

# Wind-Induced Vibration Analysis of Overhead Working Truck

Hongqi Jiang<sup>1,2</sup>, Shunca Li<sup>2</sup>, Xianbiao Mao<sup>1</sup>,

<sup>1</sup>China University of Mining & Technology; Xuzhou, jiangsu, 221008; China

<sup>2</sup>Jiangsu Normal University; Xuzhou,jiangsu, 221116; China

## Abstract

*As to the complicated characteristics of overhead working truck under effects of random dynamic wind, the traditional method is difficult to reflect its dynamic response in real time, in the study; it proposes the random wind induced vibration response analysis method based on the finite element method and pseudo-excitation method. An it regards the vibration of the fluctuating wind load as coherent random vibration under stationary random excitation, and it uses Davenport wind velocity spectrum which does not change with height, the correlation of the wind excitation are considered. It takes the folding type arm overhead working truck as example, the random wind vibration analysis are performed, and it gets the acceleration response spectrum and root mean square the of aerial work platform. The analysis results show that the low-order frequency will cause great vibration of the work platform, and the vertical one third of the root-mean-square of acceleration is below international standards, it has no uncomforted effect on operation workers.*

**Keywords:** *the pseudo-excitation method, overhead working truck, the wind vibration response, random vibration*

**Copyright © 2014 Institute of Advanced Engineering and Science. All rights reserved.**

## 1. Introduction

As a kind of engineering machinery and equipment, the overhead working truck is widely used in shipbuilding, construction, municipal construction, fire control, etc. The stability of working platform and security are one of the key technologies of overhead working truck research. With the increase of high buildings, the operation difficulty of overhead working truck height is higher and higher; the arm slenderness ratio is more and more big, the wind load effect is more apparent. As the wind loading may produce larger deformation and vibration [1-3], it will serious impact on the safety of the operating arm and operation personnel.

Natural wind in the process of flow due to the influence of various obstacles on the ground, its speed presents the random fluctuating characteristics. It is generally believed that natural wind is composed of the average wind and fluctuating wind [4], the speed of wind has an average component and a pulsating component. Therefore, under the effect of natural wind, the load structure of wind is composed of two parts: one is the average calm load under the action of the wind; the second is fluctuating load under the action of random pulse. The load structure caused by the static deformation can be obtained through static analysis of the structure; and fluctuating wind component will cause the induced vibration of the structure, the continuous vibration will cause structure fatigue damage, and also can cause the discomfort of workers.

In conventional design, it often take the wind load as the static force and then take the certain wind vibration coefficient into consideration, and the calculation results can not fully reflect the dynamic response of wind load excitation. So it is necessary to carry out the dynamic response analysis of aerial work machinery under the fluctuating wind load, in order to grasp the dynamic performance of the structure and improve the reliability of system design.

## 2. Basic Theory of Pseudo-excitation Method

According to vibration theory, under the zero initial condition, the constant coefficient linear frequency response function of the system is the ratio of input vector and output harmonic content, namely that:

$$H(\omega) = X_{\omega}(t)/Y_{\omega}(t) \quad (1)$$

Where,  $H(\omega)$  is frequency response function;  $X_{\omega}(t)$  is Fourier transform of  $x(t)$ ;  $Y_{\omega}(t)$  is Fourier transform of  $y(t)$ .

When the linear systems is affected by the stationary random excitation function  $F(t)$  of the spectral density  $S_{FF}(\omega)$ , and the response of power spectrum is as (2) [5-6].

$$S_{XX}(\omega) = |H|^2 S_{FF}(\omega) \quad (2)$$

Where  $H$  is the frequency response function, which means when the random excitation of incentive is  $e^{i\omega t}$ , the corresponding harmonic response is  $X(t) = He^{i\omega t}$ . If the incentive  $e^{i\omega t}$  is multiplied by the constant  $\sqrt{S_{FF}}$ , namely that construct a virtual incentives function  $\tilde{F}(t) = \sqrt{S_{FF}}e^{i\omega t}$ , then the corresponding virtual response is:

$$\tilde{X}(t) = \sqrt{S_{FF}}H(\omega)e^{i\omega t} \quad (3)$$

The actual response can be obtained from power spectral density and cross power spectrum density and the calculation formula are as follows:

