Parameter identification of additional forces and torques for simulated space manipulator in zero-g simulation system

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Abstract. In this paper, the strain expressions of a manipulator arm are established. The strain expressions affected by gravity, suspension force and torque are considered as well. The arm model is simplified as a cantilever beam, which makes the derivation more concise. In addition, the strain gauges are set on the arm to collect the strain data when the manipulator operates. The parameters of additional forces and torques are identified. And the fitting curve is very close to the experimental data.

1. Introduction

The space manipulator is one of the most important equipment on the space station. It can achieve a variety of on-orbit servicing missions, such as mounting the components, repairing the equipment, and assisting the astronauts in space walking [1-2]. To guarantee the safety and reliability on orbit, the space manipulator should pass all the verification tests in a zero-g simulation system on ground [3-4]. The zero-g simulation system should simulate the zero-g environment in space and allow movements of the manipulator in a safety condition. Before the tests of the space manipulator, a simulated manipulator, which has a much lower cost, is designed [5]. It replaces the space manipulator for the initial tests, which can consummate the simulation system and guarantee the safety of the space manipulator experiments. The simulated manipulator has the same mass and barycenter with the space one, while the materials and structure are different [6]. It will have some deviations between the space and simulated manipulators. Therefore, it is important to establish the theoretical model of the manipulator. Gong et al. [7] used ANSYS software to analyze and simulate a uniform strength beam with different forces. Frieler et al. [8] used strain gauges to measure the strain induced by the force on the flexure member of the sensor and found the relationship between the force and the measured strain. Bolandi et al. [9] presented a full nonlinear model of a single link flexible manipulator based on extended Hamilton-assumed mode method. Zhang et al. [10] simplified the dynamic equations of a flexible manipulator to a series of linear equations based on the Euler-Bernoulli beam theory and then obtained the beam strain feedback. In this paper, the force analysis is complex. It is difficult to derive the expressions by theoretical calculation. Therefore, we can make some experiments to collect the experimental data. Then the unknown parameters can be identified and the theoretical model can be completed.

In this paper, the strain expressions of the simulated manipulator arm are established. The strain expressions affected by gravity, suspension force and torque are considered as well. Furthermore, the
parameters of additional forces and torques are identified. The paper is organized as follows. In Section 2, the arm of the simulated manipulator is introduced and the strain analysis is conducted. In Section 3, the strain experiments are presented and the data is collected. The parameters of additional forces and torques are identified in Section 4. Conclusions are drawn in Section 5.

2. Strain analysis of simulated manipulator arm

The simulated manipulator is designed according to the space manipulator. It is a 6-DoF (Degree of Freedom) serial robot. It has seven rotary joints, two end effectors, two arms and a central controller, shown in Figure 1. The components are mounted symmetrically.

Figure 1. Structure of the simulated manipulator.

The arm of space manipulator is a carbon fiber cylinder. To reduce manufacturing costs, the arm of simulated manipulator is made of aluminum alloy. It is designed as a cage structure, shown in Figure 2. It has eight aluminum alloy profile beams and six flanges. To simplify the calculation, the arm can be considered as a cantilever beam which is fixed at one end. The suspension force is straight up and its point of action is at the other end of the arm. A coordinate \(\{O-XYZ\}\) is attached to the arm, whose origin is in the center of the fixed flange, X-axis overlaps the center axis and the Y-axis is straight up.

Figure 2. Computer model of simulated arm.

Because of the special design of simulated arm, the mass is uneven. The mass is concentrated on the flanges. The mass distribution is shown in Figure 3. The number on the X-axis are the locations where the flanges are installed.
Figure 3. Mass distribution of space and simulated arm.

It will have elastic deformation when the arm is affected by external force. The deformation will affect the joint torques. Therefore, it is necessary to establish the strain model of the arm. The aluminum alloy profile beam of the arm can be considered as a cantilever beam. So it can be simplified as a linear system, which conforms to the superposition principle. Assume that the actual strain expression of the beam \( i \) is \( \varepsilon_{0i}(x) \), the strain due to gravity is \( \varepsilon_{Gi}(x) \), the strain due to the suspension force is \( \varepsilon_{Fi}(x) \), the strain due to the 1N·m X-axis torque is \( \varepsilon_{Mi}(x) \). They satisfy the following equation:

\[
\varepsilon_{0i}(x) = \varepsilon_{Gi}(x) + a\varepsilon_{Fi}(x) + b\varepsilon_{Mi}(x)
\]

(1)

Where \( a \) means the ratio of suspension force to gravity, \( b \) means the value of torque.

We assume that the flanges are not installed. When the beam is only affected by gravity, according to the torque equilibrium, we can get the torque equation along the \( x \) direction:

\[
2\varepsilon_{Gi}(x) + 2\varepsilon_{Mi}(x) = -G M l
\]

(2)

Where \( G \) is the gravity of the arm, \( l \) is the length of the arm.

