irvine\textsuperscript{[14]} in the early 1970s, in which a continuous body model was proposed, under the conditions of taking into account of cable stiffness or not, which was employed to investigate the dynamic responses of cable-tower structures. This model was usually employed to calibrate the results of discrete models due to its high accuracy. Some years later, concerning the differences of dynamic responses, Ozono et al.\textsuperscript{[15]} developed two types of models as follows: at high frequency range, a transmission tower was simplified into a cantilever beam with the lumped mass on its top, and conductors were substituted for massless springs and jointed to the tips of the adjacent towers, which is called the tower-line coupling oscillation model. At low frequency range, while the in-plane responses are close, the multi-lumped masses model was introduced. More recently, in order to clarify the influence of different response characteristics in transmission support systems, Yasui et al.\textsuperscript{[16]} have developed a mixed infinite element model, which modeled the post members of tower as beam elements and modeled the bracing members as truss elements or beam elements, and lumping their masses on the tips of the arms and the panel points between post members and bracing members. Li et al.\textsuperscript{[17,18]} made use of the energy equilibrium principle to develop a multi-lumped mass model and to apply it to seismic response analysis of transmission line system. This model simplified conductor as many points with lumped masses and jointed them each other with rigid poles. As for transmission tower, it was modeled as multi-degree system with many lumped masses in series. Whilst the structural system experiences the out-of-plane transverse motion, the conductor can be considered as a perpendicular chain, considering the in-plane vertical motion. In turn, the conductor can be regarded as a suspension cable with two fixed ends. As above mentioned, the finite element techniques have been applied to the static or dynamic behavior analysis of power transmission systems.

The dynamic analysis procedure conventionally employs the frequency domain method or the time domain method. Based on statistical principles, the frequency method can build the relationship between excitations and response characteristics by the transferring function to describe the structural dynamic characteristics and keep up the stability between input loads and output responses in the course of stochastic process. Therefore, the frequency method has the advantages of easy understanding without more computational efforts. On the contrary, this method must be on the premise of the linearity of structural characters, and cannot comprehensively describe the nonlinearity of transmission line system. On the other hand, the time domain method is a direct integration
method. Its advantages result in the fact that it can take into consideration of structural nonlinearity, and in the meantime, can obtain the dynamic response histories and distributions with reflection of actions, i.e. earthquake or environmental loads, so that it is extensively employed for analyzing transmission line systems.

Recently, the research tendency is gradually taking into account multi-influence on dynamic responses of transmission line system, and making attempts to view power transmission tower and conductors as a continuous entirety. Ozono et al. [15] firstly considered the influences of the number of spans, boundary conditions, mass of conductor, the sag-span ratio, and the effect of tower-line coupling. Li et al. [18], [2] introduced the soil-structure action and the limited span of transmission line into anti-seismic investigation. Ghobarah et al. [20] began to consider the spatial coherence between structure and ground motion, to use multi-supporting input as earthquake input, to employ finite element method to obtaining the minimum subspace, and to analyze the influences of traveling wave effect and incoherent effect on the lateral displacement.

1.3 Experimental test of dynamic responses

It is well known that there exist certain limitations and uncertainties in the design method and corresponding parameters obtained from theoretical analysis. Therefore, as effective alternatives, experimental measurements have been introduced into the investigation for earthquake simulation, wind tunnel test, even though it also poses considerable difficulties.

Seismic vibration modeling is very efficient for earthquake simulation and theoretical verification on the seismic dynamic behavior. Li et al. [21] have firstly carried out the shaking-table test for investigating the influence of the span-distance effect of transmission line system. In their experimental test, they selected various typical ground motions represented corresponding soil conditions as inputs, and simulated the dynamic responses in longitudinal and lateral directions under the conditions of tower with and without conductors. The experimental results have indicated that seismic simulation test is in good agreement with theoretical analysis, and verified the rationality of the proposed theoretical model of tower coupling with conductors. Furthermore, the more dominant tower couples with conductors, the stronger dynamic responses from conductors to tower. Therefore, the effect of conductors acting on tower should not be neglected in design procedure.