$$\tilde{X}^* \tilde{X} = |\tilde{X}|^2 = |H|^2 S_{FF} = S_{XX} \quad (4)$$

$$\tilde{F}^* \tilde{X} = \sqrt{S_{FF}}e^{-i\omega t} \sqrt{S_{FF}}He^{i\omega t} = S_{FF}H = S_{FX} \quad (5)$$

$$\tilde{X} \tilde{F} = \sqrt{S_{FF}}H^*e^{-i\omega t} \sqrt{S_{FF}}He^{i\omega t} = H^*S_{FF} = S_{XF} \quad (6)$$

Where  $S_{XX}$  represents the actual response of the power spectral density,  $S_{FX}$  represents the actual incentive and the actual response of the power spectral density,  $S_{XF}$  represents the actual response and actual incentive cross-power spectral density.

If the system has more than one response, through the type (4) ~ (6) type, the available power spectrum matrix can be obtain:

$$S_{FF} = \tilde{X}^* \tilde{X}^T, \quad S_{FX} = \tilde{F}^* \tilde{X}^T, \quad S_{XF} = \tilde{X}^* \tilde{F}^T$$

Where \* represents complex conjugate and T represents transpose

### 3. Wind Vibration Response Analysis

Fluctuating wind loads on the structure caused by vibration, can be looked as more coherent random vibration problem under stationary random excitation, the dynamic differential equation is as (7).

$$[M]\{\ddot{Z}(t)\} + [C]\{\dot{Z}(t)\} + [K]\{Z(t)\} = \{F(t)\} \quad (7)$$

Where,  $[M]$ 、 $[C]$ 、 $[K]$  represents the mass, damping and stiffness matrix of structure, respectively;  $\{Z(t)\}$  represents the node displacement vector;  $\{F(t)\}$  represents the wind load vector of fluctuating.

According to the vibration mode decomposition method, the Equation (7) can be rewritten according to the vibration mode [7, 8].

$$\{z(t)\} = \sum_{j=1}^q \{\phi_j\} u_j(t) = [\phi] \{u(t)\} \quad (8)$$

Where,  $q$  is the selected number of vibration mode,  $u_j$  represents the displacement,  $\phi_j$  represents vibration vector.

According to the specification, the general take Davenport fluctuating wind velocity spectrum is taken as the excitation spectrum; it does not change with height, since the power spectrum of its expression is:

$$S_{ff}(n) = \frac{4K\bar{V}_{10}^2 x_0^2}{n(1+x_0^2)^{4/3}}, x_0 = \frac{1200n}{\bar{V}_{10}} \quad (9)$$

Among them:  $n = \omega/2\pi$  represents the pulsating wind frequency;  $\bar{V}_{10}$  represents average wind speed when the height is 10 m;  $K$  is the coefficient which is related to surface roughness.

As the fluctuating wind randomness, if take the correlation between different random excitation,  $coh(\omega)$ , the level of cross spectrum of fluctuating wind velocity can be expressed as [9]:

$$S_{ij}(\omega) = \sqrt{S_{ii}S_{jj}} coh(\omega)_{ij} \quad (10)$$

$$\text{Where } coh(\omega) = \exp\left(\frac{-n(C_x \Delta x^2 + C_y \Delta y^2 + C_z \Delta z^2)^{1/2}}{\bar{V}_{10}}\right)$$

$C_x = 16, C_y = C_z = 10$  represent the space attenuation coefficient  $\Delta x, \Delta y, \Delta z$  are the coordinate difference of the two points.

Through (7) and (8), the load power spectrum matrix  $S_{pp}(\omega)$  can be obtained, obviously that  $S_{pp}(\omega)$  is the Hermite matrix, so it can be decomposed through LDL\* method. Thus the (11) is obtained.

$$S_{pp}(\omega) = L^* DL^T \quad (11)$$

Where,  $L$  is the triangular matrix,  $D$  is a diagonal matrix.

