Dynamic modelling and analysis of super-high acceleration macro-micro-macro movement platform

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Abstract. In microelectronics manufacturing industry, to obtain the high-acceleration of Marco-micro movement platform was very crucial and difficult. In this paper, a new macro-micro-macro movement platform is described. In addition, by the analysis of its driving principle, nine simplified dynamic models and dynamic equations under different motion conditions are established respectively. In different driving modes (single VCM driving mode, double VCMs reverse driving mode and double VCMs same driving mode, respectively), the displacement and velocity of floating stator, macro system and micro system was calculated, respectively. These results imply that the macro-micro-macro movement platform takes a periodic reciprocating motion and the max displacement and velocity of floating stator, macro system and micro system make different change rules, respectively. It concluded that the floating stator effectively isolating the vibration of macro-micro-macro movement platform.

1. Introduction

Microelectronics manufacturing industry has played vital role in the developing level of science and technology of a country [1, 2]. In the microelectronics manufacturing field, the macro-micro movement platform is a vitally important equipment, and it is usually used to obtain the high-acceleration and super-precision positioning motion. However, the rapid enhancement of acceleration is difficult to be obtained, which cannot meet the fast development of high and new technology and the rapid rise of market demand. Therefore, it is very necessary to improve the acceleration of the macro-micro movement platform [3]. In many areas, the concept of “macro + micro” by single VCM and PZT has been widely used in the motion platform to effectively deal with the discrepancy of high-acceleration and super-precision positioning [4-7]. The macro-micro movement platform was established by the Harbin Institute of Technology, which can obtain the acceleration of 5 g and precision of ± 21 nm [8]. Heui etc has studied the research of macro-micro system by single VCM to obtain the repeat positioning accuracy of 19 nm and the acceleration of macro-micro system is increased by more than ten times [9]. Obviously, the single VCM and PSA are widely used in some macro-micro movement platforms to acquire the high acceleration [10-11]. But, the VCM usually provides a certainly-maximum output force. And the acceleration of motion platform cannot exceed the maximum acceleration to realize the ultra-high acceleration. Accordingly, the acceleration breakthrough is often at stagnant phase, and some main obstacles for further development of microelectronics manufacturing
industry.

To achieve the high acceleration of macro-micro movement platform, the “macro + micro + macro” drive mode is established. Through the research on the macro-micro movement platform, the macro-micro-macro movement platform is proposed to explore the acceleration breakthrough. In this paper, the motion platform is realized by two VCMs and single PZT, and it is preliminarily built according to related performance indexes and working conditions. Overall structure of the paper is arranged as follows: initially, a macro-micro-macro movement platform of super-high acceleration with double floating stator stage is introduced. Secondly, different driving modes are built, and dynamic theoretical analysis by different dynamic models of macro-micro-macro movement platform is established. In addition, some related performance indexes of macro-micro-macro movement platform are simulated. Finally, the conclusion is given.

2. Description of ultra-high acceleration macro-micro-macro movement platform

Using the concept of macro-micro-macro (MMM), a new movement platform is provided to obtain ultra-high acceleration. And the super-high acceleration of macro-micro-macro movement platform is obtained by the two same VCMs and floating stators and the random vibration is occurred, as shown in figure 1. Generally, two same VCMs are installed on the base, which join macro movement platform being installed on the output coils by connection arms. Two same floating stator platforms are applied in macro-micro-macro movement platform to reduce or isolate vibration between VCMs and bases, which consisted of damper, stopper, floating lock, spring, limiter, subbase, buffer device etc. peculiarly, in order to obtain different super-high acceleration, the different motion modes can adjust the quantity of output force. As the flexure hinge mechanism has some advantages of no friction, no clearance, high resolution, etc. and the PZT drive the flexure hinge mechanism can obtain an ultra-precision position. Through different VCMs driving control modes, the acceleration of macro-micro-macro movement platform can increase by more than ten times to achieve the goal of the super-high acceleration. By the coarse reading head reading and coarse grating ruler, the microscale localization will be more rapidly obtained. Simultaneously, the nanoscale localization is confirmed by fine reading head reading and fine grating ruler. The difference between microscale and nanoscale localization can be counted. In addition, the stator buffer device consisting of springs, damper and stopper and so on, can be used to reduce the vibration, and the PZT is used to reduce errors and achieve a super-precise positioning. Double stator buffer devices are located at the front and rear of two VCMs. The Macro-micro-macro movement platform is located at the base.

