Simulation Analysis of the Bed of Needling Machine Producing High Gram Weight Nonwovens

Xiaoqin Zhong, Qiqiang Ji, Linzhang Ji, Xiaojian Niu
School of Mechanical Engineering, Shanghai Institute of Technology, Office Building, room 105, No.100 HaiQuan Road, Feng Xian District, Shanghai, China
Email: zhongxq20@sina.com

Abstract. The needle punctures non-woven fabrics up and down reciprocating when the needling machine producing high gram weight nonwovens is working. The bending deformation of the supporting bed, an important part, will be caused by impact loads such as penetration force. Based on the basic principle of mechanical vibration, the vibration bending and mode shapes of the supporting were analyzed by field measurement and finite element simulation. The results showed that the deflection of the bed was affected by the penetration force under certain working conditions. But the influence value was small and the downward bending deflection was within the allowable range. The needling process would not cause resonance of the machine since its first four natural frequencies in Z direction were much larger than the working frequencies. The engineering significance of the study is to ensure that the needle punching machine meets the requirements of strength and stiffness, and realizes the function of producing high gram weight nonwovens.

1. Introduction
Nonwovens, also known as non-woven fabrics, are a new kind of fiberproducts [1]. Needle punching is one of the main processing methods of nonwovens. When needles with barbs pierce into the fiber web, the barbs will drive fibers on the surface of the web to move inward and make them tangle with each other. Needle-punched nonwovens with certain mechanical and physical properties and strength are formed after repeated acupuncture [2-3]. The original needling machines have simple structure and can only be used in the production of low gram weight nonwovens. However, the needle-punched nonwovens weighing more than 200g/m² have more compact structure, better performance and wider use. This kind of fabric has good market prospects [4].

Therefore, it is very significant to guarantee the performance of needling machine producing high gram weight nonwovens, especially to control the bending deformation of the supporting bed, which is the key component of the needling machine.

2. Modal Analysis of Supporting Bed of Needling Machine
2.1. Theoretical Analysis of Natural Frequency
Modal is the natural vibration characteristic of mechanical structure. The natural frequency of the structure and the mode of vibration can be computed by modal analysis, which is of great significance in the mechanical structure design. The supporting bed is simplified as a statically indeterminate beam with two fixed ends. The direction perpendicular to the ground is defined as Z direction, the axial direction is defined as X direction, and the transverse direction is defined as Y direction. Based on basic principles of mechanical vibration and material mechanics, the differential equation of free flexural vibration of beam can be written in equation (1) [5]:
The solution of equation (1) is separated from space and time, so the method of separation of variables can be used to solve the differential equation.

\[ w(x, t) = Z(x)F(t) \] (2)

By substituting equation (2) into the equation (1), the bending vibration equation can be updated as equation (3):

\[ \frac{\ddot{F}(t)}{F(t)} = \frac{\{EI(x)Z''(x)\}''}{\rho(x)S(x)Z(x)} = \omega^2 \] (3)

By simplifying the equation, the differential equations about space and time can be described by equation (4) and (5):

\[ \ddot{F}(t) + \omega^2 F(t) = 0 \] (4)

\[ \{EI(x)Z''(x)\}'' - \omega^2 \rho(x)S(x)F(t) = 0 \] (5)

The general solution of the equations can be expressed in equation (6) and (7):

\[ F(t) = A \sin(\alpha t + \theta) \] (6)

\[ Z(x) = C_1 \sin \beta x + C_2 \cos \beta x + C_3 \sin h \beta x + C_4 \cos h \beta x \] (7)

Partial parameters are expressed as:

\[ \rho(x) = \rho, \quad S(x) = S, \quad I(x) = I, \quad \beta^4 = \frac{\rho S}{EI} \omega^2 \] (8)

According to material mechanics theory, the boundary condition of the fixed beam is given as follows: \( Z(0) = 0, Z'(0) = 0, Z(l) = 0, Z'(l) = 0 \)

The characteristic equation is obtained by substitution: \( \cos \beta l \cos h \beta l = 1 \)

Then the circular frequency of the beam is defined by equation (9):

\[ \omega_i = (\beta_i)^2 \sqrt{\frac{EI}{\rho S}}, (i = 1, 2, 3 \cdots) \] (9)

So the natural frequency is expressed in equation (10):

\[ f_i = \frac{\omega_i}{2\pi} = \frac{\beta_i^2}{2\pi} \sqrt{\frac{EI}{\rho S}}, (i = 1, 2, 3 \cdots) \] (10)

According to material properties of the supporting bed, parameters are expressed as:

\[ l = 2.8 m, E = 200 Gpa, I = 4.9636 \times 10^{-4} m^4, \rho = 7850 kg/m^3, S = 0.017603 m^2 \]