As far as wind tunnel tests are concerned, there are basically three different types, including almost all wind-induced vibration phenomena [11,22,23]. The first one is static test, in which the mean aerodynamic forces are obtained from short lengths of full-scale conductor or conductor models. These are mounted in force balances, and then the drag and lift coefficients are obtained. Another type is dynamic test, where again a two-dimensional modeling method is employed. The model is composed of a short length of rigid conductor having full-scale values of shape and weight. The elastic properties are simulated by a spring suspension system at each end of the rigid conductor. The third one is called aeroelastic test, which can simulate the aeroelastic behavior of the transmission line system, especially, the mass, drag force, reduced frequency and aerodynamic damping should be simulated, together with the properties of the natural wind field.

As already mentioned, although a great number of experimental tests both in seismic simulation and wind tunnel tests have been performed, there are still some difficult problems to be overcome. For practical engineering, the aeroelastic wind tunnel tests based on the real transmission line systems have been continuously performed by researchers. Under the background of Jiaojiang large-crossing transmission tower, Lou et al. [24] carried out an aeroelastic wind tunnel test to investigate the aerodynamic properties of high-rise lattice transmission tower. Through converting the variables of wind velocity, angle of attack, approaching direction, etc., under the steady wind flow and turbulent wind flow conditions, they simulated and measured the responses in across- and along-wind directions, and drew some conclusions that: The responses in across-wind direction are as close as those in along-wind direction; the response in across-wind direction should not be neglected in design procedure; and the simplified formula has been given as well. In order to reveal the dynamic characteristics of transmission tower coupling with conductors, Deng et al. [25], taking Jiangyin large-crossing transmission line system (of which is 700 m + 2300 m + 700 m structural distribution, and 346.5 m height of the two main towers) as an example, performed both static and aeroelastic wind tunnel tests under uniform and turbulent wind field in a low-speed boundary lay-
er tunnel, respectively. The properties of single tower and tower coupling with conductors were simulated and analyzed. The obtained results can support the conclusions below: Compared with single tower, the natural frequency of the system is slightly higher, and for the system alone the natural frequency of the in-plane is close to that of out-of-plane. Conductors have no distinct influence on the natural frequency of tower. In turn, the system damping is sufficiently improved compared with single tower. The values of all-order wind response spectra of both single tower and the system change little, whereas with the increasing of wind velocity, the components of frequency spectrum in power spectrum become plump, which indicates that the nonlinearity of transmission line system may be gradually reinforced. Loredo-Souza et al. [22,23] proposed a novel approach for wind tunnel modelling of transmission line system using a modified horizontal length scale. On the one hand, this method essentially solved the difficult problem that the downscalled model from the law of similarity cannot be accommodated in the wind tunnel. On the other hand, both the structural geometrical properties and the wind field characteristics were comprehensively modeled under transverse and oblique incidences. The wind tunnel test demonstrated that aerodynamic damping plays an important role in the aerodynamic behavior of the conductors and of the resonant component in the determination of the total response to wind loading. The dynamic response is directly proportional to the ratio between turbulence length scale and the structural span. The correlation coefficients of the force reactions at the two cables were found to vary little with wind velocity and are bigger for the smallest separation between conductors.

1.4 Studies of seismic response

Earthquake is one of the main causes for the disruption of transmission line system, and seismic responses have the effect of spatial coupling due to the complexity of earthquake ground motion. Therefore, the investigation of seismic response for transmission line system has its own characteristics and methodologies.

A major problem that arises in the investigation of large-crossing transmission line systems has some difference among the ground motion components affecting various support points of such structure [26]. There are three principal factors that affect the seismic ground motion variation. The first factor is the traveling wave effect that results from the finite speed of the seismic waves that create a phase shift between the seismic excitations at various supports. A second factor is the incoherency effect that results from reflection and refraction of seismic waves. And a third factor is the local site effects.

Another important problem is which kind of load plays a dominant role in specific transmission line system design [20]. In almost all codes, the answer to the question is wind, but in a specific region which is exactly located in the severe earthquake belt, the answer may be reverse. Therefore, it is necessary to re-evaluate the earthquake action in concrete conditions.