![Figure 1. Structures of macro-micro-macro movement platform.](image)

3. Dynamic theoretical analysis of macro-micro-macro movement platform

According to the macro-micro-macro movement platform proposed in this paper, it mainly includes macro system and micro system. By analyzing its transmission form, the macro-micro-macro movement platform is equivalent to a mass-spring-dashpot system. In addition, according to the structural characteristics of the macro-micro-macro movement platform, three motion conditions are listed: fixed stator mode, fixe-floating stator mode, and floating stator mode. And then, according to the driving mode of VCMs and PZT, it can be divided into nine motion conditions. Through the
3.1. Dynamic theoretical analysis of macro-micro-macro movement platform using fixed stator

In fixed stator mode, it can be a linear second-order system including three motion conditions: single VCM driving mode, double VCMs reverse driving mode, double VCMs same driving mode. Simplified dynamic models are obtained as shown in figures 2-4, respectively. Its system kinetic equations are established as shown in equations (1)-(3), respectively. From equation (1) to equation (9), \( m_0, m_1 \) and \( m_2 \) is the equivalent mass of floating stator, macro system and micro system, respectively; \( k_0, k_1 \) and \( k_2 \) is the equivalent stiffness of floating stator, macro system and micro system, respectively; \( c_0, c_1 \) and \( c_2 \) is the equivalent damping of floating stator, macro system and micro system, respectively; \( F_1, F_2, \) and \( F_3 \) is the input force of VCM1, VCM2 and PZT, respectively; and \( x_0, x_1 \) and \( x_2 \) is the displacement of floating stator, macro system and micro system, respectively.

\[
\begin{align*}
\begin{cases}
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2 \\
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2
\end{cases}
\end{align*}
\tag{1}
\]

\[
\begin{align*}
\begin{cases}
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2 \\
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2
\end{cases}
\end{align*}
\tag{2}
\]

\[
\begin{align*}
\begin{cases}
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2 \\
m_2\ddot{x}_2 + 2c_2(\ddot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2
\end{cases}
\end{align*}
\tag{3}
\]

Figure 2. Simplified dynamic model of single VCM driving mode with fixed stator.

Figure 3. Simplified dynamic model of double VCMs reverse driving mode with fixed stator.

Figure 4. Simplified dynamic model of double VCMs same driving mode with fixed stator.

Figure 5. Simplified dynamic model of the single VCM driving mode with single fixed stator and single floating stator.
3.2. Dynamic theoretical analysis of macro-micro-macro movement platform using single fixed stator and single floating stator

In fixed-floating stator mode, it can be a linear second-order system including three motion conditions: single VCM driving mode, double VCMs reverse driving mode, double VCMs same driving mode. Simplified dynamic models are obtained as shown in figures 5-7, respectively. Its system kinetic equations are established as shown in equations (3)-(5), respectively.

\[
\begin{align*}
\begin{aligned}
m_0\ddot{x}_0 + 2c_0\dot{x}_0 - c_1(\dot{x}_1 - \dot{x}_0) + 2k_0x_0 - k_1(x_1 - x_0) &= -F_1 \\
m_1\ddot{x}_1 + c_1(2\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + k_1(2x_1 - x_0) - 2k_2(x_2 - x_1) &= F_1 - F_2 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) &= F_2
\end{aligned}
\end{align*}
\]

