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Detachable Robot That Moves the Baby Bouncer

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***Abstract*— A baby bouncer is a type of cradle that allows for rocking and soothing through the baby's own movements or the use of hands by an adult. An electric baby bouncer is designed to automatically rock the baby, enabling parents to soothe their child without using their hands and reducing the effort required. However, existing electric baby bouncers have the drawback of being expensive, heavy, and bulky. In this study, we propose an external attachment device that can be easily added to existing manual baby bouncers to enable automatic rocking. This device operates by transmitting the rotation of a servo motor to the baby bouncer, facilitating the rocking motion. Through experimentation, we validated that the device can adapt to variations in the baby's weight and changes in the servo motor's rotation cycle, thereby allowing for adjustments in the swing range of the baby bouncer.**

I. INTRODUCTION

A. Background

A baby bouncer is a chair for infants that can be rocked and soothed by the baby's own movements or by an adult using their hands. Baby bouncers can be categorized into two types: regular and electric. Electric baby bouncers automatically rock the seat to soothe the baby. They are particularly useful during short periods when adults are occupied, such as performing household chores or taking a bath. However, electric baby bouncers have the disadvantages of being expensive, heavy, and large. A survey was conducted to determine the differences between electric and regular baby bouncers in terms of price, weight, and size. he average price, weight, and size were calculated for nine regular baby bouncers and five electric baby bouncers, each from a different company (TABLE I).

The results indicate that electric baby bouncers are more than twice as expensive and approximately three times as heavy as regular baby bouncers. In terms of size, electric baby bouncers are larger, with increases of more than 3 cm in depth, 6 cm in width, and 30 cm in height compared to regular baby bouncers. This study highlights that electric baby bouncers are not only more expensive but also heavier and bulkier than their regular counterparts. In contrast, regular baby bouncers are often foldable, allowing for more compact storage, a feature provided by many manufacturers.

TABLE I

REGULAR BABY BOUNCERS VS. ELECTRIC BABY BOUNCERS

	Regular baby bouncers	Electric baby bouncers
Price ($)	116.7	254.2
Weight (kg)	3.0	9.1
Size (D, W, H) (cm)	73, 53, 54	77, 60, 80

Fig. 1. Detachable robot that moves the baby bouncer

Additionally, beyond the disadvantages of electric baby bouncers, many users still prefer regular baby bouncers due to their limited load capacity and short usage period. These factors are influenced by the natural growth of infants, such as when they become mobile and no longer remain in the bouncer.

To address these issues, this study proposes a compact device that can be attached to and detached from existing baby bouncers. This device enables automatic rocking while retaining the advantages of regular baby bouncers, such as their lightweight and compact design.

B. Purpose

The purpose of this study is to develop a device that automatically rocks baby bouncers to comfort infants. This paper explores the maximum extent of rocking achievable by the device and evaluates the types of rocking it can produce.

The device is positioned at the top center of the baby bouncer. By rotating servo motors, vibrations are propagated to rock the baby bouncer, as illustrated in Fig.1. A key advantage of this device is its compatibility with existing baby bouncers, as it can be easily attached and detached. This detachable feature allows the device to retain the compact, foldable, and easy-to-store characteristics of manual baby bouncers.

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Moreover, the device enables dual functionality, allowing it to be used either as a regular baby bouncer or as an electric baby bouncer. This flexibility provides adaptability to different applications and situations. To evaluate the device's performance, experiments were conducted to investigate the rocking motion induced by the device. The results demonstrated that the device could effectively sway the baby bouncer regardless of the baby's weight or the tilt angle of the bouncer. Based on these findings, the potential applications and limitations of this device are discussed.

II. RELATED WORK

A. Infant baby bouncers

Several studies have been conducted on baby bouncers, focusing on both their control mechanisms and safety. For instance, Park et al. proposed a method to control the speed of existing electric baby bouncers based on a baby's facial expressions, utilizing facial recognition technology. This technique is considered applicable as a potential extension of the approach explored in this study.

Research on baby bouncer safety has also been extensively documented. Claydon et al.[1] reported a head injury incident caused by a baby bouncer, investigating its causes and proposing preventive measures. Farmakakis et al.[2] analyzed five years of injury data in Greece, highlighting the risks associated with baby bouncers and offering precautions for their safe use. Nelson et al.[3] examined infant sleep safety and the safety of infant products, including baby bouncers. Their study identified 10 baby bouncer-related fatalities over a three-year period (2012–2014), primarily due to improper use, such as failure to wear safety restraint belts and inadequate parental supervision.

