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Carbon/epoxy composite foot structure for biped robots

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ABSTRACT

Although aluminum structures are generally used for robot structures due to their high specific strength, aluminum feet for fast running biped robots are vulnerable to fatigue failure due to the low fatigue limit and low vibration damping of aluminum structures under repeated impact loadings on the feet. On the other hand, carbon/epoxy composites not only have a much higher specific fatigue limit but also have a higher material damping than that of aluminum.

In this study, a carbon/epoxy composite foot structure of a biped robot was developed. The composite foot structure was designed for optimum performances such as weight saving, natural frequency, damping, and compliance for vibration isolation. Then its performances were analytically and experimentally obtained and compared with those of an aluminum foot structure. Finally, an optimum configuration of the composite foot structure was suggested for the reliable dynamic performance of the biped robot.

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1. Introduction

The ability of fast and agile robotic locomotion is crucial issue in dangerous situations, such as natural disasters, huge plant accidents, and reconnaissance in war scenarios that consist of environments with various obstacles. A fast legged robotic platform can be an ideal solution for rescuing or finding enemies on rough and complex terrain. Over the past several decades, many researchers have developed various types of legged robots due to their potential for rough terrain mobility compared with wheeled vehicles [1].

There are two approaches to increase the speed of the legged robot: increasing the actuator capacity and decreasing the leg inertia. Since increasing the actuator capacity causes higher actuator mass that correspondingly requires the increased leg strength and leg mass, decreasing the total inertia of the leg structure might be a more practical solution. However, the design of robot leg with low inertia but high strength to withstand large ground impacts during high speed running is coupled.

The distal part of robot leg is more critical due to its larger contribution to rotational inertia. Therefore, there have been some attempts to reduce leg inertia and apply compliance to distal parts by decreasing the load transmissibility of the robot body. To minimize leg inertia, several techniques have been used, such as under-actuated legs [2,3], locating the actuators closer to the body [4], cable driven structures [5], or applying high specific strength materials [6,7]. In addition, series-elastic actuation methods or mechanical suspensions have been used to obtain compliance [1]. Despite recent advances in robot technologies, the realization of agile dynamic movement still remains a difficult problem because of these design trade-offs.

The raptor robot was developed for agile dynamic locomotion on irregular terrain at high speed [3]. For fast running, aluminum structures are generally adopted due to their low density compared with steel. The raptor robot is composed of the under-actuated 9-bar linkage structure, which is driven by a single electrical actuator, as shown in Fig. 1(a), whose specifications are shown in Table 1. An Achilles tendon made of butyl rubber, which acts as spring and damper, was adopted to reduce ground impact and achieve efficient movement. The robot has reasonable dynamic properties, such as being light weight and having a small moment of inertia, for achieving high speed running at 27 km/h. Due to the low resilience of aluminum (yield strain 0.2%), a rib structure is required for the foot, as shown in Fig. 1(b). Because such a stiff foot structure transmits a large impact load to the robot body, damping materials were attached at the foot for protection of the body, as shown in Fig. 1(a). In spite of the damping materials, failure occurred at the body under repeated impact loading when the

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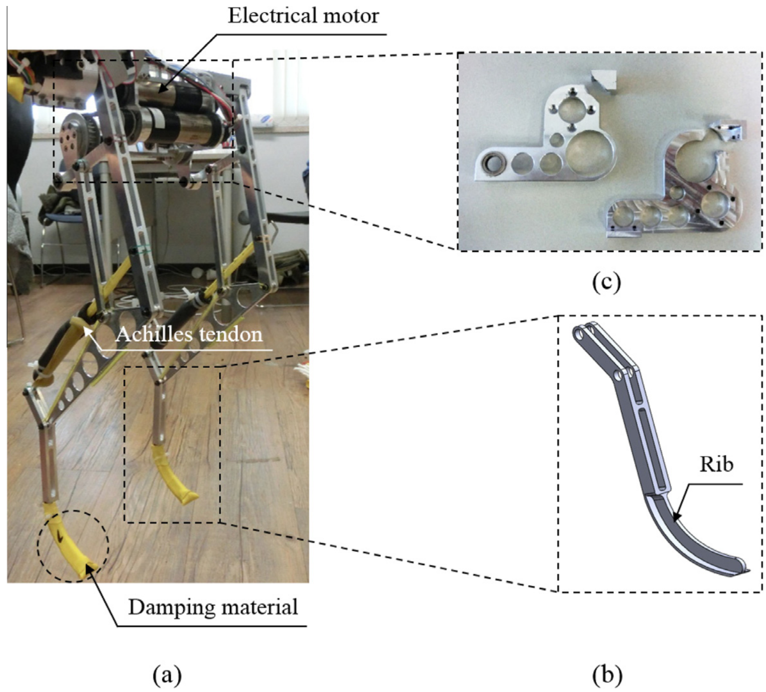

