Seismic response characteristics of transmission towers

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ABSTRACT: It is well known that seismic response of a transmission steel towers is affected by the reactions of the neighborly towers concerned with overhead wires. We have applied the frequency response method as the seismic response analysis to investigate characteristics of towers concerned with overhead wires. This method is effective to easily examine the response characteristics affected by phase differences and stiffness of the neighbors. And also this method needs less calculation time, since we can execute the single tower model which has spring elements taken into consideration of the effects of overhead wires. Then, we find that the response regions can be restricted by the present analysis method, which is compared with the multi-mass-points model analysis. Under the general condition, we also limit the response region by using the simultaneous phase analysis. Consequently, we proposed the modified antiearthquake design method including the general idea of "story-moment".

1 INTRODUCTION

Seismic response of the transmission steel tower is affected by the corresponding reaction of the neighborly towers. In case of analysis without effects of the wire, the real response could be harder than that of the analytical result. Therefore, it is important to study on seismic response characteristics of transmission steel towers with overhead wires.

This kind study has been much reported on the a case of the response characteristics for in-plane behavior of the tension steel towers which are alined each other with the same span. However, it is not much to study on effects of the behavior at the perpendicular direction, and on phase differences and stiffness ratio of the neighborly towers. And also it is not realized how much the real behavior with the wire is estimated to be larger than that of the single tower.

This study represents quantitatively relationship between the response value and the phase condition or stiffness ratio of the neighborly tower, or kinds of earthquakes. These were obtained by the coupled response analysis with frequency response method for the tension tower which is considered to be much affected by the overhead wire. Furthermore, we propose a method of antiearthquake design considering coupled response and also a method of translation of the coupled model to the single tower model.

2 COUPLED RESPONSE ANALYSIS USING FREQUENCY RESPONSE METHOD

The frequency response method is a method of re-sponse calculation at the frequency band transformed from the time band by Fourier transformation. In this method the response calculation at the time band is performed by invert Fourier transformation to the response value obtained from multiplied complex amplitude content in the seismic frequency by the concerned amplification characteristics to the each frequency content.

By this method the calculation is simplified because degree of the freedom is reduced by putting a dynamic spring on the analytical tower model.

2.1 Theoretical equations

A vibration equation for multi-mass-points model, shown in Fig.1, is described in the equation (1).

$$M\ddot{X} + C\dot{X} + KX = -MI\ddot{y} \tag{1}$$

X: displacement vector $\ddot{y}$: seismic acceleration
I: unit string vector   M: mass matrix
C: damping coefficient matrix   K: stiffness matrix

And Fourier transformed seismic acceleration is represented in the equation (2).

$$\ddot{y}(t_k) = \sum_{j=0}^{N-1}\left\{\omega_j \cdot V(\omega_j) \cdot e^{i\omega_j t_k}\right\} \tag{2}$$

t_k: time at k step ($= k \cdot \Delta t$) ω_j: angular frequency
Note that $V(\omega_j)$ is given by the equation (3).
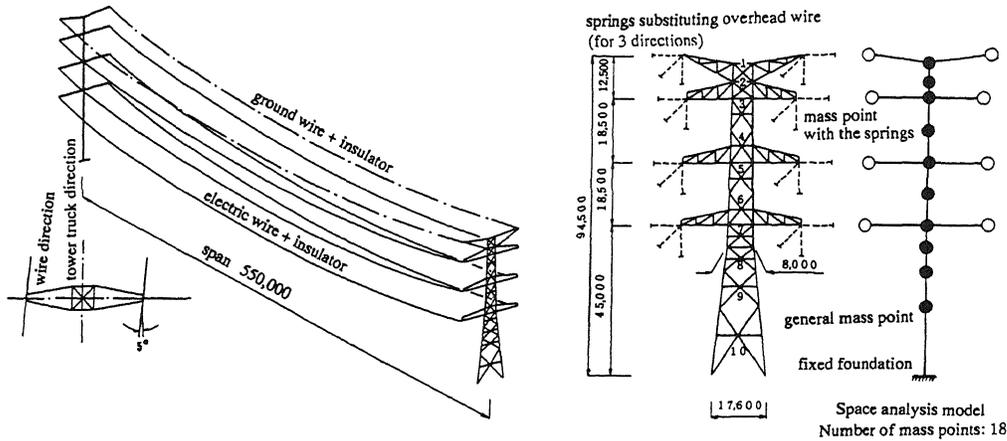
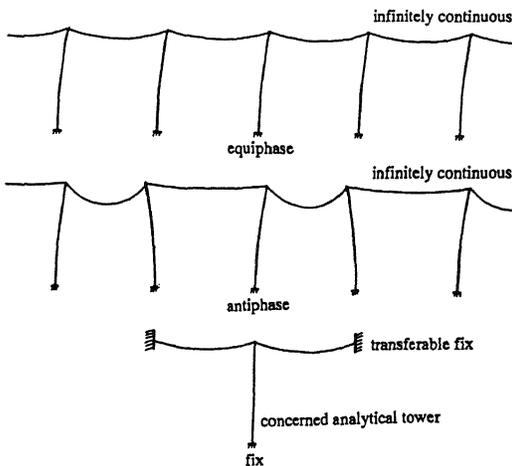Fig.1 Modelling of the dynamic response analysis for the tension tower