For the above-mentioned reasons, the purpose of seismic response investigation is to ensure structural safety and to establish practical design method. Therefore, in recent years, by means of various structural models, together with specific earthquake ground motion records, the seismic responses with respect to various ground conditions have been adequately analyzed, and some effective results have been obtained. In this context, considering the influence of initial axial force and large deformation, Ghabari et al. [20,26] have developed a spatial truss mechanical model used to seismic response analysis of transmission line system. Then, based on the effects of wave propagation velocity, wave travel and the coherency of the seismic waves input, the earthquake action was treated as multi-support excitation from uniform ground motion. The results obtained from response analysis under various loadings have demonstrated that the multi-support excitation is much closer to the real situations especially the accurate representation of large displacement and internal forces of transmission line system. The incoherence effect has larger influence on dynamic response than the traveling wave effect, whilst the wave propagation velocity of ground motion predominantly influences the maximum displacement. In the meantime, Li et al. [21,27] also performed some remarkable work. First, a multi-particle model was presented, which simplifies a conductor as a chain consisted of finite particles with lumped mass as well as linkages with rigid hinges, and simplifies transmission tower as a multi-degree system with finite lumped masses. Second, one finite element method based on the energy conservation law was established, which can be employed to analyze the seismic responses of transmission line system, including the in-plane vertical and longitudinal responses, the out-of-plane oscillation. Meanwhile, the effects of
soil-pole-structure interaction, moment component of ground motion were taken into consideration. Finally, combined with the results from theoretical analysis and experimental test, they proposed the recommending limit of transmission span considering the influence of conductors and equivalent incidental mass coefficient of transmission tower. All these help to advance the antiseismic design level of transmission line system and lay down theoretical fundament for the three-dimension concept of antiseismic study.

1.5 Control of dynamic response

As a large-crossing high-rise structure, power transmission line system will produce large displacement at the top of tower under earthquake and environmental loads. This phenomenon is conventionally called as the effect of “whip end”. If the dynamic behavior cannot be governed at the given level, power transmission line system may be in danger of instability or transient collapse events. Therefore, it is necessary to take the anti-seismic and vibration-reducing measures, namely, by means of structural optimization design or installing vibration-reducing or -separating devices, to control the dynamic response within the acceptable level.

As far as the dynamic response control of transmission line system is concerned, there are several conventional measures by using some simple control members to realize the controlling objective. Concerning power transmission lines, the controlling measure\textsuperscript{[28]} usually depends on either improving conductors damping or shortening span-wise of bundled conductors. In turn, for power transmission towers, the controlling measure is often taken into consideration with various types of dampers, such as, NLPD (non-linear pendulum-like dampers)\textsuperscript{[29]}, suspended water-tank pendulum and viscoelastic damping pendulum\textsuperscript{[30]}. These measures are all based on the mechanism of energy equilibrium, dissipating the external input energy from wind or earthquake by various dampers or spacers and realizing to reduce the large amplitude vibration of system so as to alleviate its fatigue damage and disruption. In essential, the conventional controlling measures should be classified into passive controlling method, which is a sort of economical and practical controlling approach for power transmission line system.

The application of control theories of transmission line system began relatively later, and is in the stage of development and consummation. Currently, there are three key ways to realize vibration control for transmission line system\textsuperscript{[31]}. The first method\textsuperscript{[32]} is to convert the fluctuating response function $h(t)$, namely, to change the intrinsic characteristics of the distribution pertaining to the ratio of damping $\xi$, frequency $\omega$ and mass of structure so as to weaken the structural dynamic responses. The purpose of theoretical analysis is that, according to the dynamic characteristics of structure, one can select separating or damping devices adapted to structural natures, optimize their technological coefficients, and finally realize the optimal controlling effect. The second method is dependent on reducing the value of exterior excitation on structures to alleviate dynamic responses, namely, in the windward direction, setting up the control system of active air keep-off plate and air pulsating devices. Due to the limitations of sophisticated conditions, this method is seldom used in practice. The third method\textsuperscript{[33]} is that, in terms of structural features pertaining to dynamic behavior and loads, the dynamic criteria of the kinetic stability of the transmission line system can be built, which is employed to adjust structural design parameters, realizing the objective of ensuring structural kinetic stability. In this connection, the successful applied case is the Dong Hart galloping controlling. From the abovementioned theories, henceforth, the methods for transmission line system control will concentrated more on their dynamic responses and nonlinearities, and gradually transfer the vibration type control to the real time control.