If take the first  $k$  column of the vector  $\{L_k\}$ ,  $D$  no  $k$  diagonal elements  $d_k$ , can construct virtual excitation vector  $n$  as follows:

$$\{\bar{x}_k(t)\} = \{L_k\} \cdot d_k \cdot e^{i\omega t}, (k = 1, 2, \dots, n) \quad (12)$$

The virtual response of the structure can be obtained.

$$\{z_k(t)\} = [\phi][H][\phi]^T \{L_k\} \sqrt{d_k} e^{i\omega t} \quad (13)$$

Where  $H$  represents the frequency response function.

$$H_j(\omega) = \frac{1}{\omega_j^2 - \omega^2 + 2i\zeta_j \omega_j \omega} \quad (14)$$

Where  $\omega_j$ 、 $\zeta_j$  represent the natural frequency and damping ratio, Through (3), the Power spectrum matrix  $\{z\}$  is as (15):

$$[S_{zz}] = \sum_{k=1}^n \{z_k\}^* \{z_k\}^T \quad (15)$$

#### 4. Wind Vibration Response Analysis

In the study, the work high arm is composed of rectangular cross section of the upper arm, lower arm. The upper arm head work platform are used for transporting people and goods, the arm up and down are through the oil cylinder lifting, and adopts the light vehicle chassis (which is as shown in Figure 1). When the work arm is in the elevated position, the steel processing can be adopted in oil cylinder, upper arm and lower arm can use the element simulation of Euler Bernoulli beam, oil cylinder can be simulated through using a one-dimensional bar element. the constraint processing are adopted in the lower arm oil cylinder and the lower arm, the simplified operation arm is as shown in Figure 2 ,It is the finite element model which is composed of seven nodes and seven units.

The working height is about 14,  $l_{13}=5.95m$ ,  $l_{36}=5.6m$ ,  $l_{23}=0.495m$ ,  $l_{56}=1.4m$ ,  $l_{67}=0.45m$ ,  $E=20700MPa$ , Upper arm  $A1=3.86 \times 10^{-3}m^2$ ,  $I1=3.85 \times 10^{-5}m^4$ , Lower arm  $A2=3.64 \times 10^{-3}m^2$ ,  $I2=3.07 \times 10^{-5}m^4$ . Oil cylinder  $A=7.53 \times 10^{-3}m^2$ ,  $I=1.39 \times 10^{-5}m^4$ .

Landscape coefficient K is 0.039, the basic wind pressure is 0.9 KN/m<sup>2</sup>, the Davenport fluctuating wind speed spectrum is looked as the standard wind speed. Through the software of ANSYS, the finite element model of operating arm is established. In the model analysis, the first 4 order vibration mode is selected, the model damping ratio is set as 0.02. The description mode shapes and diagram are as shown in Table 1 and Figure 3.

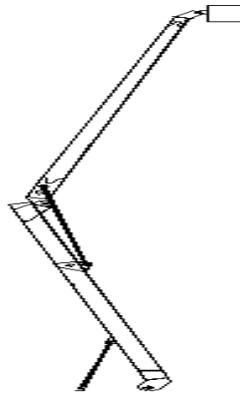


Figure 1. Diagram of the Working Arm

Table 1. The First Four Order Vibration Mode

Order time	Natural frequency /Hz	Modal descriptions
1	4.85	Overall vertical arm swinging
2	12.07	Upper arm bent
3	18.40	Upper and lower arms
4	48.23	Under the arms bent

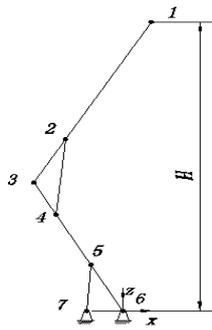


Figure 2. The Finite Element Model Operation Arm

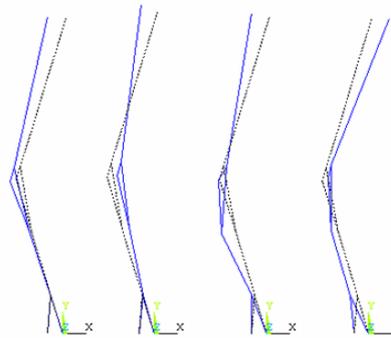


Figure 3. The First 4 Order Modal Vibration Mode

In the frequency range of 0.2Hz to 50Hz, through the Matlab simulation program, the assignments arm at the front of node 1 horizontal and vertical displacement and the acceleration power spectrum are shown in Figure 4 to Figure 7.