The small deflection differential equation of the beam can be written as:

\[
\frac{d^2\omega}{dx^2} = -\frac{M(x)}{EI}
\]

(3)

Where \( E \) is Young's modulus, \( I \) is the inertia torsion moment of the cross section of the beam, \( \omega \) is the small deflection.

By substituting Equation 2 to Equation 3, and calculating the integral:

\[
EI\omega = \frac{G}{24l}(l-x)^4 + Cx + D
\]

(4)

For we consider it as a cantilever beam, the boundary condition can be written as:

\[
x = 0, \quad \omega = 0; x = 0, \quad \theta = \frac{d\omega}{dx} = 0
\]

(5)

By substituting the boundary condition to Equation 4, we can calculate \( C \) and \( D \):

\[
C = \frac{Gl^2}{6}, \quad D = \frac{Gl^2}{24}
\]

(6)

Bring the result to Equation 4, the deflection curve equation of gravity can be obtained:

\[
\omega_{Gi}(x) = \frac{G}{24ELl}(x^4 + 6l^2x^2 - 4lx^3)
\]

(7)

Similarly, the deflection curve equation of suspension force \( F \) can be obtained as well:

\[
\omega_{Fi}(x) = \frac{F}{6El}(x^3 - 3lx^2)
\]

(8)

The expression of strain and deflection is:
\[ \varepsilon = -y \frac{d^2 \omega}{dx^2} \]  

Equation (9)

Where \( y \) is the y-coordinate of the beam.

Therefore, the strain of gravity and suspension force can be expressed as:

\[ e_g(x) = \frac{Gy}{24EI}(12x^2 - 24lx + 12l^2) \]
\[ e_{fy}(x) = \frac{F_{fy}}{EI}(x - l) \]  

Equation (10)

The cross section of the beam is simplified as a square whose side length is \( a_s \). When the beam is only affected by torque \( M_x \), the expression of shear stress at the midpoint of the edge line is:

\[ \tau = \frac{M_x}{0.208a_s^3} \]  

Equation (11)

\( \nu \) is Poisson's ratio of aluminum alloy, the strain of torque can be expressed as:

\[ e_{S}(x) = -\nu \frac{\tau}{E} = -\frac{\nu M_x}{0.208a_s^3E} \]  

Equation (12)

3. Strain experiment of arm

We number four of the beams from 1 to 4, shown in Figure 4, and place the strain gauges on these four beams. Considering the interference of data collecting, the strain gauges should be placed on the maximum strain locations of the beam. To make the curve more accurately, the gauges should be maintained in an appropriate distance. The x coordinates we choose are 0.115mm, 0.315mm, 0.836mm, and 0.936mm. The locations of the strain gauges are show in Figure 4.

![Figure 4. Beam number of simulated arm.](image)

The strain gauges are collected in the direction of Y-axis strain. Before the experiment begin, the data returns to zero. Due to the complicated deformation of the manipulator, we only consider the additional torque when it returns to the original state. The strain curves are illustrated in Figure 5, which contains 16 text points in 4 beams. The result shows that, after returning to the original position, the arm has great deformation. The final strain on beam 1 and 3 are negative and it on beam 2 and 4 are positive. The average value of strain in last 10 seconds are calculated, shown in Table 1.

| Beam number\Location | a (με) | b (με) | c (με) | d (με) |
|----------------------|--------|--------|--------|--------|
| 1                    | -40.68 | -10.95 | -57.26 | -31.60 |
| 2                    | 71.44  | 22.78  | 61.19  | 41.98  |
| 3                    | -61.59 | -19.89 | -55.83 | -36.46 |
| 4                    | 68.64  | 17.30  | 65.11  | 39.55  |

Table 1. Average value of strain in last 10 seconds.
4. Parameter identification of additional forces and torques

What we should do are identify the parameter $a$ and $b$ in Equation 1 and fit the curve approximates to the experimental data as much as possible. Take beam 1 as an example.

We use ANSYS to conduct the strain analysis and plot the strain curves. Then, according to the simulating data, the parameters in the strain equations of the beam only affected by gravity, suspension force, and torque can be calculated. The strain equations can be written as follow:

$$\varepsilon_{gi}(x) = a_1 x^2 + b_1 x + c_1$$
$$\varepsilon_{fi}(x) = a_2 x + b_2$$
$$\varepsilon_{mi}(x) = a_3 x + b_3$$

(13)

Where $\varepsilon_{gi}(x)$ is a quadratic function, $\varepsilon_{fi}(x)$ and $\varepsilon_{mi}(x)$ are linear functions, as we derived in Section 2. $a_1$, $a_2$, $a_3$, $b_1$, $b_2$, and $c_1$ are the coefficients of the equations.

Because of the flanges, the strain curves will be presented piecewise variation. We fit the curves in these 5 intervals separately. The fitting parameters are shown in Table 2 and the fitting curves are shown in Figure 6.