For high-rise tower structures, the style of vibrating control devices has experienced passive control to active control, and then to intelligent semi-active control phase. In parallel, the controlling device itself has also experienced the transition from the open-circle system without feedback action to the close-circle system with feedback feature. Previous studies demonstrated that in general cases, wind-induced response of high-rise transmission towers is mostly located in the range of linearity, and considering the first order only or the former three orders at most; the perfect effect of controlling can be achieved. The sophisticated controlling facilities applied on the large-scale transmission towers are restricted by the factors of both structural natures and economy, and need to be further exploited.

The application of existing transmission line systems is based on two aspects; With the increase of the
scale of transmission line system, the conception of structural control has transformed from controlling transmission line accidents to that of controlling catastrophes of structural system; and the corresponding countermeasures have also been converted form vibrating line’s control to vibrating system’s control. Hence, based on the stochastic theory and structural control theory, several sorts of appropriate optimal control theories adapted to the corresponding control model have been developed.

1.6 Fatigue and service life prediction

It is well known that in generic loading conditions, the disruptions of transmission line system including towers and conductors can be mostly attributed to fatigue damage caused by the pulsation action of dynamic loads. However, by now, the study on fatigue and service life prediction relevant to transmission line system has been little reported. The current researches mainly concentrate on self-supporting lattice tower, guyed mast and offshore platform, etc., acted by gust wind.

The service life is specified as the period from the beginning of the structure operation up to the cessation of service as a result of formation and propagation of fatigue cracks in members or sections of power transmission tower. Service life prediction of transmission line system results in developing the period evaluation method by taking into account the characteristics of loads and materials.

The well-known damage criterion for assessment of fatigue lifetime is the Palmgren-Miner law that normally investigates fatigue with respect to random stationary Gaussian narrow band, seldom extends to broad-band process and non-Gaussian process. Currently, fatigue analyses under wind loads usually follow two distinct approaches: the first deals with the problem by frequency domain criterion in a fully probabilistic environment, which applies basic principles of random dynamics. The total damage is calculated by taking the occurrence probability of the fluctuating stress processes associated with different values of the mean wind velocity into account. Dealing with flexible and lightly damped structures, the responses are considered as narrow-band, the evaluation of the number of cycles is linked to the peak distribution. The second makes recourse to traditional cycle counting procedures in the time domain, which are carried out by Monte Carlo simulations of turbulence histories or by processing pressures measured in wind tunnel tests. The cycle counting applied to simulated time histories adopts classical deterministic criterion such as the rain-flow method. Based on the above-mentioned theories, the developed methods have been derived from some practical methodological investigation.

Following the previous theoretical achievements, the method of fatigue analysis and service life prediction relevant to transmission line system can be refined herein. Firstly, the various factors influencing cumulative fatigue damage and service life should be determined above all, which mainly include the strength of material, the structural parameters, and the feature of environmental loads. Secondly, introducing some appropriate assumptions, the problem of determining the circle-stress level and the circle-stress root-mean square of the loads, determining the relationship of circle number and fatigue life, and whether the fluctuation of wind load and the variation of material parameters should be considered or not can be rationally solved. Currently, the generic method assumes that the circle-stress level is related to the intensity of mean wind pressure, whilst the root of mean square of circle stress is related to the fluctuating wind load. Then, associating with the correlation between stress waves and variation of wind load, the statistical relationship between the numbers of fatigue damage circle and the stress range can be built, and the formula dealing with wind loads and fatigue service life can be derived. The fatigue service life can be calculated by the equivalent stress method or the equivalent narrow-band method if the analytical modeling is built on random vibration theory. In parallel, if the analytical modeling is based on the experimental data, the rain flow method can be used.

The present researches indicated that as a structural system, the problem of fatigue accumulative damage of transmission line system is quite sophisticated, which is associated with the variability of wind load, structural dynamic features, and fatigue of material, etc. At present, there exists a limitation, i.e. when investigating the problems of structural fatigue and life prediction, in most cases, only the randomness of actions is taken into account, whereas the variability of material is neglected. Moreover, because the investigation for fatigue life prediction of lattice-type guyed mast and tower structures locates at the starting phase, there are many problems with respect to theory and experiments to be done.
1.7 Structural design method

As far as the design methodologies of transmission line system are concerned, there are two issues to be studied, the structural design theory\(^{[38-41]}\) and the optimization of the structural system\(^{[42,43]}\).