Fig. 2 Condition of the neighborly towers

Fig.3 Seismic velocity response spectrum

$$V(\omega_j) = 1/ (N\omega_j) \cdot \sum_{k=0}^{N-1} \left\{ \ddot{y}(t_k) \cdot e^{-i\omega j \iota k} \right\} \qquad (3)$$

Thus, displacement of the each mass point can be obtained from the equation (4) which is given by substituting the equation (2) to the equation (1).

$$X(t_k) = \sum_{j=0}^{N-1} \left\{ R(\omega_j) \cdot V(\omega_j) \cdot e^{-i\omega j \iota k} \right\} \qquad (4)$$

Then, frequency response function R(wj) for velocity amplitude is described in the equation (5).

$$R(\omega_j) = -\left\{ -\omega_j^2 M + i\omega_j C + K \right\}^{-1} MI\omega_j \qquad (5)$$

2.2 Frequency response function of the overhead wire

Three kinds of conditions, shown in Fig.2, were used in the present analysis. In case that the towers having the
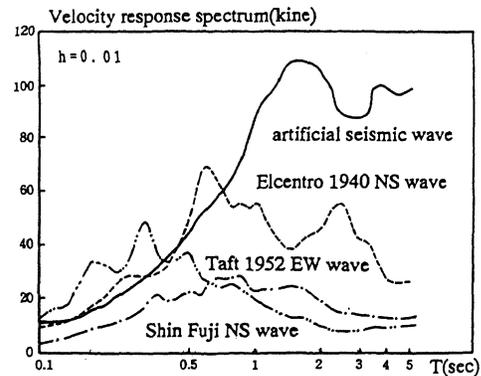
same rigidity are infinitely continuously alined at even distance, the first condition is called as equiphase and the second condition is called as the antiphase.

The third condition is called as the fix which means the both neighborly towers are regarded as completely rigid body. Reaction force F at the loading point was obtained when sin vibration with the constant displacement a and amplitude frequency ω was applied to the end of the concerned tower.

3 COUPLED RESPONSE CHARACTERISTICS

The objective of this analysis, shown in Fig. 1, is the tension tower, a transmission line is fixed on the arm, which is located at 550m distance and is arranged with 5 degree dislocation between the wire and the tower.

