Paper:

Design and Prototype of Variable Gravity Compensation Mechanism (VGCM)

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A machine moving vertically requires strong gravitational resistance. Gravity compensation mechanisms devised to reduce actuator force mostly compensate for constant weight, but practical use requires that the mechanism compensate for weight variations. This paper presents a Variable Gravity Compensation Mechanism (VGCM) that uses two types of linear springs and changes the equilibrium position of one. The mechanism principle is described and the prototype is designed. Performance is experimentally confirmed.

Keywords: gravity compensation, mechanism, spring, balance, weight

1. Introduction

Machines involved in vertical component movement against gravitation require actuators large enough to sustain their own gravity. Therefore, mechanisms capable of compensating for gravitation have been devised to reduce actuator size.

Simply constructed counterweights invariably increase in size and construction in handling heavy loads, and are poorly suited to acceleration and deceleration due to large inertia around bearings.

Simple spring balancers require springs selected appropriately for stiffness, length, expansion, contraction, etc. If heavy gravity must be compensated for, springmass becomes too large to be negligible, potentially causing too much variation in compensation, depending on machine positioning – when springs are selected appropriately [1–3], the moment of inertia does not increase much, ensuring good equilibrium for any machine positioning. One approach to compensation not depending on machine positioning uses a pantograph mechanism with springs at the bottom [4]. A certain degree of gravity compensation does not depend on machine positioning if pulleys are appropriate [5–8], but heavy gravity somewhat decreases stiffness and robustness, perhaps due to wires. To improve machine reliability in response to these concerns, using an oscillating block slider crank mechanism has been proposed [9]. Even with this, however, spring mass is transferred too far to be negligible if springs are large and heavy. Another way of improving robustness without using wires and without changing the Center Of Gravity (COG) of spring by positioning is a gravity compensation mechanism using cams and springs [10–12]. Cams appropriately predesigned ensure a certain degree of gravitational compensation regardless of positioning, but different cams are required for differing gravity. A constant repulsive force spring model using two types of springs has been proposed for the pantograph mechanism [13, 14], applying spring force to cope with horizontal and vertical displacement. It is adapted to nearly constant gravity by adjusting parameters. A similar method is a gravitational balancer using two types of springs fixed at one end to the robot arm at a 90° phase difference in rotation axis [15]. It is identical in principle to the pantograph mechanism and balancing is achieved for nearly constant weight.

Most of these proposed gravitational compensation mechanisms are not designed, however, to handle gravity variations, and fail to balance gravity, causing excessive loads on motors if gravity changes from that in design specifications or if work mass varies widely. Gravity compensation methods able to cope with gravity variation by shifting bearing points [16] based on the principle in [1–3], however, use wires compromising robustness.

We propose a Variable Gravity Compensation Mechanism (VGCM) that copes with variable gravity without using wires or being adversely affected by positioning. Section 2 describes the principle that enables compensation for constant gravity regardless of positioning, at which point variable gravity can be handled without a problem. Our proposed VGCM uses two types of springs with a 90° phase difference in the same way as [13–15], but it is adaptable to variable gravity by deriving complete balancing conditions. Section 3 describes configurations and prototype design actually implemented based on this basic principle. Unique features of our proposed prototype are that joint angles respond to multiple rotations up to 360°. Section 4 confirms features through experiments. Section 5 summarizes the VGCMand its projected prospects.

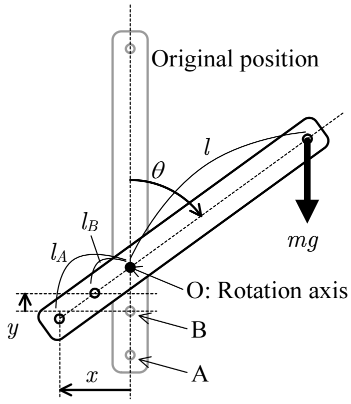


Fig. 1. Gravity compensation mechanism concept.

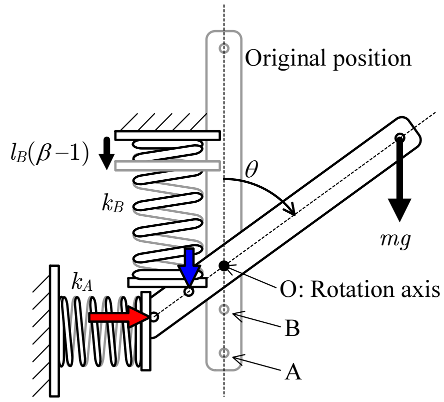


Fig. 2. VGCM concept.