Based on the conventional probabilistic reliability theory, taking into account wind-induced loads, structural dynamic characters, errors from fabrication and installation, and material strength variation, the design methodology based on performance has been developed. In general, the performance of transmission tower can be described by a performance or limit state function \(G(x)\), the form of which is

\[
G(x) = C(x_e, d_e) - D(x_d, d_d),
\]

(1)

where \(G(x)\) is a function of the intervening variables and can always be written as the difference between two functions, a capacity \(C\) and a demand \(D\). The variables may be divided into two groups: one, \((x_e, d_e)\), related to the capacity \(C\), and a second, \((x_d, d_d)\), associated with the demand \(D\). The vectors \(x_e, x_d\) include all those variables which are random or uncertain, while the vectors \(d_e, d_d\) include all those quantities which are deterministic or known with sufficient certainty. For the performance function (1), non-performance will correspond to situations where the variables combine to make \(D > C\) or \(G < 0\). Thus, estimating the probability of non-performance is equivalent to estimating the probability of the event \(G<0\). This will be the “probability of failure” \(P_F\), and the reliability will be the complement \(1- P_F\).

The term “failure” is used here in a generic fashion, as non-performance may not be associated with actual failure or collapse but with serviceability limit state. As for the specific application to transmission tower design see Ref. [39].

On the other hand, the dynamic influence has been gradually taken into account for transmission line system design in recent years. Based on statistical methods, Loredo-Souza et al. performed the gust response factor (GRF) method\(^{[44,45]}\). In this method, the total response is formed by the three components: mean response in time; background response; the energy is spread over a broad range in the low frequency range; resonant response; consists of a series of highly concentrated peaks centered on the natural frequencies of the structure. A typical form of response for structures subjected to wind loading is illustrated in Fig. 2. In detail, the mean response is given by

\[
\ddot{r} = \int_0^l \frac{1}{2} \rho_x \overline{V^2} C_d d_i(x) dx = \frac{1}{2} \rho_x \overline{V^2} C_d \int_0^l i(x) dx.
\]

(2)

![Graph](image)

Fig. 2. Response of a structure to wind: (a) time history; and (b) power spectrum.

The background response is given by

\[
\ddot{r}^2 = (2q C_D d l_v)^2 \int_0^l \int_0^l e^{-i(\Delta x/l_v)} i(x) i(x') dx dx'.
\]

(3)

The resonant response is given by

\[
\ddot{r}_{R_j} = \frac{1}{4} \left( \xi_{y_0} + \xi_{y_0} \right) \int_0^l \int_0^l m(x) \mu_j(x) i(x) dx dx',
\]

(4)

where

\[
f_j S_{q_0}(f_j) = (2q C_D d l_v) \int_0^l \int_0^l e^{-i(\Delta x/l_v)} \mu_j(x) i(x') dx dx',
\]

(5)

\[
\mu_j(x) = \mu_j(x) \mu_j(x) \mu_j(x) \mu_j(x) \mu_j(x) \mu_j(x)
\]

where \(S_v(f)\) is the spectral density of horizontal wind velocity at reference height. In the equation above, \(C_D\) is the drag coefficient, \(\rho_x\) the air density, \(d\) the cable diameter, \(l\) the cable length, \(\overline{V}\) the mean wind speed, \(l_v\) the intensity of turbulence, \(q = \frac{1}{2} \rho_x V^2\) the dynamic pressure, \(l_v\) the transverse length scale of turbulence, \(m(x)\) the mass per unit length, \(\mu_j(x)\) the mode shape, \(f_j\) the natural frequency of the \(j\)th mode shape and \(i(x)\) an influence function.

The response could represent a wide range of structural actions including resultant force, bending
moments, cable tension, as well as deflections and accelerations. For the design purposes, the peak dynamic response, $\tilde{r}$ may be expressed as

$$\tilde{r} = \bar{r} + \tilde{r}^*,$$

(6)

where $\bar{r}$ is the mean or time average response, $\tilde{r}$ is the RMS of the fluctuating response, and $\tilde{r}^*$ is a statistical peak factor, generally in the range of $3 \rightarrow 4$.

The total mean square fluctuating response can be calculated as the sum of the background response plus the contribution from each significant vibration mode. Hence,

$$\tilde{r} = \sqrt{\tilde{r}_B^2 + \sum \tilde{r}_{Rj}^2},$$

(7)

here, $\tilde{r}_B$ is the RMS background response and $\tilde{r}_{Rj}$ is the RMS resonant response in the $j$th mode of vibration.