3.1 The coupled amplitude characteristics

In case of the single tower model involving reaction force characteristics of the wire, Fig. 4 shows relation-
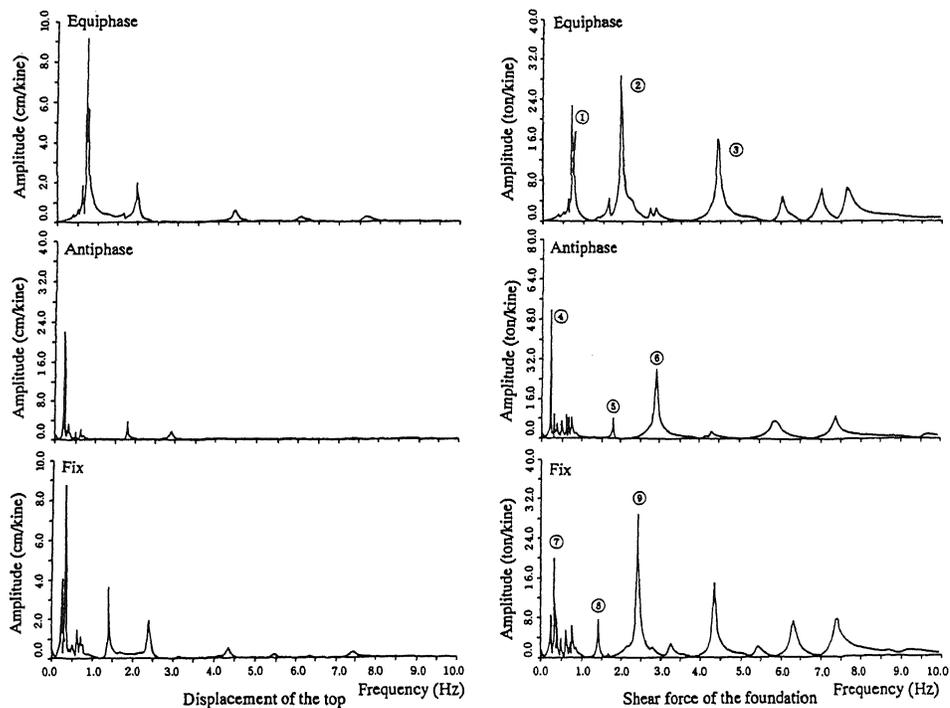
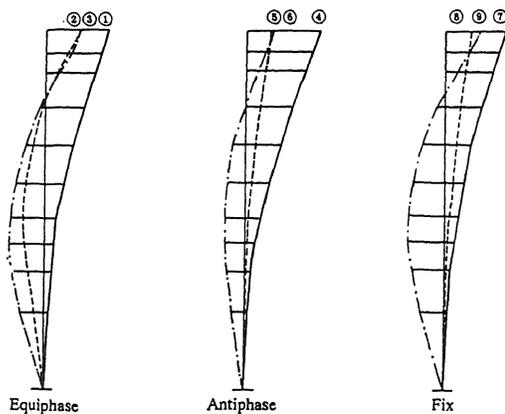Fig.4 Coupled amplitude characteristics (at tower truck direction)

Fig.5 Vibration mode of the tower (truck direction)

Table 1 Excited frequency for the coupled, natural frequency for the single tower

		Single tower	Coupled system		
			Equiphase	Fix	Antiphase
Tower truck direction	Primary	0.99	0.75	0.34 1.42	0.22 1.81
	Secondary	2.90	1.79	2.42	2.90
	Tertiary	4.88	4.43	4.37	4.29
Perpendicular direction	Primary	0.99	1.05	1.05	1.02
	Secondary	2.76	2.61	2.61	2.56
	Tertiary	4.18	4.08	4.17	4.13

ship between the frequency and displacement of top of the tower at the tower truck direction or shear force at the foundation. Vibration mode of the tower corresponding to the dominant frequency is shown in Fig. 5.

An equivalent damping ratio of the tower is set to 1% for the primary frequency. However, it set to be proportional to frequency for the higher order frequency, and that of the wire is set to 0.4%. Thus, amplification characteristics is dominant at several cases of the primary frequency, and case of the secondary or tertiary frequency. Displacement of top of the tower is only affected by the primary frequency. However, shear

force of the foundation is more strongly affected by the higher order frequency.