Given these findings and acknowledging the risks associated with baby bouncers, this study assumes that the proposed device will be used under proper parental supervision. With this premise, the device aims to leverage the rocking motion of baby bouncers to maximize their baby-soothing benefits while addressing safety considerations.

B. External devices for extended functionality

Research on the development of devices that extend the functionality of existing objects has been widely conducted. Such studies often aim to enhance or add new functionalities to existing objects. For example, Furukawa et al.[4] utilized servomotors to instantly stiffen fibers on clothing. Osawa et al.[5] proposed "display robots" that anthropomorphize objects by attaching body parts, discussing the effects of anthropomorphism on user interaction. Yonezawa et al.[6] explored a wearable partner agent that combines tactile stimuli with anthropomorphic movements to investigate physical contact responses influenced by the user's attire, posture, and context detection.

Koizumi et al.[7] introduced a platform for creating moving toys from ordinary printed paper with minimal physical modification, suggesting the potential for developing a wireless moving paper platform. Maekawa et al.[8] proposed a robotic appendage as a human balance support tool that does not rely on environmental contact, demonstrating through experiments that the controlled appendage improves balance ability. Kawakami et al.[9] developed "PotPet," a flowerpot-type robot designed to enhance the enjoyment and effectiveness of plant cultivation. These examples highlight the broad scope of research in extending the functionality of existing objects.

A related area of research focuses on objects that provide motion. For instance, Parshakova et al.[10] employed servo motors to move a small chair as a preliminary step toward enabling furniture mobility using a small vibration source. Suyama et al.[11] proposed Extail, a wearable hair extender that mimics a tail's motion to present information to the wearer.

Inspired by the form and versatility of such external devices, this study was designed to leverage the detachability of these devices to maximize functionality and adaptability.

C. Sleep and Vibrations

Because we thought it would be good if the baby bouncer could be rocked to help put the baby to sleep, we looked for studies about sleep and about vibrations that promote sleep. There were studies on the effects of rocking on sleep and on improving sleep quality and memory by continuous rocking throughout the night. Perrault et al.[12] investigated that continuous rocking stimulation enhances deep sleep via neural entrainment of endogenous sleep oscillations. Bayer et al.[13] suggested that rhythmic rocking may enhance synchronous activity within thalamocortical networks and facilitate sleep onset and its maintenance. Kishi et al.[14] demonstrated that the subsensory slow oscillation GVS facilitates the wake-sleep transition and improves objective and subjective sleep quality.

Based on these studies, it has been shown that rocking is beneficial for sleep. By rocking a baby bouncer, it is also possible to promote sleep in babies. Therefore, this study utilizes examples of rocking to develop a method for controlling the baby bouncer's motion using the proposed device.

III. MODELING OF BABY BOUNCER

In order to clarify the principle of operation of the baby bouncer, this chapter describes the experimental principle for the estimation of the maximum amplitude period of the baby bouncer, which will be done in Section 5.5.

A. Equation of motion

In this study, we analyze the temporal angle variation of the baby bouncer. We let θ_t and θ_0 denote the angle of the baby bouncer and the initial angle of the baby bouncer, respectively. Further, we let $\Delta\theta_t$, ω_t, and α_t denote the angular displacement, the angular velocity, and the angular acceleration, respectively. It holds that $\Delta\theta_t = \theta_t - \theta_0$. The dynamics of the baby bouncer is modeled by the following equation of motion: Eq.(1)

$$\alpha_t + 2\xi\omega_n\omega_t + \omega_n^2\Delta\theta_t = K\omega_n^2 f(t) \tag{1}$$

where $f(t)$ represents the external input, which in this study corresponds to the vibration caused by the device. Symbol ξ represents the damping ratio, which defines the characteristics of vibration damping. The closer it is to 0, the more oscillatory the system is, the closer it is to 1, the more it damps vibration, and above 1, it indicates no vibration at all.

Parameter ω_n represents the natural frequency, which defines the quick response of the system, and K is called the gain. Oscillation is characterized by ξ and ω_n. These parameters can be estimated from the initial value response data, namely, the unforced response where $f(t) = 0$. By deriving these, it is possible to determine whether oscillation is occurring and to identify the frequency at which oscillation is most likely to occur.

