Parametric Study for Nonlinear Dynamic Behaviors using Integrated Cable Elongation Model of Cable Driven Parallel Robot

Sung-Hyun Choi and Kyoung-Su Park

Abstract—Polymer is one of the most widely used cable materials in the CDPR system due to its light weight and low inertia. However, it is not easily to achieve high accuracy because of the complicated response of polymer cable while CDPR is operated. In our previous study, the integrated dynamics model of cable was derived with the visco-elastic model. With the integrated dynamics model of cable, the parametric studies were carried out for the cable length, the applied force and the tensile rate for various nonlinear cable elongation behaviors. At first, dynamic creep behavior was defined and investigated in CDPR system. Dynamic creep was saturated with one value as the cyclic load/unload is continuously carried out. The saturation number was inversely proportional to the cable length because of the residual stress. And as the tensile rate was increased, the dynamic creep was decreased linearly. In long-term recovery, the long-term recovery is finished more quickly for the case of a shorter cable.

Index Terms—Integrated non-linear dynamic model, dynamic creep, hysteresis, short- and long- term recovery, hardening effect

I. INTRODUCTION

IN recent years, cable-driven parallel robots (CDPRs) have become popular due to their advantages over conventional link parallel robots, such as high sensitivity to movement, ease of maintenance and large workspace [1, 2]. To achieve the high sensitivity and large workspace, they have used 3 to 8 cable members. The polymer cable is one of the most widely used materials in the CDPR system due to its light weight and inertia. However, the complex responses of polymer cables make it difficult to operate CDPR systems with a high precision [3, 4]. Polymer cables have several important characteristics: hardening effects, creep, short- and long-term recovery, hysteresis and so on. When combined, these characteristics have a significant impact on position control. Even though many studies have tried to compensate these characteristics in static condition, they were not effective [5, 6].

In this study, we conducted the experimental studies and simulation to analyze the elongation characteristics on polymer cable for various cable lengths and tensile rates. In the first and second section of this paper, we describe the experiment and integrated non-linear dynamic model. Next, we report the

results of our parametric study for the design parameters which we mentioned above. Finally, the effect of parameters for the nonlinear cable elongation is evaluated for CDPR system.

II. EXPERIMENTAL SETUP AND CHARACTERISTICS OF THE POLYMER CABLE USED IN CDPR

A. Experimental setup

The parametric studies were based on tensile loading tests. We investigated the dynamic characteristics of a Dyneema polyethylene SK78 cable using a tensile tester. We applied forces of 100 N to the cables. As the end-effector pose is changed, the length of cable is changed. Thus, it is necessary to investigate the length effect of cable. Therefore, we used the two kinds of cable lengths (100 mm and 300 mm). And, constant tensile rates corresponding to CDPR speed are based on the 3 mm/min and 50 mm/min. Also, we measured a long-term recovery after rest times of 24, 48 and 72 hours

III. DYNAMIC CHARACTERISTICS OF POLYMER CABLE

The polymer cables used in CDPR have complex dynamic characteristics, including nonlinear elongation, hysteresis, creep, and short- and long-term recovery. Each characteristic interacts with each other while operating CDPRs. Hysteresis is the result of this interaction. In our previous research [7], the dynamics model was derived based on the visco-elastic model for time-dependent applied force not static force.

$$\varepsilon(t) = \left(\frac{F_f}{E_{1,c}A} \right)^{h(\varepsilon_{r-1})} - \frac{F_f}{E_{1,r}A} \quad (1)$$

$$+ \frac{\int_0^{t_{total}} F(t)dt}{t_{total}} \left(\frac{1}{E_{2,c}A} (1 - e^{-t_{total}/t_r}) + \frac{1}{\eta_0 A} - \frac{1}{E_{2,r}A} (1 - e^{-t_{total}/t_{r,1}}) \right) \quad (2)$$