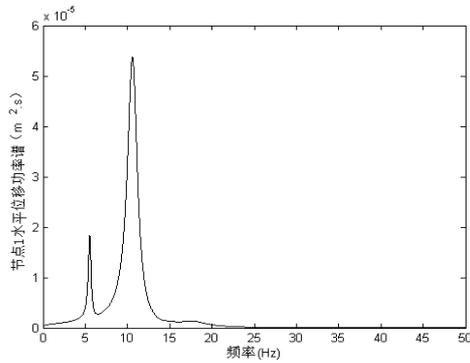


Figure 4. Horizontal Power Spectrum of Node 1

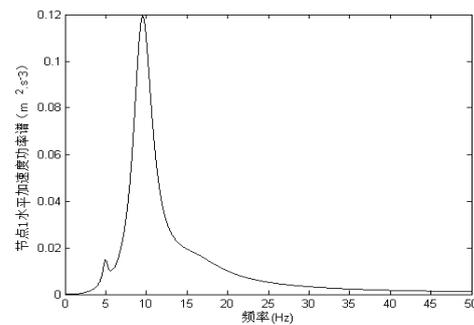


Figure 5. Acceleration Power Spectrum of Node 1

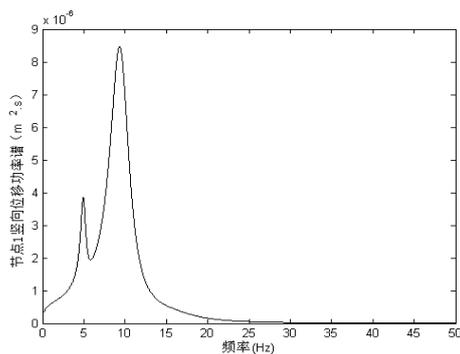


Figure 6. Vertical Displacement Power Spectrum of Node 1

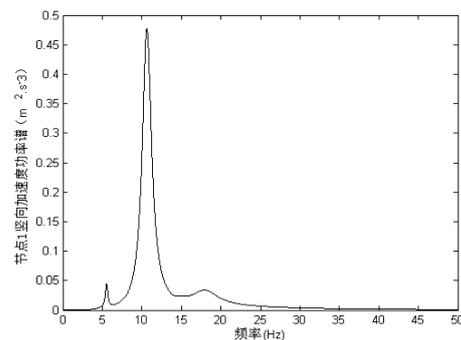


Figure 7. Vertical Acceleration Power Spectrum Node 1

From the Figure 4 to Figure 7 it can be seen that, in the first order natural frequency of 5Hz and second order natural frequency 12Hz, vibration response of node 1 work platform is

obvious, in the other frequency, the vibration is relatively small, the natural frequency of vibration frequency and the main vibration mode frequency are nearly the same.

Recent studies have shown that [10], frequency sensitive frequency of human body in the up and down fluctuation is between 4 and 8Hz, and the sensitive frequency of vibration back and forth is between 1-2Hz, and some area of the body can produce resonance, with the increase of frequency, sensitivity, and the vibration will influence the comfort. The severe vibration response is less than 30Hz, and the influence of vertical vibration on comfort is about 70%, horizontal vibration is about 12%. In order to study the effect of vibration on personnel comfort degree, the response spectrum is calculated through pseudo-excitation method, in frequency range of 1 to 20Hz, a series of discrete frequency points are selected, through the type (13), the mean square root of acceleration can be calculated.

$$\sigma_{1/3} = \sqrt{\int_{0.89f_r}^{1.12f_r} S_{zz} d\omega} \quad (16)$$

Table 2 and table 3 lists the operating arm head respectively the horizontal and vertical 1/3 frequency multiplication operation platform acceleration root mean square. According to the international standard ISO 2631 body fatigue/efficiency lower limit, the acceleration root mean square of the type of overhead working truck are standard 8 hours working efficiency under the lower limit, which can ensure that workers in eight small basic is not influenced by wind vibration in the working time.