2. VGCM

2.1. Principle Compensating for Constant Gravity

In this section, we explain a principle in which the gravity compensation mechanism using two types of springs with a 90° phase difference is completely balanced against constant gravity. Fig. 1 shows the concept, in which mass m is concentrated at the forward link length l away from the rotation axis. A and B denote points l_A and l_B away from the rotation axis on the straight link line. θ denotes the angle at which the link is rotated. Torque produced by gravity is expressed as follows:

$$\tau_g = mgl\sin\theta \quad (1)$$

Gravity torque is compensated for if torque generated by spring balances the gravity-induced torque above.

To return the link to initial positioning ($\theta = 0$), force f_A is applied horizontally and f_B vertically to the link at Points A and B, then horizontal displacement x of Point A and vertical displacement y of Point B are expressed as follows:

$$x = l_A\sin\theta \quad (2)$$
$$y = l_B(1-\cos\theta) \quad (3)$$

Derived spring force is as follows:

$$f_A = k_A x = k_A l_A \sin\theta \quad (4)$$
$$f_B = k_B y = k_B l_B(1-\cos\theta) \quad (5)$$

Torque produced by spring force around rotation axis is obtained as follows:

$$\tau_A = k_A l_A^2 \sin\theta\cos\theta \quad (6)$$
$$\tau_B = k_B l_B^2(1-\cos\theta)\sin\theta \quad (7)$$

Total torque thus produced is obtained as follows:

$$\tau_k = k_A l_A^2\sin\theta\cos\theta + k_B l_B^2(1-\cos\theta)\sin\theta \quad (8)$$

Total torque is expressed as following Eq. (10), assuming that Eq. (9) conditions are met:

$$k_A l_A^2 = k_B l_B^2 = C \quad (9)$$
$$\tau_k = C\sin\theta \quad (10)$$

A comparison with gravity torque expressed by Eq. (1) shows that total spring torque and gravity torque are balanced if $C = mgl$.

In this principle, two types of springs are arranged on a 90° phase the same as [13, 14], while two types of springs are arranged almost parallel and fitted to the arm in a 90° phase in [15]. No specific conditions are provided to balance gravity torque completely in [13–15]. We establish conditions under which gravity torque is completely balanced.

2.2. Variable Gravity Compensation Principle

Having explainedmethods for balancing constant gravity, we propose compensating for variable gravity as follows.

To add initial tension to spring force at Point B, the equilibrium point is shifted by $l'_B = l_B(\beta-1)$, as shown in Fig. 2, and Spring B tension is expressed by Eq. (11) and total torque by Eq. (12):

$$f_y = k_B l_B(\beta - \cos\theta) \quad (11)$$
$$\tau_k = C\beta\sin\theta \quad (12)$$

where $\beta = 1$ denotes $l'_B = 0$ corresponding to original gravity m. When for example $\beta = 2$, initial displacement becomes $l'_B = l_B$, enabling the gravity to be handled to be twice as large as m. This gravity is adjusted by changing initial displacement (equilibrium point), as shown in Fig. 2.

It is also possible to vary the gravity to be handled by shifting spring bearing positions [16], but using wires raises concerns, requiring that we account for a COG shift due to spring deformation. To compensate for gravity using counterweights, large (heavy) weightsmust bemoved, making machine large and complex. Our proposal, in contrast, achieves the variable gravity compensation mechanism simply by shifting spring end points.

Table 1. Prototype specification.

m	0.952 [kg]
β	1〜3.2
l	0.3 [m]
l_A, l_B	0.01 [m]
k_A, k_B	2.8×10^4 [N/m]

3. Prototype Design

3.1. Prototype Specifications

We design our prototype under the conditions: weight mass $m = 1$–3 kg and link length $l = 0.3$ m. With base mass $m = 1$ kg and link length $l_A = l_B = 0.01$ m, spring stiffness meeting conditions in Eq. (9) is calculated as follows:

$$k_A = k_B = \frac{mgl}{l_A^2} = 29400\,[\mathrm{N/m}]$$

Then, at $0 \leq \theta \leq \pi$, maximum spring displacement becomes $s_A = l_A = 0.01$ m and $s_B = 2l_B = 0.02$ m. To adapt the prototype up to $m = 3$ kg, the equilibrium point of Spring B must be shifted by $l'_B = 2l_B$, requiring the prototype to have total allowable displacement $s_B = 4l_B = 0.04$ m.