B. Transfer function representation

The input-output response of Eq.(1) is expressed in the Laplace domain as described by $\Delta\bar{\theta}(s) = G(s)\bar{f}(s)$, where $\Delta\bar{\theta}(s)$ and $\bar{f}(s)$ represents the Laplace transform of $\Delta\theta(t)$ and $f(t)$, respectively. Symbol $G(s)$ represents the transfer function given by Eq.(2).

$$G(s) = \frac{K\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (2)$$

Parameters ξ and ω_n of $G(s)$ can be obtained by the least squares method and expressed as a Bode diagram to predict the rocking of the baby bouncer under arbitrary conditions. The Bode plot consists of a gain curve representing the change in gain with respect to the angular frequency ω_n and a phase curve representing the change in phase difference. The advantages are that the schematic characteristics of the system can be easily and accurately grasped and that a wide frequency band can be handled with a single drawing.

Analyze the amplitude of the vibration caused by the device when the frequency frequency is varied. Compare the calculated frequency response with the Bode plot obtained in Section 3.2.1 to determine if Section 3.2.1 is an accurate model.

In Section 5.5, it is used for modeling the resonance frequency.

IV. PROPOSED METHOD

A. System configuration

This device used an Arduino and a PC; the Arduino was connected to a circuit that drives a servo motor and an acceleration sensor.

This controls the rotation speed and angle of the servo motor.

Sensor values read by the Arduino are sent to the PC using serial communication.

B. Hardware

The hardware of this device primarily consists of an arm, a servo motor, and a lead weight.

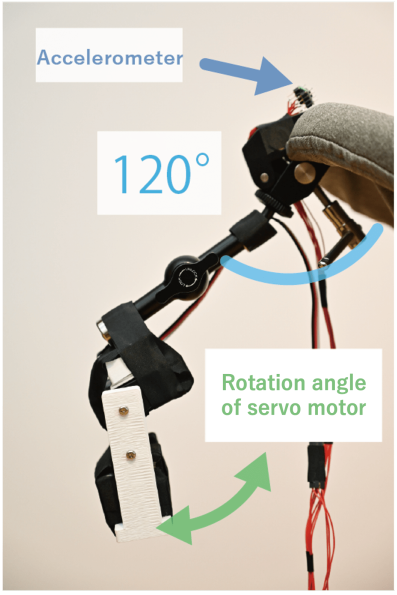

Fig. 2. Appearance of device

The servo motor was attached to the arm. A 3D-printed rectangular block with a hole in its center was used to cover the screw at the connection point, and this block was attached to the arm. The servo motor and the rectangular block were secured using double-sided tape. An L-shaped plate, produced by a 3D printer, was attached to the rotating part of the servo motor. Two holes were drilled into the long side of the L-shaped plate to match the size of the screw holes on the servo motor, and screws were inserted to secure the connection between the servo motor and the L-shaped plate. A lead weight of approximately 400 g was attached to the L-shaped plate, with about 300 g positioned at the center and 100 g placed farther out in the direction of rotation to amplify vibrations caused by the rotation.

The arm was installed at the top and center of the baby bouncer using a clamp. The angle between the arm and the baby bouncer was set to 120 degrees. The servo motor rotated up to 50 degrees in the direction of the baby bouncer from the orientation shown in Fig. 2.

An acceleration sensor for measuring vibration frequency was installed on the clamp.

V. EXPERIMENTS

Five experiments were conducted to evaluate the extent to which the device developed in this study can rock the baby bouncer. In Section 5.1, the effect of the device's rotation on the period of the baby bouncer is investigated. In Section 5.2, the change in the baby bouncer's period due to variations in the baby's weight is analyzed. In Section 5.3, the amplitude change of the baby bouncer when the device's rotation period is varied is examined. In Section 5.4, the effect of varying the device's rotation angle on the baby bouncer's amplitude is explored. In Section 5.5, the estimation of the maximum amplitude period of the baby bouncer is discussed.

Fig. 3. Three types of baby bouncer inclination: (a)High, (b)Middle, (c)Low

The baby bouncer used in the experiments was the ”Woggy” model from Pigeon. This baby bouncer offers three inclination levels, labeled High, Middle, and Low, in order of decreasing angle (Fig.3). When nothing was placed on the bouncer, the angles were 39, 33, and 26 degrees, respectively. To simulate the weight of a baby, a 3 kg bathing doll and five 2 L water bottles were used as weights, allowing for various weight configurations. In each experiment, the simulated baby's weight is noted, which excludes the weight of the device and only includes the total weight of the bathing doll and water placed on the baby bouncer.