Table 1 shows dominant frequency of the coupled model. The primary frequency is less than natural frequency of the single tower at the tower truck direction. It is obtained that frequency of single tower becomes smaller for the case of equiphase, fix, antiphase accordingly, since the wire vibrated up and down and moving parallel to the tower causes dynamic inertial force. On the other hand, at the perpendicular tower truck direction the primary frequency is equal to the natural frequency of the single tower, since the
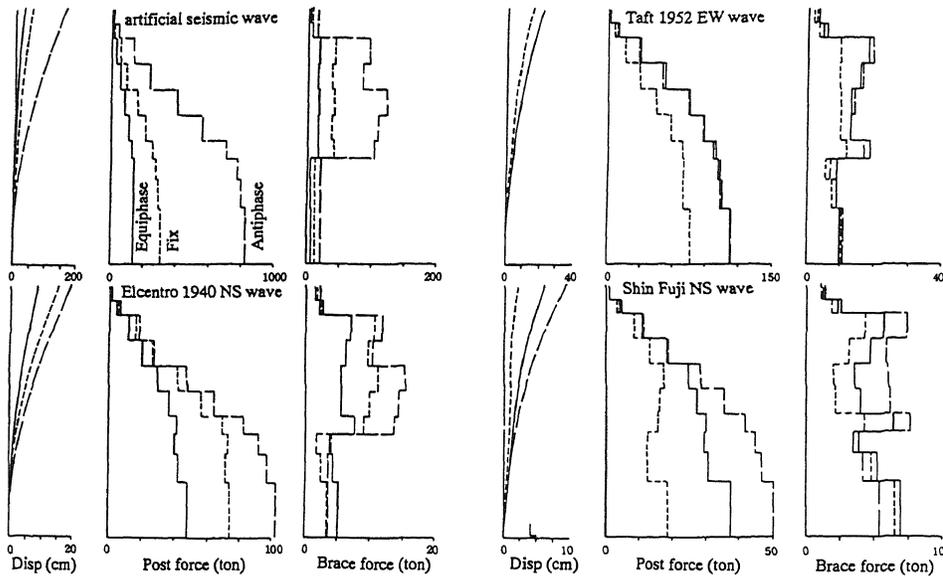
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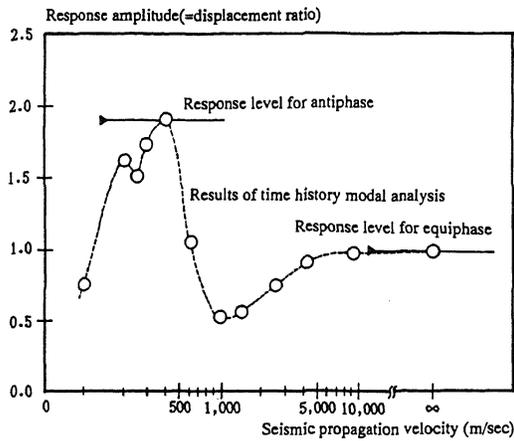Fig.6 Distribution of the coupled response value (truck direction)

Fig.7 Relationship between maximum displacement of the top and seismic propagation velocity

Fig.8 Relationship between story shear force coefficient of the foundation and stiffness ratio to the neighborly tower

spring for this direction is weak to alter frequency of the tower.

3.2 The coupled response characteristics

Figure 6 shows the maximum seismic axial stress response distribution and displacement response distribution of the column and brace members for the tower truck direction. In general case, the maximum response value becomes smaller for the case of antiphase, fix, equiphase accordingly which is following to lower order of the primary frequency regarding the couple amplification characteristics.
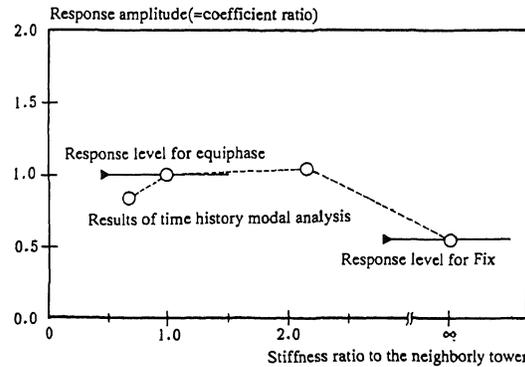
If seismic wave involves more long-period frequency, this tendency is harder. However, if seismic wave involves less long-period frequency, for example Sin Fuji wave or Taft wave, the maximum response value becomes smaller for the case of antiphase, equiphase, fix accordingly, because it is affected by frequency characteristics of the seismic wave.

4 RELATIONSHIP BETWEEN THE RESPONSE VALUE AND CONDITION OF THE NEIGHBORLY TOWER

Results of the frequency response analysis method for the case of equiphase, antiphase, and fix are justified by
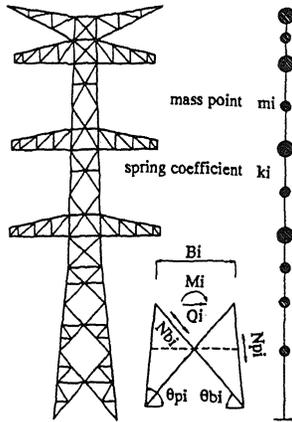
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Fig.9 Schematic of the transmission steel tower

the response value is divided by that for the infinite propagation velocity of the seismic wave.

As the results, the case of equiphase in the frequency analysis is corresponding to a case of infinite propagation velocity of the seismic wave, and the case of antiphase is corresponding to the maximum of response value. And also at range of the ordinary propagation velocity, the maximum response value is less than that at infinite propagation velocity; however, at range of the lower propagation velocity (200-400m/sec), it is higher. It is considered as a reason that natural frequency mode is excited by phase differences, which is not occurred in case of the same vibration applying to all towers.

comparing results of the conventional modal method. An analytical model for the modal method is three towers with multi-mass-points. For the frequency response analysis method, the analytical model is center symmetric single tower with reaction force characteristics of the wire. And the used seismic wave is an artificial earthquake for the both cases.