Table 2. Fitting parameters of strain equations.

|                | 1      | 2      | 3      | 4      | 5      |
|----------------|--------|--------|--------|--------|--------|
| 2nd-order $a_1$ ($\times 10^{-3}$) | 0.0478 | 0.0465 | 0.0457 | 0.0438 | 0.0394 |
| 1st-order $b_1$ ($\times 10^{-3}$) | -0.4843| -0.4061| -0.3905| -0.3666| -0.3232|
| Const. term $c_1$ ($\times 10^{-3}$) | 0.2462 | 0.4138 | 0.5678 | 0.6468 | 0.6272 |
| 2nd-order $a_2$ ($\times 10^{-3}$) | 0.2414 | 0.2190 | 0.2194 | 0.2189 | 0.2423 |
| Inter. $b_2$ ($\times 10^{-3}$) | -0.1640| -0.2830| -0.4282| -0.5716| -0.7819|
| 2nd-order $a_3$ ($\times 10^{-3}$) | 0.647  | 0.637  | 0.633  | 0.634  | 0.627  |
| Inter. $b_3$ ($\times 10^{-3}$) | -0.250 | -0.695 | -1.15  | -1.60  | -2.03  |
By substituting the fitting strain to Equation 1, the expression can be written as:

\[
-40.68 \times 10^6 = \varepsilon_{G1}(0.115) + a\varepsilon_F(0.115) + b\varepsilon_M(0.115) \\
-10.95 \times 10^6 = \varepsilon_{G1}(0.315) + a\varepsilon_F(0.315) + b\varepsilon_M(0.315) \\
-57.26 \times 10^6 = \varepsilon_{G1}(0.837) + a\varepsilon_F(0.837) + b\varepsilon_M(0.837) \\
-31.6 \times 10^6 = \varepsilon_{G1}(0.937) + a\varepsilon_F(0.937) + b\varepsilon_M(0.937)
\] (14)

By quadratic regression method, \(a=1.15\) \(b=40\) can be calculated. Thus, Equation 1 will be:

\[
\varepsilon_{gf}(x) = \varepsilon_{G1}(x) + 1.15 \times \varepsilon_F(x) + 40 \times \varepsilon_M(x)
\] (15)

The Parameter \(a\) means the suspension force is 1.15 times larger than the gravity. The parameter \(b\) means the torque in the end of the beam is 40 N·m. Considering these three strains, the fitting curve is illustrated in Figure 7.

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**Figure 6.** Fitting curves of strain.
5. Conclusion
In this paper, the strain expressions of a manipulator arm were established. The strain affected by gravity, suspension force and torque were considered as well. Different from the arm of space manipulator, the simulated arm has a cage structure, which made the problem more complex. So we simplified the arm as a cantilever beam, which made the derivation more concise.

In addition, we placed the strain gauges in four beams to collect the strain data when the manipulator operated. We can find that after the arm returned to the original position, it still had great deformation. The deformation is resulting from the additional joint torque and the suspension force. We identified the parameters of additional forces and torques. The fitting curve was very close to the experimental data.

In the future experiments involving the actual space manipulator, we can predict the additional forces and torques. It can guarantee the safety of the experiments.

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References
[1] Flores-A A, Ma O, Pham K, et al 2014 A review of space robotics technologies for on-orbit servicing Progress in Aerospace Sciences 68 1-26
[2] Ellery A, Kreisel , Sommer B 2008 The case for robotic on-orbit servicing of spacecraft: Spacecraft reliability is a myth Acta Astronautica 63 632-648
[3] Dengyun Y U 2007 Suggestion on Development of Chinese Space Manipulator Technology Spacecraft Engineering
[4] Cardenas R, Pea R, Clare J, et al 2001 Analytical and Experimental Evaluation of a WECS Based on a Cage Induction Generator Fed by a Matrix Converter Energy Conversion IEEE Transactions 26(1) 204-215
[5] Tian S, Tang X, Xiang C 2017 Equivalence Analysis of Mass and Inertia for Simulated Space Manipulator Based on Constant Mass Machines 31-40
[6] Tian S, Tang X , Li Y 2019 Analysis and Evaluation on Unloading Ratio of Zero-g Simulation System Based on Torques of Space Manipulator Robotica 1-14
[7] Cao C, Gong H, Song H, et al 2013 ANSYS simulation and experiment of the FBG cantilever strain sensor Optical Communication Technology 037(003) 12-14
[8] Frieler T, Groll R 2018 A torsional sub-milli-Newton thrust balance based on a spring leaf strain gauge sensor The Review of scientific instruments 89 7
[9] Bolandi H, Esmaeelzadeh S M 2008 Analytical modelling and nonlinear strain feedback control of a flexible robot ARM Automatic Control and Computer Sciences 42(5) 236-248
[10] Zhang T M, Liu Y W, Yan S Z, et al 1996 Comparative study on the acceleration feedback and the strain feedback of a flexible manipulator IEEE International Conference on Systems. IEEE