By substituting the parameters into equation (10), the first four natural frequencies of the bed in \( Z \) direction can be calculated as:

\[ f_1 = 121.734 Hz; f_2 = 335.636 Hz; f_3 = 657.847 Hz; f_4 = 1087.462 Hz \]

2.2. Finite Element Modal Analysis

Three-dimensional model was first built by NX software, and then it was imported into the software of ANSYS Workbench for finite element analysis. The material of the bed is defined as Q235A and Poisson's ratio is 0.3. Then mesh generation and constraint were performed in the model directly, and a finite element simulation model is built.
The Z directional vibration is the main research object, first four natural frequencies of the bed are solved:

\[ f_1 = 122.51 \, \text{Hz}; \quad f_2 = 333.88 \, \text{Hz}; \quad f_3 = 618.36 \, \text{Hz}; \quad f_4 = 1084.2 \, \text{Hz} \]

Figure 1 shows the different order modal. The modal frequencies after the fourth order are too large to be further analyzed.

![Figure 1](image)

**Figure 1.** First four mode shapes in Z direction.

It is found that natural frequencies of two results are basically the same and the error is small by comparing the natural frequencies derived from the bending vibration equation with the finite element modal analysis.

### 3. Vibration Testing Analysis Of Supporting Bed

#### 3.1. Testing Instrument

Data Acquisition Instrument INV3060V, three-direction acceleration transducer, vibration velocity transducer, pull on the rope displacement sensor, analysis software, strain gauges, DC Power Supply and other instruments were used to measure the dynamic characteristics of the supporting bed.

#### 3.2. Test point Arrangement

As shown in figure 2, the bed was divided into 6 equal parts according to the length direction of the structure. Acceleration transducers and velocity transducers were installed at measuring points from 1 to 5 to collect signals. Four groups of full-bridge circuits were formed by pasting strain gauges on the connecting rods of the acupuncture mechanism to collect strain signals.

![Figure 2](image)

**Figure 2.** Test point arrangement for vibration testing.

#### 3.3. Data Acquisition

Data acquisition was carried out in the built test system. Sampling frequency should be set larger than signal frequency, which is generally 2.56 times the signal frequency\(^6\). Therefore the sampling frequency of the test was set to 256Hz. The channel parameters were set according to the sensor model and the needling frequency was 165 times/min. The field measurement was carried out under load and no-load conditions.

#### 3.4. Time Domain Analysis

The original data of velocity transducers collected in DASP software were integrated once. Figure 3 depicts the vibration displacement waveform along the needle direction, and several data points are selected as the displacement measured data in the waveform. The trend in data indicated that when the needling machine repeatedly needled the fiber web, the resistance of the needle to puncture fiber web was gradually increasing, which led to the increase of the downward deflection of the bed. Moreover,
the maximum downward deflection occurred at the midpoint of its span, with a value of about 0.3518mm.

![Figure 3. Analysis curve of measured data.](image)

The comprehensive displacement measured in the field are caused by vibration, penetration force and other factors. Then according to the measured downward deflection under no-load condition was 0.0559mm, the maximum downward deflection caused by penetration force was calculated to be about 0.2959mm under the load condition. The value could meet the requirement of controlling the downward bending deflection within 0.5mm.

3.5. Frequency Domain Analysis
The velocity signal is transformed from time domain to frequency domain, as illustrated in figure 4. By choosing the peak points on the graph, it was found that the working frequency of the needling machine was mainly in the low frequency and the fundamental frequency was 2.8125 Hz under the field working condition. The needling frequency of the machine was 165 times/min corresponding to the power frequency of 2.75Hz, which was basically consistent with the fundamental frequency. These proved the accuracy of the test data.

![Figure 4. Frequency domain waveform of velocity signal.](image)

4. Testing Analysis of Penetration Force
Penetration force refers to the resistance of the needle to puncture fiber web in the process of needling. Its change process indirectly reflects the transfer effect and damage degree of needling on fibers. Though testing the parameters of penetration force, the dynamic change of penetration force
was analyzed. The deformation conditions and the influence of the change of penetration force on the dynamic rigidity character of the supporting bed were studied.

4.1. Test of Penetration Force
The force acting on the connecting rod of the needle-punching mechanism in the vertical direction was taken as the test object. Because of the complexity of the field working condition, the test was also carried out under load and no-load conditions, and the results were compared to obtain the strain mainly caused by the penetration force. The waveform of measuring point 4 was taken as the research object. The calibration value between output voltage and strain was revised to 0.0026 mV/µε according to the system bridge voltage. Figure 5 shows the amplification diagram of strain signal under load condition.