We decided to use two springs (MISUMI Corp., SWU26-35), 0.035 m in natural length, 0.021 m in allowable displacement and $\bar{k}_A = 1.4 \times 10^4$ N/m in elastic coefficient, for Spring A, and two springs (MISUMI Corp, SWU43-70), 0.07 m in natural length, 0.042 m in allowable displacement and $\bar{k}_B = 1.4 \times 10^4$ N/m in elastic coefficient, for Spring B because of spring conformity with the above requirements.

With these springs, actual base mass is:

$$m = \frac{k_A l_A^2}{gl} \simeq 0.952\,[\mathrm{kg}]$$

For an allowable displacement of 0.042 m, maximum gravity compensated for is 3.05 kg. Table 1 gives prototype specifications.

3.2. Sharing of Compensation by Positioning

Our proposed gravity compensation mechanism has two types of springs to share required compensation. We checked through simulation how such sharing is changed by positioning θ.

Based on design values (specifications) above, Eqs. (1), (6), and (7) are denoted by graphs in Fig. 3.

Torque is converted to vertical force at the forward end of the arm, so the gravity to be compensated for is expressed as follows:

$$w_g = mg = C/l = w_A + w_B \quad \text{. . . . . (13)}$$

Force w_A borne by Spring A is expressed as follows:

$$w_A = \frac{k_A l_A^2}{l} \cos\theta \quad \text{. . . . . (14)}$$

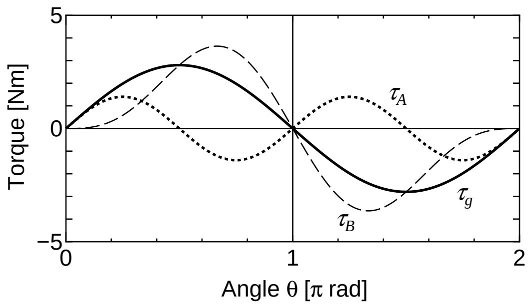


Fig. 3. Torque simulation.

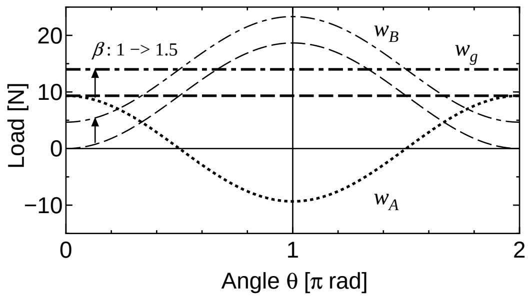


Fig. 4. Load force simulation.

Force w_B borne by Spring B is expressed as follows:

$$w_B = \frac{k_B l_B^2}{l}(\beta - \cos\theta) \quad \text{. . . . . (15)}$$

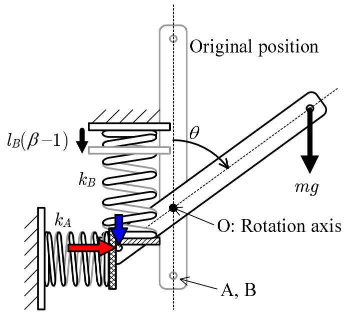
The relationship among these elements is shown in Fig. 4, in which w_A is denoted by a dotted line, w_B, by a broken line, and w_g, by a heavy broken line. When Spring B equilibrium point is shifted from $\beta = 1$ to $\beta = 1.5$, for example, wg changes from the heavy broken line to the dot-dash line.