(4)

\[
\begin{align*}
\begin{aligned}
m_0\ddot{x}_0 + 2c_0\dot{x}_0 - c_1(\dot{x}_1 - \dot{x}_0) + 2k_0x_0 - k_1(x_1 - x_0) &= -F_1 - F_3 \\
m_1\ddot{x}_1 + c_1(2\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + k_1(2x_1 - x_0) - 2k_2(x_2 - x_1) &= F_1 - F_2 + F_3 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) &= F_2
\end{aligned}
\end{align*}
\]

(5)

\[
\begin{align*}
\begin{aligned}
m_0\ddot{x}_0 + 2c_0\dot{x}_0 - c_1(\dot{x}_1 - \dot{x}_0) + 2k_0x_0 - k_1(x_1 - x_0) &= -F_1 + F_3 \\
m_1\ddot{x}_1 + c_1(2\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + k_1(2x_1 - x_0) - 2k_2(x_2 - x_1) &= F_1 - F_2 - F_3 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) &= F_2
\end{aligned}
\end{align*}
\]

(6)

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure6.png}
\caption{Simplified dynamic model of the double VCMs same driving mode with single fixed stator and single floating stator.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure7.png}
\caption{Simplified dynamic model of the double VCMs reverse driving mode with single fixed stator and single floating stator.}
\end{figure}

3.3. Dynamic theoretical analysis of macro-micro-macro movement platform using double floating stator

In floating stator mode, it can be a linear second-order system including three motion conditions: single VCM driving mode, double VCMs reverse driving mode, double VCMs same driving mode. Simplified dynamic models are obtained as shown in figures 8-10, respectively. Its system kinetic equations are established as shown in equations (7)-(9), respectively.

\[
\begin{align*}
\begin{aligned}
2m_0\ddot{x}_0 + 4c_0\dot{x}_0 - 2c_1(\dot{x}_1 - \dot{x}_0) + 4k_0x_0 - 2k_1(x_1 - x_0) &= -F_1 \\
m_1\ddot{x}_1 + 2c_1(\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_1(x_1 - x_0) - 2k_2(x_2 - x_1) &= F_1 - F_2 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) &= F_2
\end{aligned}
\end{align*}
\]

(7)

\[
\begin{align*}
\begin{aligned}
2m_0\ddot{x}_0 + 4c_0\dot{x}_0 - 2c_1(\dot{x}_1 - \dot{x}_0) + 4k_0x_0 - 2k_1(x_1 - x_0) &= -F_1 - F_3 \\
m_1\ddot{x}_1 + 2c_1(\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_1(x_1 - x_0) - 2k_2(x_2 - x_1) &= F_1 + F_3 - F_2 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) &= F_2
\end{aligned}
\end{align*}
\]

(8)
\begin{equation}
\begin{cases}
2m_0\ddot{x}_0 + 4c_0\dot{x}_0 - 2c_1(\dot{x}_1 - \dot{x}_0) + 4k_0x_0 - 2k_1(x_1 - x_0) = -F_1 + F_3 \\
m_1\ddot{x}_1 + 2c_1(\dot{x}_1 - \dot{x}_0) - 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_1(x_1 - x_0) - 2k_2(x_2 - x_1) = F_1 - F_3 - F_2 \\
m_2\ddot{x}_2 + 2c_2(\dot{x}_2 - \dot{x}_1) + 2k_2(x_2 - x_1) = F_2
\end{cases}
\end{equation}

Figure 8. Simplified dynamic model of the single VCM driving mode with double floating stator.

Figure 9. Simplified dynamic model of the double VCMs same driving mode with double floating stator.

Figure 10. Simplified dynamic model of the double VCMs reverse driving mode with double floating stator.