From figure 5 we can see that the signal interval is 0.36s, which is coincided with the needling frequency. So the signal frequency is consistent with the load frequency. In addition, the waveform oscillates slightly at the zero point in the marked area A. The reason is that needles are resisted when they puncture surface of fiber web, and they are pulled by the fibers when they leave. The maximum strain of penetration force is about 17.089 by comparing the load and no-load data.

![Figure 5. Amplification diagram of strain signal under load condition.](image)

4.2. Calibration Test of Penetration Force
The specimen with diameter of 55mm was fixed on the tension and compression test machine for calibration. The maximum test force was 200kN and the gradient of 20kN was set for 10 times. Several groups of tests were carried out and one group was selected for analysis. The main load-bearing area of actual components is 0~20kN. Therefore, we amplify the first section of the gradient load waveform of channel 1 and study the relationship between force loading and linear strain output, as shown in figure 6.
Figure 6. Measured data.

By fitting the data points, based on the load fitting equation, the transformation formula of the penetration force can be defined by equation (11):

$$F = 4F_p = \varepsilon / 0.0004975$$  \hspace{1cm} (11)

The penetration force parameters under different layers of grey cloth thickness are obtained by substituting the strain of the connecting rod into equation (11), as shown in table 1.

| Layer number of nonwovens | Strain of single connecting rod(\(\mu\varepsilon\)) | Penetration force(N) |
|---------------------------|-----------------------------------------------|----------------------|
| 1                         | 15.958                                        | 32076.38             |
| 2                         | 16.594                                        | 33354.77             |
| 3                         | 16.842                                        | 33853.27             |
| 4                         | 17.089                                        | 34349.75             |

From table 1, it can be seen that the fibers become tighter and the friction resistance factor between fibers increases in the process of needling, so that the resistance of the needle to puncture fiber web increases gradually, which would affect the bending deformation of the bed. In actual production, the deformation can be improved by strengthening the rigidity of the equipment and other ways.

5. Structural Static Simulation of Supporting Bed

The maximum penetration force of 34350N in the above analysis was taken as the load parameter, and then simulation analysis of the supporting bed was carried out. After the mesh generation and constraint are performed in the model, the uniform load is applied to the 2m part in the middle of the bed platform. Finally, the deformations cloud diagram in Z direction are obtained by calculating in the solver, as shown in figure 7.
From figure 7 we can see that the negative value "Min" represents the maximum displacement point in Z direction, that is, the maximum downward deflection is 0.261mm in the middle of the bed. The simulation value is basically consistent with the vibration test result. Therefore, the deflection and the strain of penetration force measured by vibration test are basically correct, and the stiffness and strength of the supporting bed can meet the production requirements.

6. Conclusions
(1) Combining theoretical calculation and finite analysis, it was found that the first four natural frequencies of the supporting bed in Z direction were much larger than the working frequencies. Therefore, the needling machine would not produce resonance during needling, which ensured the safety and stability of the equipment.

(2) In the process of repeated needling of non-woven fabrics by needling machine, the fibers in the web become tighter and thicker, and the penetration force gradually increases. As a result, the deflection of the bed will deepen continuously. The results of field test and finite element analysis show that the deflection caused by the penetration force is small under certain working conditions, and the downward bending deflection is within the allowable range, which can guarantee the fiber properties of high gram weight fiber web. Thus the production function of high gram weight nonwovens can be realized.

7. References
[1] Jianwei Ma and Shaojuan Chen 2008 Introduction to Nonwovens Technology [M] Beijing: China Textile & Apparel Press
[2] Zilong Tang 2012 Experimental Analysis of Dynamic Characteristics of Needle-punching Machine [D] Xi’an Polytechnic University
[3] Jianghong Cui, Haipeng Liu, Guohong Bing, Xiaojing Du, Zhiguang Wang and Qinghe Xiao 2017 Research status and development trend of nonwoven needle-punch technology[J] Shanghai Textile Science & Technology45(11):1-4
[4] Xiao Zhou 2012 Development of HeavyNeedlingMachine for High Gram WeightBlanket[J] East China Pulp& Paper Industry43(05):50-53
[5] Le Wang and Muchun Yu 2018 Effect of Axial Force on the Lateral Vibration Characteristics of Timoshenko Beam Under Free Boundary Condition[J] Journal of Ordnance Equipment Engineering 39(03):36-39
[6] Cundong Xu, Lianying Ding, Yanan Wang, Junkun Nie, Qinyu Wen and Rongrong Wang 2016 Research on Vibration Source Identification of Pressure Pipeline Based on DASP at Large Pump Stations[J]China Rural Water and Hydropower2016(12):172-175