3.3. Prototype

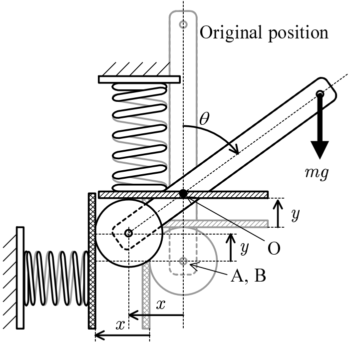
The principle scheme (Fig. 5(a)) shows spring force applied directly to Points A and B on the link. In actual implementation, however, force is applied by springs constrained to a single Degree Of Freedom (DOF) to the table contacting followers at Points A and B. Even using these followers, no displacement difference occurs at Points A and B or on the table contacting followers (Fig. 5(b)), ensuring that the gravity compensation principle is applicable as is.

Figure 5(b) shows implementation with relatively small followers. When θ is small, no problems arise, but when the range of movement is large, interference occurs between the table for Spring B and the rotation axis. Alternative use of a larger follower containing the rotation axis invariably positions the table for Spring B above the rotation axis, so no interference arises with the rotation axis, ensuring the large movement range shown in Fig. 5(c).

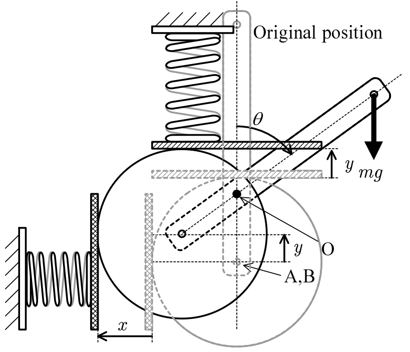
Figure 6 shows the VGCM prototyped under the above specifications, together with major dimensions. The main material is stainless steel, weighs 7.5 kg. Fig. 7 shows the



(a) Principle scheme



(b) Implementation scheme with small follower



(c) Implementation scheme with large follower

Fig. 5. VGCM implementation.

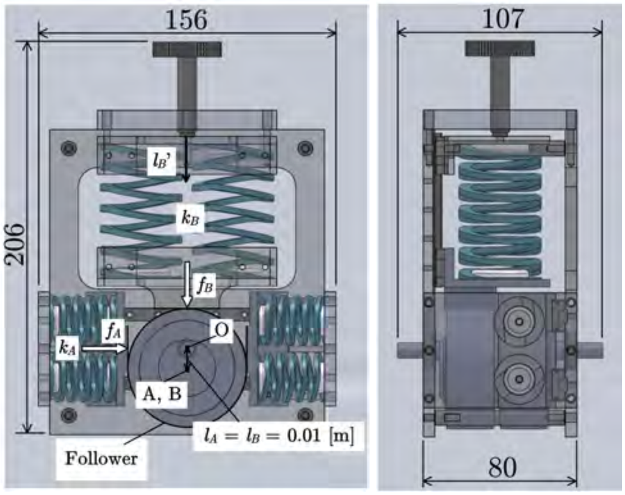


Fig. 6. VGCM configuration.

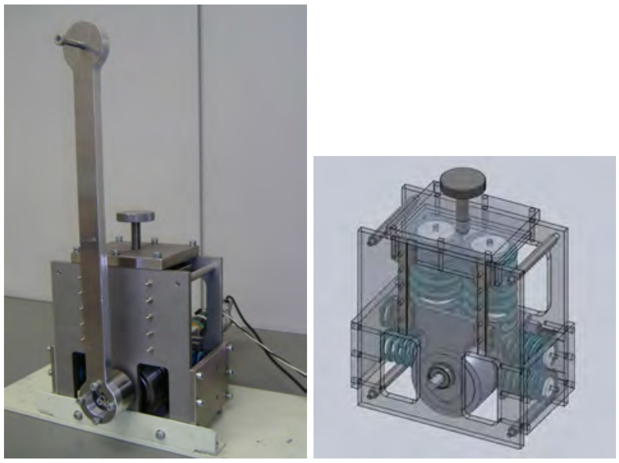


Fig. 7. VGCM prototype.

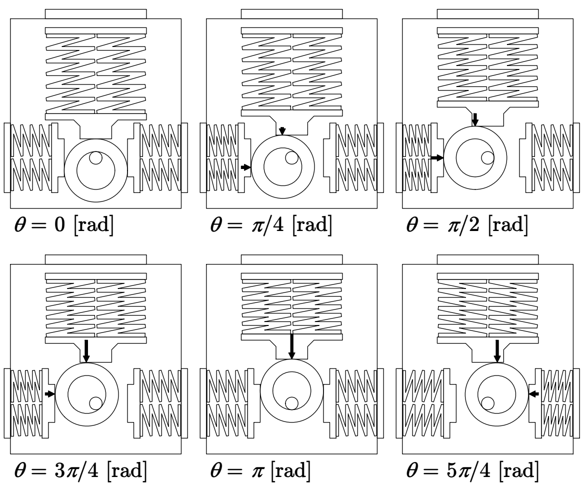


Fig. 8. VGCM schematic.

prototype VGCM and its CAD assembly plan.