This method successfully associates the dynamic response of transmission structures with the turbulence intensity level and its spectrum, and allows for the inclusion of many specific factors in the design methodology.

In addition, the structural optimization is developing an effective way to power transmission line system design, which investigates and develops an efficient optimal method for determining the optimum solutions to the structural shape, cross-sectional dimensions, and material type of all member elements of large-scale transmission tower truss structures subjected to static and dynamic loads. The ideal of this method is to find the balanced point between the structural safety and the minimized cost. Both dynamic analysis and optimization are in close connection with safety and economic costs for transmission line system design. Therefore, they have been extensively investigated in the civil community in recent years.

2 Perspective of further investigation

From the above retrospective summary, it can be seen that the investigation for the response characteristics of transmission line system have made great progress and some valuable results have been obtained. However, the frequent occurring disaster events indicates clearly that there still exist some complex problems for further investigation, so as to comprehensively meet construction requirements of large scale power transmission line system. By virtue of both the promising construction perspective and the existing results of investigation, the authors scrupulously and boldly refine the problems for further investigation as follows.

2.1 Loads and their characteristics

(i) Considering the increasing adjacent span of power transmission line system, it is necessary to reevaluate the analytical effect of the conventional loading input model of earthquake, and to refine practical loading input model suitable to the requirement of large span structure.

(ii) Based on the existing wind power spectra, the novel wind power spectra which are suitable to the topographical features of transmission line system extensively distributed should be further developed, particularly in the mountainous areas with windy disasters. The wind properties should be included in wind orientation spectrum, velocity profile, correlation characteristics and power spectrum density, etc.

(iii) The responses of large crossing transmission line system caused by earthquake, environmental loads and self-excitation are usually different. They should be scientifically and systematically identified and classified with reference to their respective occurring mechanism and conditions. And then, the dynamic response types can be accurately defined.

(iv) Considering the simplicity of the conventional design method to deal with external loads, the quasi-static loading analytical method based on static and dynamic response analysis of transmission line system should be established, which will meet the requirements for improving the structural design code.

2.2 Mechanical modeling and dynamic response analysis

According to the difference between lattice towers (including sectional shape, material and loading condition), load types, field condition and wind properties, etc., the mechanical model for dynamic response analysis can be further developed, so that the experimental test, theoretical analysis and computational simulation can be accurately implemented.

Aiming at the characteristics of nonlinearity and coupling effect of transmission line system, the dynamic response analytical method considering nonlinearity and coupling effect in combination with the existing analytical method should be presented.

Since the most damage events of transmission
line system were caused by conductor’s kinetic instability or tower’s dynamic collapse, based on the viewpoints of kinetic stability, structural control and dynamic reliability, it may be a theoretical developing direction which sets up the dynamic stability theory of transmission line system.

2.3 Experimental test

(i) The experimental investigation for transmission line system mainly depends on earthquake vibration flat test and wind tunnel test. Being restricted by experimental condition and testing method, there exist, to some extent, some approximate errors with simulated parameters so that the achieved parameters only can be employed to qualitative analysis. Hence, it is the incessantly exploring problems that improve testing approach, optimize experimental design, adopting innovatory testing technique and apparatus, which can improve the accuracy of collected data and analytical results.

(ii) Generally, there are two difficulties in the modeling design of transmission line system according to geometrical similarity. On the one hand, the downscale of model is smaller, and the accuracy is higher. On the contrary, the geometrical similar ratio depends on structural prototype height, wind tunnel sectional dimension and gradient of simulated turbulent flow, etc. On the other hand, since the sectional dimensions of members and entire structure are comparatively smaller, it is quite difficult to meet the requirements of model’s material selection. Similarly, it also seems to be impossible for the absolute realization of elastic modulus similitude according to similitude law. Therefore, it is bound to be momentous research work to modify the modeling design method and perfect the similitude experimental theory under the foundation of experiment and theoretical analysis.

(iii) Besides verifying the validity of theoretical analysis, the other important purpose of model experiment is to provide technological parameters for theoretical studies. However, the changes of structural parameters generally have influence on the characteristics of structural dynamic response. Hence, in order to obtain the quantities or qualitative understanding of dynamic response, there are large numbers of specific experiments to be carried on.

