Abstract—The solar energy is converted to electric energy on solar cell. While the solar cell is manufactured, the solar cell manipulator transports the solar cell in each process. The manipulator picks and places the solar cell on its forks. The size of solar cell is growing larger to convert more solar energy to electric energy. Manipulator forks need to get larger corresponding to the size and operate stably for accurate positioning. In this study, a program is developed to create and control a multi-body dynamics model of solar cell manipulator. The flexible multi-body dynamics model is created using the developed program. The model contains multi-body dynamics model and control model. Though two models are analyzed separately, some parameters are shared by each model to integrate the models.

Keywords—Solar cell manipulator, Multi-body dynamics, Flexible link, Control model

I. INTRODUCTION

The solar energy which is one of alternative energy converted to electric energy on a solar cell. The solar energy makes electron on solar cell move to electrode and the movement of electron is converted to electric energy. The solar cell is produced on a glass substrate using silicon crystal. The size of solar cell is growing larger by generation to produce more electric energy. In manufacturing process, the solar cell is transferred by manipulator on its fork. When the solar cell glass was small, the characteristic of forks was not so important. However, as the generation of solar cell is progressed, the length of fork gets longer to cover the size of solar cell glass. So deflection, vibration, weight and other characteristic of fork is gradually taken into consideration because these problems may cause error of positioning of manipulator. In this study, a program to investigate the characteristic of solar cell manipulator is developed. A flexible multi-body dynamics model with position control is created using the developed program. The manipulator has large rotational or translational operation. Relatively the fork has small deformation on its tip. So floating frame of reference frame method (FFRF) is used to present the flexible body.[1-5] The displacement of the solar cell manipulator and deflection of manipulator fork is analyzed while the manipulation is operation in normal condition. The result is compared to the commercial flexible multi-body dynamics analysis program to verify the developed program. The tip of manipulator fork should converge to stable state quickly. If not, the time for one cycle in normal operating condition would increase and it may result in poor productivity. State-space equation of fork is derived and control force equation is defined using gains. The force equation is applied to the developed program for accurate positioning of manipulator fork.[6-8]

II. FLEXIBLE MULTI-BODY DYNAMICS MODEL OF SOLAR CELL MANIPULATOR

Fig.1 shows the solar cell manipulator. The multi-body dynamics model of solar cell manipulator is composed of rigid bodies and flexible bodies. Most of the bodies are assumed to be rigid bodies as they have small deformation that can be neglected. However, the fork of the solar cell manipulator is
very long with relatively small cross-section area. The forks have deflection due to weight of itself and solar cells. Also the fork vibrates while the manipulator translates or rotates. So the fork model is treated as a flexible body. Table 1 shows the information of flexible multi-body dynamics model of solar cell manipulator. One end of the forks is fixed on the manipulator and another end is free. So the forks are assumed to be cantilever beam model. Table 2 shows the material property and geometry information of the fork.

Fig. 2 shows the coordinate system of deformable body. The position of an arbitrary point \( P \) on the body is written in the following equations,

\[
\begin{align*}
\mathbf{r}_P &= \mathbf{R}^i + A^i \mathbf{u}_i^o + A^i (\mathbf{u}_i^f + \mathbf{u}_f) \\
&= \mathbf{R}^i + A^i (\mathbf{u}_o^f + S \mathbf{q}) 
\end{align*}
\]  

(1)

The mass matrix of deformable body is derived from kinetic energy of deformable body.

\[
\begin{align*}
\mathbf{T}^i &= \frac{1}{2} \int_{V^i} \rho^i \dot{\mathbf{r}}^i \dot{\mathbf{r}}^i dV^i \\
&= \frac{1}{2} \dot{\mathbf{q}}^i \mathbf{M}^i \dot{\mathbf{q}}^i 
\end{align*}
\]  

(2)

The virtual work caused by the elastic force is written as,

\[
\begin{align*}
\mathbf{\delta W}^i &= -\int_{V^i} \sigma^i \mathbf{e} \mathbf{e}^T dV^i \\
&= -\mathbf{R}^f \mathbf{T}^f \mathbf{q}^f \mathbf{T}^f \mathbf{q}^f \left[ \begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_f \end{array} \right] \mathbf{q}^f 
\end{align*}
\]  