The prototype uses an eccentric follower with the rotation axis inside. Since rotation speed of followers on tables differ between Springs A and B, two followers are concentrically arranged side by side. Tables contacting followers are constrained to single-DOF motion by the linear guide, and spring force is applied to the opposite side of the table contacting followers. Springs are retained by the holder so that they are not dislocated. Spring B ' s table motions are constrained to single DOF by the linear guide at the top of Spring B. Spring B 's equilibrium point is shifted by rotating the knob at the top of the device and moving the table. Arranging Spring A on each side of the rotation axis enables rotating the device 360° (Fig. 6). Fig. 8 schematically diagrams the device during rotation.

Geared actuator (Harmonic Drive Systems Inc., RH-11-6001) and encoder (Canon Marketing Japan Inc., TR-1) are connected to the rotation axis on the opposite side

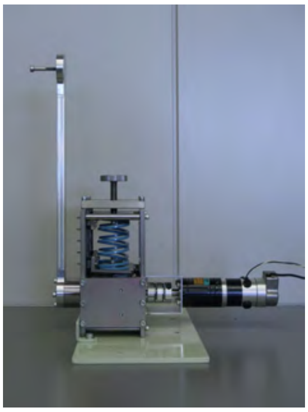


Fig. 9. Side view of VGCM

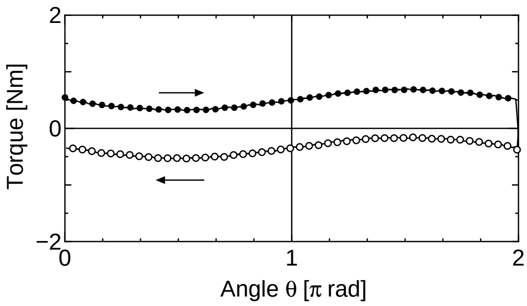


Fig. 10. Motor torque with followers and arm.

of the arm as shown in Fig. 9. Design specifications allow for compensation of gravity up to 3 kg, but evaluation experiments, which follow, are limited to gravity up to 2.5 kg due to maximum motor torque.

4. Experiments

In experiments, the axis is rotated 360° from 0 rad (vertically upright) clockwise in 12 s at a constant speed of $30°/\text{s} = \pi/6$ rad/s by angular motor control. It is rotated anticlockwise back to the original position at the same constant speed as clockwise rotation. Angles and motor torque are measured during link rotation.

4.1. Basics

Figure 10 shows angles andmotor torque when the axis is rotated using only with followers and an arm is installed (or in a spring-less state). Filled circles denote data for clockwise rotation and open circles data for anticlockwise rotation.

Sinusoidal waveforms denote gravitational torque due to arm and follower eccentricity. With an arm length of $l = 0.3$ m and the COG at 0.15 m or half the length of the arm, arm mass m_a produces a gravitational torque of $\tau_a = \frac{m_a g l}{2} \sin\theta$.

With the center of followers displaced by $l_A = l_B = 0.01$ m to the opposite side of the arm, mass m_f of followers produces a gravitational torque of $\tau_f = -m_f g l_A \sin\theta$.

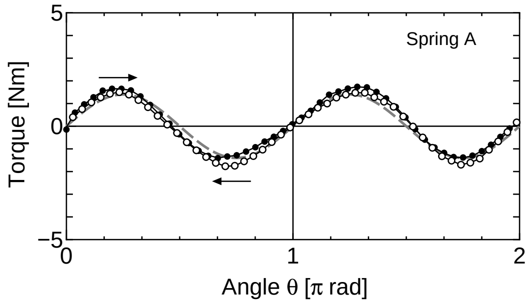


Fig. 11. Spring torque with Spring A.