Each parameter was defined in the [7]. Equation (1) is the strain equation for constant strain rate from 0 to t_{total} of loading/unloading time. The first term of equation (1) is a nonlinear elongation. And the second term is the time dependent dynamic creep and short time recovery. However, it is difficult to analyze the non-linear dynamic behavior for time-dependent applied force. Therefore, we were carried out the cyclic test and numerical simulation for case of constant

S.H. Choi is with the Gachon University, 1342 Seongnamdaero, Sujeong-gu, Seongnam-si, Gyeonggi-do, 461-701, Korea (e-mail: csh5974@gc.gachon.ac.kr)

K.S. Park is with the Gachon University, 1342 Seongnamdaero, Sujeong-gu, Seongnam-si, Gyeonggi-do, 461-701, Korea (e-mail: pks6348@gachon.ac.kr)

strain rate. For the case, equation (1) can be solved by calculating the loading and unloading time. To numerically resolve this problem, Newton-Raphson method is applied based on the condition that equation (1) is equal to (2) for constant strain rate. After then, the dynamic strains (Eqs. (3) and (4)) are derived using the predicted loading and unloading time for loading and unloading cases as following:

$$\varepsilon_{i-loading} = \left(\frac{F_f}{E_1 A} \right)^{h(\varepsilon_{i-1})} - \frac{\int_0^{t_{total}} F(t) dt}{t_{total}} \left(\frac{1}{E_2 A} (1 - e^{-t_{total}/t_c}) + \frac{1}{\eta_0 A} \right) \quad (3)$$

$$\varepsilon_{i-unloading} = \left(\frac{F_f}{E_1 A} \right)^{h(\varepsilon_{i-1})} - \frac{F_f}{E_{1,j} A} + \frac{\int_0^{t_{total}} F(t) dt}{t_{total}} \left(\frac{1}{E_2 A} (1 - e^{-t_{total}/t_c}) + \frac{1}{\eta_0 A} - \frac{1}{E_{2,j} A} (1 - e^{-t_{total}/t_{c,j}}) \right) - \frac{\Delta F}{E_{3,j} A} (1 - e^{-t_{total}/t_{r,j}}) \quad (4)$$

The equations contain the non-linear elongation as mentioned above. The model is divided into two cases, loading and unloading. Figure 1 shows the qualitative dynamic behavior of the cable based on this dynamic model. Sections in Fig. 1 are divided into five parts. Section ① shows the behavior of static elongation and dynamic creep. In section ②, cable has been hardened because of a residual stress. So, the gradient becomes stiff. Section ③ shows the effect of time dependent-dynamic creep while progressing the loading cycle. Section ④ shows the unloading process. When the cable is unloaded, the short-term recovery and dynamic creep occurs simultaneously. And then, the cable remains unloading state. The long term recovery dominantly occurred like ⑤ for a long time. Because of elongation difference between the loading and unloading, the hysteresis is generated in cyclic loading/unloading process.

Fig. 1. The qualitative dynamic behaviors based on the cyclic loading and unloading process.

Fig. 2. The cable elongation behavior under the cyclic loading according to the cable length

IV. PARAMETRIC STUDIES OF DYNAMIC BEHAVIOR

A. The investigation of dynamic creep

The dynamic creep is dependent on the loading time. To investigate the dynamic creep, the simulation is performed based on the 10 times of cyclic loading/unloading process as shown in Fig. 2. The tensile rate is a 3 mm/min in this simulation. In Fig. 2, the each colored line means the experiment result for a different cable length. The black dot line means the simulation result. The analysis of dynamic creep, hardening, short-term recovery, and hysteresis are based on the simulation results as shown in Fig. 2. Figure 3 shows the dynamic creep according to the cycle number for a different cable length. In overall, the dynamic creep is saturated as the loading cycle is processed. And the saturation is delayed as cable length is longer. This is because the longer the cable length is, the larger amount of residual stress the cable molecules have. Therefore, it takes a long time for the long cable to be saturated by creep. Another factor that affects the dynamic creep is the tensile rate. Figure 4 shows the dynamic creep with the tensile rate. As the tensile rate increases, the dynamic creep decreases linearly. In the case of high strain rate, since the loading time to approaching at the same final applied force is shorter than that of low strain rate, the effect of time-dependent creep is smaller. As the result, less dynamic creep is occurred at high strain rate.