A. Experiment 1: Effect of device on baby bouncer period

1) Overview: To verify whether the device's rotation period matches the baby bouncer's oscillation period, the effect of device rotation on the baby bouncer's period was investigated.

An accelerometer was installed at the clamp located at the top of the baby bouncer to measure its oscillation period. The device was used to rock the baby bouncer, and acceleration data were collected at a sampling rate of 20 Hz for 60 seconds.

The rotation period of the device was set to 700 ms. The baby bouncer's oscillation period was examined under varying conditions of inclination, simulated baby weight, and device rotation angle. The bouncer's inclination was set to Low, Middle, and High, while the simulated baby weight was set to 3 kg, 5 kg, and 7 kg. The device's rotation angle was set to 10°, 20°, and 30°. A total of 81 measurements were conducted, with three trials for each combination of conditions. The results were averaged and compared for each condition.

For comparison, the rotation period of the device itself was also analyzed. An accelerometer was installed on the rotating part of the device to acquire acceleration data during its rotation.

Using the acquired data, a Fast Fourier Transform (FFT) was performed on 1024 data points, ranging from the 101st to the 1124th data points. The first peak value of the FFT was identified as the baby bouncer's oscillation period and was used for further calculations.

2) Results and Discussion: Fast Fourier Transform analysis revealed that the period was 1.40 seconds for all 81 events. The rotation period of the device itself was also 1.40 seconds.

These results demonstrate that it is possible to synchronize the rocking period of the baby bouncer with the device's rotation period by using the device.

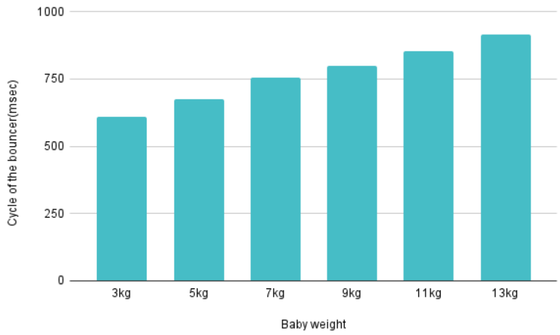

Fig. 4. Changes in baby weight and baby bouncer cycle

B. Experiment 2: baby bouncer cycle variation with baby weight

1) Overview: The relationship between changes in baby weight and the baby bouncer's cycle was investigated.

To measure the cycle of the bouncer, an accelerometer was attached to the clamp section of the device located at the top of the bouncer. Using the device, the bouncer was rocked for only half a cycle and then stopped. To analyze the subsequent rocking motion of the bouncer, acceleration data were recorded at a sampling rate of 20 Hz for 15 seconds.

The baby bouncer inclination was set to High, the device rotation period to 700 ms, and the device rotation angle to 30 degrees. The effect of varying the baby's weight on the bouncer's cycle was investigated under six weight conditions: 3 kg, 5 kg, 7 kg, 9 kg, 11 kg, and 13 kg. A total of 18 experiments were conducted, with three trials for each weight condition. The results were averaged and compared.

To exclude the initial change in the baby bouncer caused by the external input from the device, the first 15 data points were omitted. Fast Fourier Transform (FFT) analysis was performed on 256 data points, ranging from the 16th to the 271st data point. The first peak value of the FFT was assumed to represent the baby bouncer's cycle and was calculated accordingly.

2) Results and Discussion: The results of the Fast Fourier Transform analysis are shown in Fig. 4. When the baby's weight was 3 kg, the period was the shortest at 610 ms, and when the baby's weight was 13 kg, the period was the longest at 914 ms. The results indicate that the cycle was shorter when the baby was lighter and became longer as the baby's weight increased.

The cycle of the baby bouncer itself also varied with the baby's weight. Heavier babies resulted in a longer cycle for the baby bouncer.