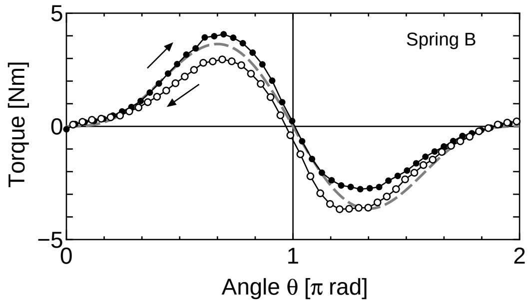


Fig. 12. Spring torque with Spring B.

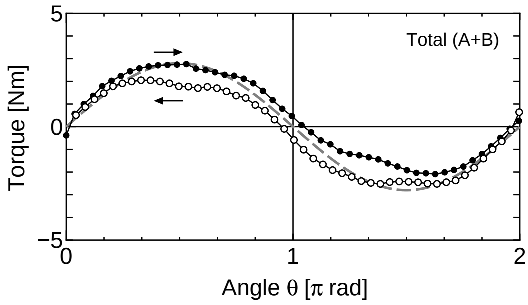


Fig. 13. Spring torque with Springs A and B.

Combined torques acts on the rotation axis as gravity (basic features), so motor torque in Fig. 10 denotes a gravitational torque of $-0.2\sin\theta$ [N·m] as opposite sinusoidal torque. In experiments, a weight of 1–2.5 kg is fitted at the forward end of the arm ($l = 0.3$ m) to cause gravitational torque of 3–7.5 N·m.

Any clockwise and anticlockwise rotation difference in torque is attributed to friction. Frictional torque of 0.5 N·mis observed in clockwise rotation and of 0.4 N·min anticlockwise rotation. Torque produced by springs is estimated from motor torque from which frictional torque was deducted.

Experimental results using one or more springs are shown in Figs. 11–13. Fig. 11 shows results for Spring A only, Fig. 12 for Spring B only, and Fig. 13 for both springs. Filled circles denote clockwise and open circles anticlockwise rotation. Data corresponds to gravitational compensation torque τ_A, τ_B, and τ_k by springs.

Although some difference in results exists between rotational directions, features similar to simulation results

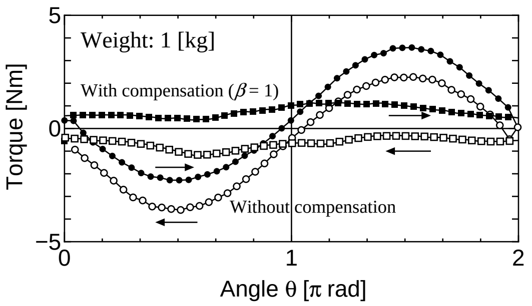


Fig. 14. Motor torque during rotating the weight of 1 [kg]

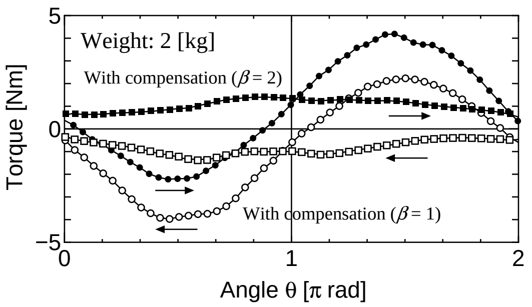


Fig. 15. Motor torque during rotating the weight of 2 [kg]