(3)

Considering external force and quadratic velocity vector, the equation of motion is written as,

\[
\begin{align*}
\begin{bmatrix} m_{xx} & m_{yx} & m_{zx} \\ m_{yx} & m_{yy} & m_{zy} \\ m_{zx} & m_{zy} & m_{zz} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{R}}^i \\ \mathbf{\dot{\theta}}^i \\ \dot{\mathbf{q}}^f \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \mathbf{\dot{\theta}}^i + \begin{bmatrix} \mathbf{C}_R^T \\ \mathbf{C}_\theta^T \\ \mathbf{C}_q^T \end{bmatrix} \lambda \\
\begin{bmatrix} (Q_x) \n_i \\ (Q_y) \n_i \\ (Q_z) \n_i \\ (Q) \n_i \end{bmatrix} + \begin{bmatrix} (Q_x) \n_f \\ (Q_y) \n_f \\ (Q) \n_f \end{bmatrix} \\
\end{align*}
\]  

(4)

When the equation of motion is derived, the appropriate boundary condition needs to be enforced for the finite element approximation of the deformation. One end of the fork of the manipulator is fixed on the manipulator and another end is free. Fig. 3 shows the tip displacement of manipulator fork when only gravity is applied as external force in static state. Fig. 4 shows the dynamic deflection of fork when an arbitrary damping ratio is applied to make fork converge. The result is almost same compared to structural dynamics analysis program, so the developed program is reliable. Using the developed program, simulation is carried out by manipulator trajectory.
Fig 5. Displacement of manipulator fork in motion

Fig 6. Block diagram of the active control logic

To apply the state-space control approach to the system, Eq. 5 can be written in state-space form,

\[
\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_z \\ \dot{q}_z \end{bmatrix} = \begin{bmatrix} -[m_z]^{-1} [k_z] \\ [f] \end{bmatrix} q + \begin{bmatrix} -[m_z]^{-1} [\psi] \end{bmatrix} \begin{bmatrix} \Lambda \end{bmatrix}^T \mathbf{u}_c \\
\begin{bmatrix} A_q \\ B_q \end{bmatrix} \mathbf{u}_c
\]

(6)

The control force is defined and calculated as,

\[
\mathbf{u}_c = -[G_z] q - \left[\begin{bmatrix} \Lambda \end{bmatrix}^T \begin{bmatrix} [g_z] \end{bmatrix} \right] \mathbf{q} = \left(\begin{bmatrix} \Lambda \end{bmatrix}^T \begin{bmatrix} [g_z] \end{bmatrix} \right) \mathbf{q}
\]

(7)

Two gains are related to damping ratio and stiffness of the system. One gain related to stiffness is set to zero to keep the same system natural frequency. So the control force is calculated using only a gain related to damping ratio.

In this study, the gains are calculated using desired eigenvalues. Two arbitrary gain is applied to change the desired eigenvalue. The location of real part of pole in s-plane means the stability of a system. And it also represents the desired eigenvalues. As the pole is far from the imaginary axis of s-plane, the system is stable. So the real part of pole is moved to minus direction. The imaginary part is not changed to keep same system natural frequency. Fig. 7 shows pole positions of the system used to apply control strategy.

The control model analysis is carried out when the manipulator has no motion. The only the fork has deflection due to gravity. Fig. 8 shows the tip displacement of the manipulator fork. When the control strategy is not applied, the tip of fork keeps vibrating. However, as the gain becomes larger, the result converges more quickly.
IV. CONCLUSION

In this study, a flexible dynamics and control analysis program is developed. The multi-body dynamics model contains flexible forks of the solar cell manipulator. The flexible body model is analyzed using FFRF method. The deflection of manipulator fork is calculated to verify the developed program by comparing to structural dynamics analysis program. Dynamics deflection analysis of the solar cell manipulator in manufacturing process is carried out. For the accurate positioning of fork while the manipulator operates by trajectory, a model based control is applied. The simulation is carried out when the manipulator has no motion. The result shows that tip converge quickly and the control strategy is adequate. In future work, the control will be applied when the multibody dynamics model operateing by trajectory.

REFERENCES