4.1 *Relationship between propagation velocity of the seismic wave and the response value*

Figure 7 shows the relation between the maximum response displacement at top of the tower and propagation velocity of the seismic wave, which is represented as the plotting points and dotted line. In this figure solid lines represent the maximum response levels obtained by the frequency response method for the case of equiphase and antiphase. Note that abscissa of this figure is the dimensionless response amplitude which

4.2 *Relationship between stiffness of the neighborly tower and the response value*

Figure 8 shows the relation between shear force coefficient at foundation of the tower CBS and stiffness ratio to the neighborly tower, which is represented in the equation (7) for time history modal method to the analytical model, height of the tower is 111.5m and the span is 450m.

Solid lines in this figure represent the maximum response levels obtained by the frequency response method for the case of equiphase and fix. Note that abscissa of this figure is shear force coefficient in case of 1.0 stiffness ratio, and the ordinate is dimensionless value which the neighborly tower stiffness is divided by the concerned tower stiffness. It is decided as bending stiffness at the column member slope alternating point. And the seismic propagation velocity is infinite, which means the case of equiphase.

As the results, the case of equiphase in the frequency analysis is corresponding to a case of 1.0 stiffness ratio, and the case of fix is corresponding to the infinite stiffness. And also in case of the infinite stiffness ratio, story shear force coefficient becomes half of that for
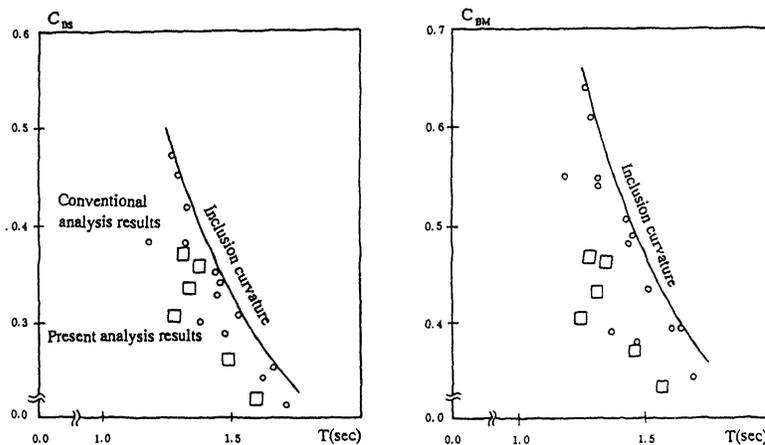

Fig.10 Relationship between natural frequency and story shear force coefficient of the foundation, or story moment coefficient
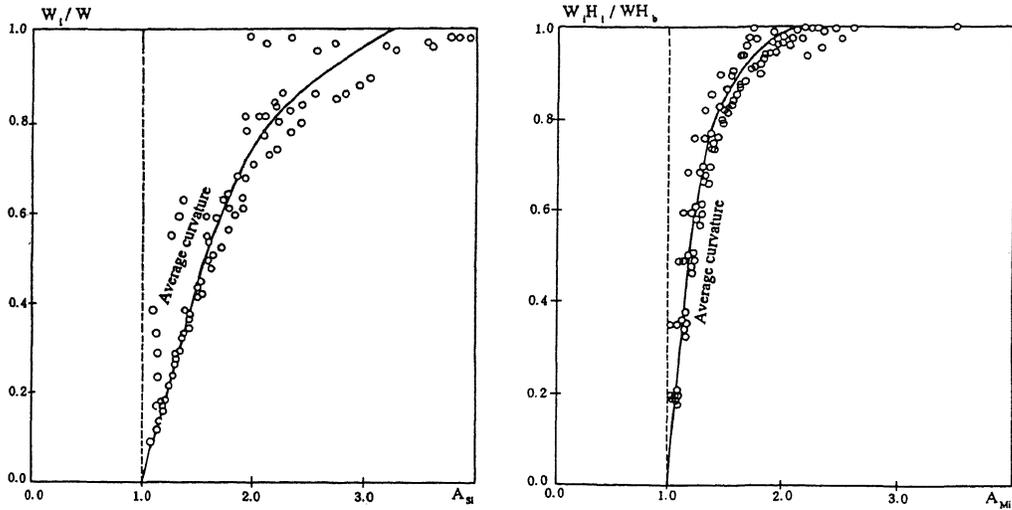
Fig.11 Distribution of story shear force and story moment at the rising direction

the case of 1.0 stiffness ratio; however, at range of the ordinary stiffness ratio (0.5-2.0), they are not almost different.