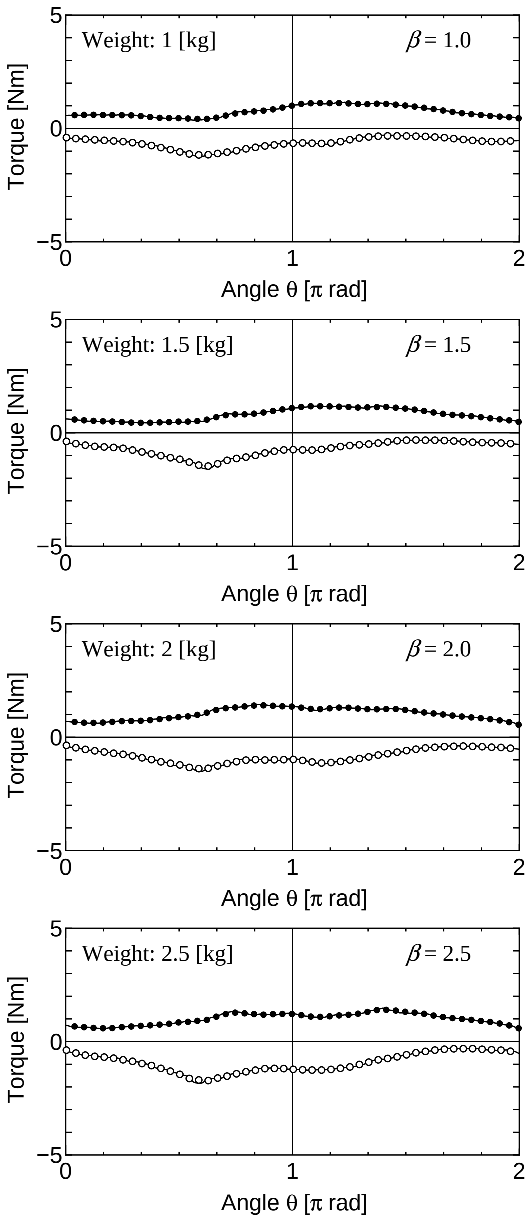


Fig. 16. Motor torque in cases of various equilibrium with equivalent weight

denoted by a gray broken line in Fig. 3 are realized.

4.2. Reduction in Motor Load due to Gravitational Compensation

Having confirmed that gravitational compensation by springs is possible when equilibrium point $\beta = 1.0$, we rotate a device weighing 1 kg fitted at the forward end of the arm 0.3 m away from the rotation axis. Fig. 14 shows motor torque by circles without springs fitted — no gravitational compensation — and that by squares when springs are fitted to compensate for gravity.

With gravitational torque produced by weight of 3 N·mand frictional torque of the actuator 0.5 N·m, peak motor torque is 3.5 N·mwithout compensation.

When springs compensate somewhat for gravitation, torque falls within 1 N·mor less regardless of positioning (angles), indicating that motor load is reduced.

We rotate a device weighing 2 kg fitted at the forward end of the arm. Rotating the device with equilibrium point $\beta = 1.0$ produced the results shown by circles in Fig. 15. 1 kg of the 2 kg weight has been compensated for with the remaining 1 kg managed by compensatory motor torque. Rotating the device with the equilibrium point shifted to $\beta = 2$ corresponding to 2 kg produced results shown by squares in Fig. 15, confirming that the device is driven by motor torque of 1–1.5 N·mas in using a 1 kg weight (Fig. 14).

Figure 16 shows motor torque required to rotate devices weighting 1, 1.5, 2.0, and 2.5 kg corresponding to $\beta = 1$, 1.5, 2.0, and 2.5. Results confirm that the device is rotated with almost constant torque of 1–2 N/m. A weight of 2.5 kg generally requires a peak torque of 7.5 N·mto manage gravitational torque, but our proposed device demonstrates that it can be driven by torque one-fifth of that.

4.3. Variations in Compensation Torque due to Equilibrium Shift

Having confirmed gravitational compensation effects, we show compensation torque of springs in Fig. 17 when the device is rotated at different equilibria of springs at $\beta = 1$, 1.5, 2.0, and 2.5. Filled circles denote data for clockwise and open circles data for anticlockwise rotation. The gray broken line denotes design values. Fig. 17 confirms that compensation torque varies with the equi-