Table 2. Mean Square Root of Acceleration of One Third Frequency Doubling (horizontal)

Center frequency /Hz	1	2	3	4	5	6	7	8	9	10
$\sigma_{1/3} / (m \cdot s^{-1})$	0.002	0.003	0.005	0.006	0.008	0.010	0.018	0.024	0.016	0.015
	5	9	2	5	1	3	5	2	9	4
Center frequency /Hz	11	12	13	14	15	16	17	18	19	20
$\sigma_{1/3} / (m \cdot s^{-1})$	0.031	0.084	0.090	0.087	0.065	0.018	0.011	0.010	0.010	0.009
	6	5	1	6	7	2	2	2	1	7

Table 3. Mean Square Root of Acceleration of One Third Frequency Doubling (vertical)

Center frequency /Hz	1	2	3	4	5	6	7	8	9	10
$\sigma_{1/3} / (m \cdot s^{-1})$	0.006	0.0072	0.0151	0.0174	0.0194	0.033	0.0572	0.0893	0.0568	0.0463
	5									
Center frequency /Hz	11	12	13	14	15	16	17	18	19	20
$\sigma_{1/3} / (m \cdot s^{-1})$	0.095	0.255	0.2906	0.2649	0.1936	0.0611	0.0403	0.0387	0.0348	0.0277
	2									

## 5. Conclusion

As the complex characteristics of working truck under random dynamic wind load, the traditional design can not reflect its dynamic response accurately, in the study, the finite element method and pseudo-excitation method are adopted in the wind induced vibration response analysis of working truck, it can both accurately reflects the operation arm vibration response caused by a fluctuating wind load, and also can improve the efficiency of computing, and it can provide a feasible way for wind induced vibration analysis of working truck.

Through the analysis of the level of operation platform, vertical displacement and acceleration power spectrum, the first and second order frequency vibration response are significantly, and the vertical vibration response is greater than the horizontal vibration response.

One third acceleration mean square root of the working arm operation platform at each frequency point is below the international body fatigue/efficiency standards of ISO2631, and it has no significantly effects on the workers.

### References

- [1] Sun Dongke, Lin Lin hao, Zhang Yahui, etc. The wind induced random vibration analysis of complex structures. *Journal of mechanical engineering*. 2001; 5(3): 55-61.
- [2] XU Youlin, ZHANG Wenshou, KO J M, et al. The Pseudo - excitation method for vibration analysis of wind - Excitedstructures. *Journal of Wind Engineering and Industrial Aero Dynamics*. Turned 1999: 443-454.
- [3] WTX u, JHL in, YHZ Hang. 2 d moving element method for random vibration analysis of of vehicles on Kirchhoff plate with Kelvin foundation. *Journal of Latin America - Solid and Structures*. 2009; 6:169-183.
- [4] Wang Fanglin, Gao wei, Chen Jianjun. Prescribed by ritual law incentive antenna structure under random vibration analysis. *Journal of engineering mechanics*. 2006; 23(2): 168-172.
- [5] Lin hao Zhang Yahui. Random vibration of the pseudo-excitation method. Beijing: science press. 2004.
- [6] Sun Zuoyu, wang hui. Structural random vibration analysis of equivalent excitation method. *Journal of engineering mechanics*. 2010; 27(1): 20-23.
- [7] Wang wei dong, Sun Lining Du Zhijiang. Move the arm vibration analysis based on pseudo-excitation method. *Journal of jilin university (engineering science)*. 2010; 40(4): 1082-1085.
- [8] Bu Guo Xiong Tan Ping, zhang ying, etc. Large random wind vibration response of tall building analysis. *Journal of Harbin institute of technology*. 2010; (2): 175-179.
- [9] Sun Jianrui Xu Changsheng. Marine deck crane boom structure wind vibration response study. *Journal of lifting the transport machinery*. 2009; 12: 20-23.
- [10] Li Lingxuan Song Guiqiu, flow, etc. Based on ANSYS, the analysis of the effect of natural vibration characteristics of passenger train. *Journal of vibration and shock*. 2011; 30(1): 121-123.