4.3 Relationship between condition of the neighborly tower and the response value

The maximum response value can be estimated by the coupled response analysis using the frequency response method for the case of fix, antiphase, equiphase. However, in particular the case of antiphase is very rare and the case of fix is unrealistic because stiffness ratio to the neighborly tower is usually up to 2.0.

Consequently, at the ordinary range of the seismic propagation velocity and stiffness ratio to the neighborly tower and so on, basically it is appropriate to use stress for the case of equiphase.

5 ANTIEARTHQUAKE DESIGN CONSIDERED WITH THE COUPLED RESPONSE CHARACTER ISTICS

We propose an antiearthquake design for the tower with consideration of effect of the wire at the tower truck direction, which is based on results of the coupled response analyses on the artificial earthquake.

Stress of the column member or the brace member is affected by both of shear force and bending moment shown in the equation (6), because column member of the transmission tower is bent as shown in Fig.9.

$$N_{pi} = \sin \theta_{bi} / \sin (\theta_{pi} + \theta_{bi}) M_i / B_i$$
$$+ \sin \theta_{bi} / \sin (\theta_{pi} + \theta_{bi}) Q_i / 2$$
$$N_{bi} = - \sin \theta_{pi} / \sin (\theta_{pi} + \theta_{bi}) M_i / B_i \qquad (6)$$
$$+ \sin \theta_{pi} / \sin (\theta_{pi} + \theta_{bi}) Q_i / 2$$

Therefore, to calculate stress of the member at the earthquake, it is necessary to introduce the story moment other than the ordinary story shear force.

5.1 Story shear force coefficient of the foundation and the story moment coefficient

Story shear force coefficient of the foundation C_{BS} and the story moment coefficient C_{BM} are described with the story shear force Q_B and the story moment M_B in the equation (7).

$$C_{BS} = Q_B / W, \quad C_{BM} = M_B / WH_b \qquad (7)$$

Note that W is weight of the tower considered with effects of the wire and Hb is height of center of gravity point of the tower.

Figure 15 shows relation between the frequency and the story force coefficient or the story moment coefficient. The frequency at tower truck direction can be simply described with the equation (8) which is obtained from results of the analysis considering half weight of the wire.

$$T = 1.25 \left\{ (W_t + 0.5W_{co})H^3 / EI_t \right\}^{4/7} \qquad (8)$$

As the results, the story shear force coefficient and the story moment coefficient are strongly effective to frequency of the tower. This relationship is included by the curvature shown as solid line in this figure.

5.2 Distribution coefficient at rising direction of the tower of the story shear force and the story moment

Distribution coefficients at rising direction of the tower

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Asi and Ami for the story shear force Qi and the story
moment Mi respectively are described in the equation (9).

$$A_{Si} = Q_i / (W_i C_{BS})$$
$$A_{Mi} = M_i / (W_i H_i C_{BM})$$

(9)

Figure 11 shows relation between the story shear force
distribution coefficient and the parameter Wi/W, and
relation between the story moment distribution coeffi-
cient and the parameter WiHi/(WHb). It is considered
that to unify antiearthquake capability of the tower
from top to bottom, these relation curvatures are fixed
as the average curvature against the plotted points.

5.3 The response value of the each member

The story shear force and moment of the each panel are
calculated by multiplying the shear force of the founda-
tion and the moment which are obtained on the fre-
quency considering effects of the wire by the each
distribution coefficient. The response value of the each
member is represented in the equation (8).

6 CONCLUSION

Applying the proposed coupled response analysis
method by using the frequency response method to the
tower with the wire, it is relatively easy to obtain the
response value for the definite phase or stiffness condi-
tion, which is the case of equiphase, antiphase, or fix.
    From results of the proposed method, range of the
response value can be estimated. At the general range
of the response value, it is determined to be able to use
results of this method for the case of equiphase.
    From the present results, we propose an
antiearthquake design for the tension transmission
tower with a new concept of the story moment.

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