2.4 Seismic and wind-resistant studies

(i) The developing tendency of the antiseismic and wind resistant theory gradually transforms not only from planar method to spatial dynamic analysis, but also from linearity into nonlinearity (including material and geometrical nonlinearity). In parallel, the analyzed problem also turns from strength safety to performance safety. The studies of this aspect will have benefit to the development and perfection of the dynamic theory of transmission line system.

(ii) In theoretical and experimental studies, the seismic analytical modeling should be used with multi-support excitation substituted for uniform load input, and the influencing factors should include traveling wave effect, incoherence effect and ground motion effect. All these studies need carrying out a lot of theoretical and experimental research work in many aspects.

(iii) It is well known that the transmission line system is a long-span and distributed structural system. The anti-seismic and wind resistant studies considering the geological features, the situation of earthquake and wind activities and their action types along its distribution route can provide the technological data involving the route orientation, structural type and foundation design information, etc. Therefore, the anti-seismic and wind resistant objective can be partially realized by means of programming and design.

2.5 Fatigue damage and service life

(i) Based on the fatigue theory of random vibration, the investigations of constructional feasibility, operating management and health monitor, etc., depend on fatigue accumulative damage and service life with respect to structural features, load characteristics and material strength of transmission line system. It can be seen that there is a promising application to develop the fatigue damage criterion and the service life prediction.

(ii) It is useful for economical characteristics and serviceability of transmission line structures to establish analytical method of reducing their fatigue damage or protracting their service life. This theoretical development, which combines vibration control assessment with structure’s fatigue damage analysis, needs a great deal of work, and is an interesting problem.

(iii) The transmission line system is an important lifeline engineering project. Based on the theories of probability and reliability, the investigations of ser-
vice life prediction and health diagnose are significant for the maintenance of transmission tower and the replacement of conductor, which can provide technique date for the updating of transmission lines and for using assessment of large scale transmission tower, and can also develop into an important research branch in fatigue-service life of transmission line direction.

2.6 Design theory and methodology

(i) Based on the results of dynamic response investigation of transmission line system, the transmission line systems should be classified according to their scales, and then, the standard of scale identification can be determined. Finally, the problem of whether the dynamic factors should be considered or not is bound to be solved.

(ii) The reliability design method based on the theory of probability is an extensively adopted design procedure, in which an independently systematic theory encompasses analysis of loads and resistances, establishes ultimate state equation, solution of multi-variable reliability index and determination of target reliability index. All these methods involve the aspects of loading capacity, normal service condition and fatigue damage. Continuous investigation of this problem can lay the theoretical foundation for design code modification.

(iii) The present results from the studies of dynamic properties, structure control and reliability of transmission line system has gradually indicated that it is necessary to establish a mechanical model for kinetic stability analysis, and to deeply investigate the overturning collapse mechanism of transmission line system, and then to formulate a set of stability design methods, by which the structure’s dynamic responses and loading conditions are considered.

(iv) Numerical simulation has become an important investigating approach since the computer simulation technology appeared. The numerical simulation analysis of transmission line system under artificial earthquake field conditions or in numerical wind tunnels on computers is a recent research method, which can improve the study efficiency and in reverse can save the investment of experimental test.

3 Conclusions

Currently, the construction affair of power transmission line system has stepped into a large-scale development stage worldwide. From the previous research work, the investigating tendency has changed as follows: Firstly, for earthquake, the consistent loading input is further rationally substituted by multi-support excitations, and also considering traveling wave effect; for environmental loads, such as wind, rain and ice accretion, the dynamic response analysis further realizes the influence of fluctuating components. Secondly, the theoretical analysis methods gradually tend to adopt the time history-based finite element analysis method, which is well consistent with the real practical conditions, and even considering the coupling effect between conductors and tower. Thirdly, the corresponding fields of research have been expanded from the single strength safety to dynamic reliability, kinetic stability, and structure control and fatigue serviceability. Fourthly, the application of numerical simulation has become an accessorrial approach of modeling experiment with economical efficiency and large application space. Thus, it is absolutely necessary to deeply investigate the remainder complex problems and to further understand the cognitive limitation of design code of steel lattice high-rise structure under earthquake and environmental loads. Meanwhile, it can be seen that continuous research work on the mechanism of disastrous loads and structural response properties will be beneficial to modification of design code, engineering construction, structural health diagnose and disaster-proof and-reduction of transmission line system.

References