4. Results and discussion
The reference values of kinetic parameters are shown in table 1. Equations (1)-(9) are converted to the matrix equation as follows:

\begin{equation}
MX + CX + KX = F
\end{equation}

**Table 1.** The values of dynamic parameters.

| m_0 (kg) | k_0 (N/m) | c_0 (N s/m) | m_1 (kg) | k_1 (N/m) | c_1 (N s/m) | m_2 (kg) | k_2 (N/m) | c_2 (N s/m) |
|----------|-----------|-------------|----------|-----------|-------------|----------|-----------|-------------|
| 13       | 2.8x10^7  | 0.02        | 0.942    | 6.6x10^7  | 0.05        | 1.227    | 2.8x10^7  | 0.02        |

Defined \( F = 0 \) and \( C = 0 \), the equation (10) can be converted by equation (11):

\begin{equation}
MX + KX = 0
\end{equation}

So, in different motor mode, by the values of table 1 and equation (11), the natural frequency of movement platform can be calculated. In fixed stator mode, the system’s natural frequency are 596 Hz and 1825 Hz respectively, and in fixed-floating stator mode, the system’s natural frequency are 941 Hz, 941 Hz and 2371 Hz respectively, and in floating stator mode, the system’s natural frequency are 886 Hz, 886 Hz and 2345 Hz respectively. Therefore, they are far less than the driver frequency of PZT (20 kHz). The results indicate that the motion platform cannot appear the resonance, and the system of motion platform can be regard as a rigid body motion system.

Identified \( F_1 = 300 \) N, \( F_2 = 3000 \) N and \( F_3 = 100 \) N, respectively, the displacement and velocity of
macro-micro-macro motion platform are obtained by MATLAB. In different driving modes (single VCM driving mode, double VCMs reverse driving mode and double VCMs same driving mode, respectively), the displacement and velocity of floating stator, macro system and micro system are shown in figures 11-13, respectively. These results imply that the system takes a periodic reciprocating motion. In different VCM driving modes (single VCM driving mode, double VCMs reverse driving mode and double VCMs same driving mode, respectively) with fixed stator, the max velocity of macro system and micro system nearly reached at 1.1988 m/s and 1.9054 m/s, respectively. In addition, the max displacement and max velocity of macro system and micro system gradually increases by different VCM driving modes. In different VCM driving modes (single VCM driving mode, double VCMs reverse driving mode and double VCMs same driving mode, respectively) with fixed-floating stator, the max velocity of floating stator, macro system and micro system nearly reached at 0.5249 m/s, 1.1002 m/s and 1.8315 m/s, respectively.

![Figure 11](image1.png)

**Figure 11.** The displacement (a) and velocity (b) of driving modes with fixed stator.

![Figure 12](image2.png)

**Figure 12.** The displacement (a) and velocity (b) of driving modes with single fixed stator and single floating stator.

Meanwhile, by different VCM driving modes, the max displacement of floating stator and macro system gradually decreases firstly and then increases, reversely, the max displacement of micro system gradually increases firstly and then decreases, and the max velocity of floating stator, macro system and micro system gradually increases firstly and then decreases. In different VCM driving modes (single VCM driving mode, double VCMs reverse driving mode and double VCMs same driving mode, respectively) with floating stator, the max velocity of floating stator, macro system and micro system nearly reached at 0.5676 m/s, 0.9412 m/s and 1.8488 m/s, respectively.
By different VCM driving modes, the max displacement of floating stator and micro system gradually decreases at firstly and then increases; reversely, and the max displacement of macro system gradually decreases. In addition, the max velocity of floating stator and micro system gradually increases firstly and then decreases. However, the max velocity of macro system gradually decreases firstly and then increases. By compared with the max velocity of floating stator, macro system and micro system, respectively, it indicated that floating stator nearly weaken the vibration of macro-micro-macro movement platform in same driving modes.

5. Conclusion

In this paper, a new macro-micro-macro movement platform is provided. Its different dynamic models were obtained by different VCM driving modes. By the simulation results, it can be concluded that the macro-micro-macro movement platform takes a periodic reciprocating motion and the floating stator nearly isolates the vibration of macro-micro-macro movement platform.

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