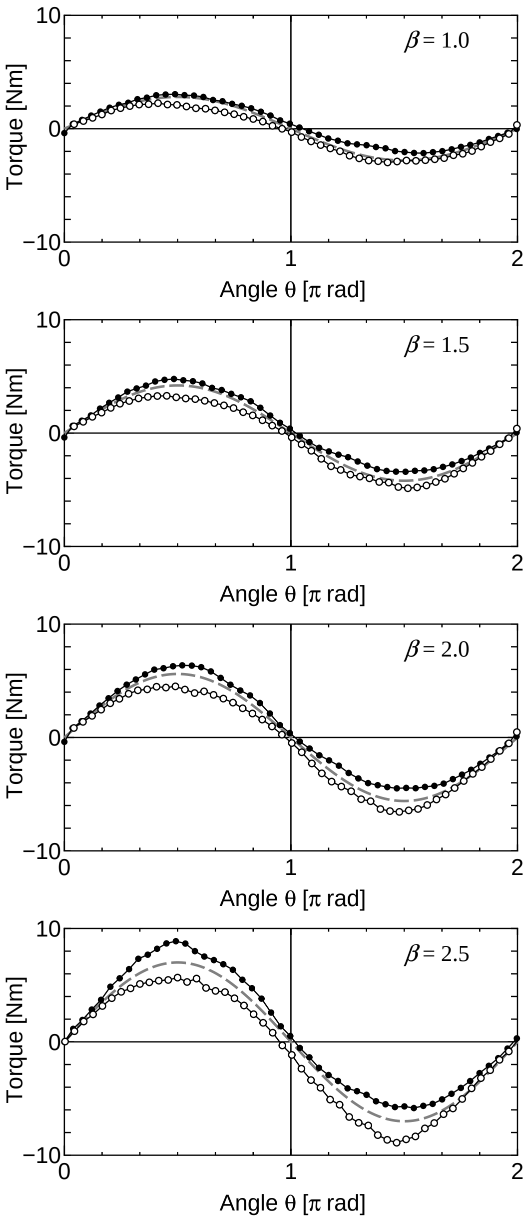


Fig. 17. Spring torque in cases of various equilibrium

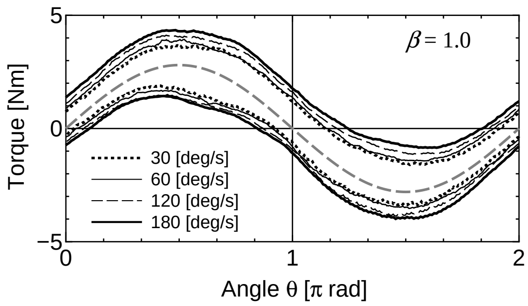


Fig. 18. Motor torque in cases of various velocity

librium shift as designed.

4.4. Variations in Motor Torque due to Rotation Speed

Having conducted experiments relatively slowly, i.e., one round rotation in 12 seconds (30°/s), we examine possible effects of differing rotation speed. Fig. 18 shows motor torque when the device is rotated without load with equilibrium $\beta = 1.0$ at 30°/s, 60°/s, 120°/s, and 180°/s. Fig. 18 shows data corresponding to rotation speed of 30°/s (heavy dotted line), 60°/s (thin solid line), 120°/s (thin broken line), and 180°/s (heavy solid line). The gray broken line denotes design values.

Figure 18 demonstrates that motor load torque in general increases with rotation speed. Incremental load torque in line with speed suggests that the load torque increase is due to viscous friction. The lack of substantial change in sinusoidal waveforms suggests that increase in load torque only negligibly affects gravitational compensation for springs.

Experimental results thus show some increase in load torque due to viscous resistance, limited to within 1 N·mat maximum at any rotation speed up to 180°/s, in turn demonstrating that our proposed device reduces gravitational torque considerably for the motor.

5. Conclusions

Our research outcome is summarized as follows:

1 We have devised and explained the principle of a gravity compensation mechanism that handles variable gravity using Springs A and B with differing equilibrium points for Spring B.

2 We have designed and prototyped a gravity compensation mechanism making multiple rotations and easily altering gravity.

3 We have confirmed through evaluation experiments on the prototype that gravity compensation was realized as designed.

4 We have confirmed through experiments that motor load torque is considerably reduced even under significant gravity.

The device we have introduced here requires further study for miniaturization and lighter weight. This mechanism is expected to be applied to multi-DOF robots. In such serial applications, miniaturization and lighter weight must be addressed. Other possible applications include: multiaxial robot arms with horizontal and lifting axes with our proposed VGCM built in, multi-DOF parallel-link robots, and energy-saving lifts.

Acknowledgements

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- "Position Control Methods of Spherical Ultrasonic Motor," Proc. of IROS 2010, pp.3061-3066, 2010.
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Membership in Learned Societies:

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• "Human-robot collaboration in precise positioning of a three-dimensional object," Automatica (Journal of IFAC), Vol.45, Issue 2 February 2009
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• "Network-based Micro Teleoperation," Proc. of 2000 Japan-USA Symposium on Flexible Automation, Vol.13044, No.1-6, 2000. (Best Paper Award)

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