Fig. 3. Cable elongation with the cycling number and cable length

Fig. 4. The amount of dynamic creep with various tensile rates (length:300 mm)

Fig. 5. Cable stiffness with the cycling number and cable length

Fig. 6. The long-term recovery with various cable lengths

B. The investigation of hardening effect

The hardening is dependent on the strain of the cable. Figure 5 shows the stiffness with loading cycle and cable length. As the cycle is carried out, the stiffness increases and then saturates. This means the cable is no longer stretched because it is sufficiently hardened. In the CDPR system, it is very important to consider the hardening effect because the variation of the stiffness is about two times as large as that of the first operation. So, the warming up process might be effective in order to improve the control accuracy of CDPR.

C. The investigation of short- and long-term recovery

The short-term recovery occurs as soon as the unloading begins in the CDPR system. Table I summarizes the amount of short-term recovery for the cycle and cable length. The short-term recovery tends to decrease as the cycle is carried out, and finally saturated. Thus, the short term recovery has the opposite tendency to dynamic creep and hardening effect. And Fig. 6 shows a long- term recovery behavior for the time and cable length. At the cable length of 100 mm and 300mm, the cable length is completely recovered after 20, 120 hours. In cast that the cable length is long, the long-term recovery time increases exponentially. The result is very important to operate the CDPR system because it is continuously operated and rated sometimes.

D. The investigation of hysteresis characteristics

Hysteresis is result of dynamic behavior interactions as shown in Fig. 2. The loading part of hysteresis is caused by dynamic creep and hardening effect, the unloading part is caused by dynamic creep and short-term recovery. To investigate hysteresis, the area of hysteresis is used (Table II). The area is decreased and then saturated by the combined dynamic characteristics as the loading cycles are progressed. It is because the hysteresis is result of the combined dynamic behaviors. Also, it critically affects CDPR's accuracy because the elongated length for the loading step is largely different from that for the unloading step at the same applied force

TABLE I. THE SHORT-TERM RECOVERY

Cycle		1	2	3	4	5
Short-term recovery [mm]	100 mm	0.64	0.51	0.46	0.42	0.38.
	300 mm	2.03	1.56	1.22	1.14	1.13
Cycle		6	7	8	9	10
Short-term recovery [mm]	100 mm	0.36	0.36	0.36	0.36	0.36
	300 mm	1.13	1.13	1.12	1.12	1.11

TABLE II. AREA OF THE HYSTERESIS

Cycle		1	2	3	4	5
Hysteresis energy dissipation[J]	100mm	0.250	0.092	0.084	0.076	0.070
	300mm	0.777	0.226	0.184	0.170	0.150
Cycle		6	7	8	9	10
Hysteresis energy dissipation [J]	100mm	0.067	0.063	0.062	0.060	0.060
	300mm	0.149	0.141	0.138	0.138	0.138

V. CONCLUSIONS

In this paper, we investigated the non-linear dynamics behavior of cable according to the various effective parameters using the derived model. It contained a hardening effect, a dynamic creep, a short and a long- term recovery and hysteresis. To investigate the effect of the effective parameters, we focused on the individual characteristics based on the cyclic loading test. As the loading cycle was increased, dynamic creep and hardening effect are increased and then, saturated. In contrary, short-term recovery is decreased and saturated. The longer the cable length, the longer-term recovery time is increased. Finally the hysteresis is decreased and then saturated by the combined dynamic characteristics as the loading cycles are progressed. As a result, slow CDPR system should be considered the cable dynamics because it makes the complicated errors.

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