Fig. 1. Fast biped raptor robot: (a) raptor robot with a conventional aluminum foot and damping materials; (b) rib structure of the aluminum foot; (c) fractured components of the robot body during the running test.

Table 1
Specification of the biped robot with the aluminum foot structure.

	Specification
Total height (mm)	500
Mass (kg)	2.5
Max. speed (km/h)	27
Body material	Aluminum 7075
Leg material	Aluminum 7075

speed of the robot increased to over 27 km/h, as shown in Fig. 1(c). Therefore, attaching damping materials was not an appropriate solution for protection of the body.

Carbon composites have high specific strength, high damping, high failure strain, and low coefficient of thermal expansion (CTE) [8]. Because of their excellent properties, carbon composites have been widely used in robot structures as well as in aircraft and spacecraft structures, machines, automotive structures, and prosthetic structures for amputees [6,8–18]. Therefore, it might be possible to design a simple and compliant foot structure to reduce the transmitted load from impact and the moment of inertia using composite materials. Moreover, additional damping materials are unnecessary due to the compliance of the foot.

The purpose of this study is to develop a carbon/epoxy foot structure for a biped raptor robot to improve the running performance and life cycles of the robot. The composite foot structure is designed considering its levels of performance, such as weight saving, natural frequency, and damping and compliance for vibration isolation. For the design of optimum configuration of the composite foot, strain energy method and the maximum strain failure criterion was selected. Its performances were analytically and experimentally obtained and compared with those of the aluminum foot structure. Finally, the developed composite foot structure was experimentally verified for the reliable dynamic performance and life cycles of biped robot.

2. Design of the composite foot structure

2.1. Design of a composite foot model using the strain energy method

The composite foot of the raptor robot has a curvilinear shape, with a cantilever beam joined to a semicircular beam, as shown in Fig. 2(a). The cantilever beam of the foot structure is connected to the aluminum foot connector using screw bolts. To design the composite foot, a cantilever model and a simple curved beam model were used, as shown in Fig. 2(b). Table 2 describes the parameters and values used in the formulations. The subscripts c and s are indicated curved beam and straight beam (cantilever beam), respectively. The vertical deflection at the ground contact point of the foot B is caused by the axial force, shear force and bending moment. However, the contributions of the axial load and shear are negligible when the radius to thickness ratio (r/h) is larger than 10 [19]. Therefore, the strain energy that was due

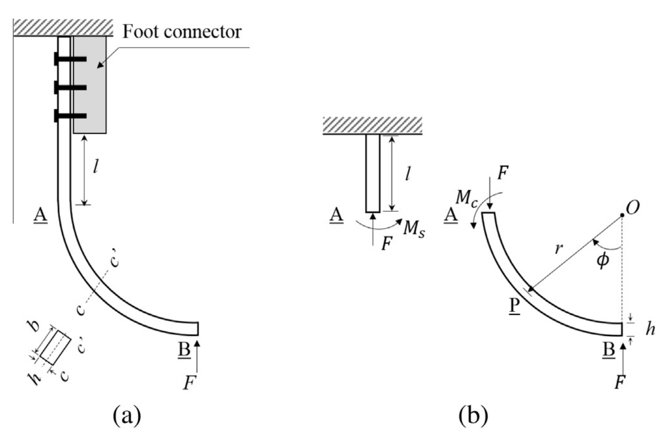

Fig. 2. Schematic diagram of composite foot structure: (a) curvilinear shape of the composite foot structure; (b) free body diagram.

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