C. Experiment 3: Amplitude variation of baby bouncers when device period is varied

1) Overview: From Section 5.1, it was demonstrated that this device can alter the period of the baby bouncer. Section 5.2 showed how the period of the baby bouncer changes depending on the baby's weight. Based on these findings,

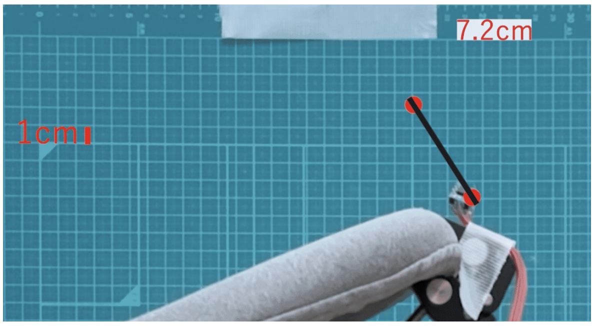

Fig. 5. Amplitude analysis image when the baby weighs 5 kg and the period is 650 msec

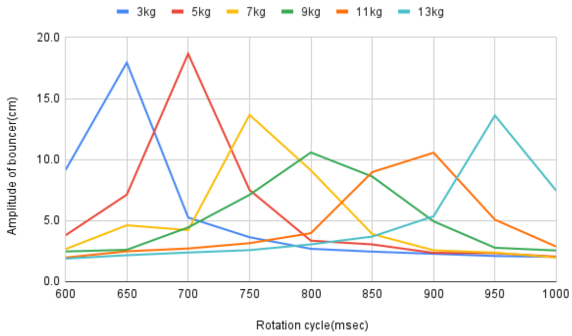

Fig. 6. Changes in baby weight and baby bouncer cycle

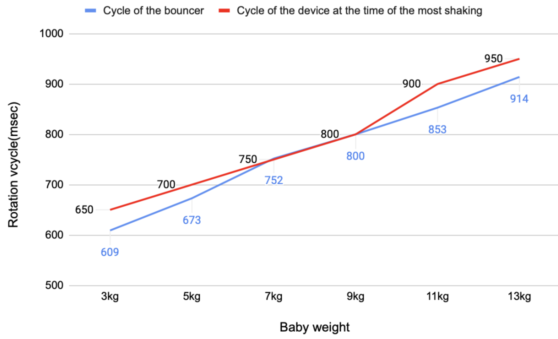

Fig. 7. Period of the baby bouncer itself and amplitude change at the time of the most rocking

we hypothesized that synchronizing the period of the device with the period of the baby bouncer could produce larger rocking amplitudes. To verify this hypothesis, we investigated changes in the amplitude of the baby bouncer when the period of the device was varied.

The amplitude of the baby bouncer was measured by analyzing video footage recorded during the experiments (Fig. 5). The device was installed at the top and center of the baby bouncer, and the bouncer was filmed from a height of approximately 40 cm and a distance of about 90 cm. The camera, background, and baby bouncer were positioned parallel to each other. A craft mat with 1 cm square grids was placed behind the baby bouncer as a reference.

The recorded video footage was analyzed using video editing software. First, a 1 cm reference length was defined based on the grid on the craft mat. The amplitude was then calculated by plotting the highest and lowest points of the baby bouncer's motion generated by the device and comparing the measured length between these points with the defined 1 cm parameter.

The baby bouncer inclination was set to High, and the device's rotation angle was set to 30 degrees. Experiments were conducted under six weight conditions for the baby (3 kg, 5 kg, 7 kg, 9 kg, 11 kg, and 13 kg) and nine rotation period conditions for the device (600 ms, 650 ms, 700 ms, 750 ms, 800 ms, 850 ms, 900 ms, 950 ms, and 1000 ms). A total of 162 amplitude measurements were performed, with three trials conducted under each condition. The results were averaged and compared for each condition.

2) Results and Discussion: The relationship between the device's period and the baby bouncer's amplitude is shown in Fig. 6. The results indicate that as the baby's weight increases, the period at which the largest rocking occurs also increases. Additionally, the amplitude at the period of the largest rocking is significantly greater compared to the amplitudes at other periods.

Fig. 7 presents a comparison between the period of the baby bouncer itself, as investigated in Section 5.2, and the period of the device that produced the largest rocking, as determined in this section.

From these results, it can be concluded that the error is less than 47 milliseconds for all baby weights, indicating that the overall error is negligible. However, for weights of 3 kg, 11 kg, and 13 kg, the error exceeded 30 milliseconds, which is larger compared to other conditions. This discrepancy is presumed to be due to the 50-millisecond interval used for setting the device's period. To investigate this hypothesis, future studies will examine the error when the interval is further refined, such as to 25 milliseconds.

In conclusion, it was found that synchronizing the period of the device with the period of the baby bouncer can generate larger rocking amplitudes.

D. Experiment 4: Amplitude variation with device rotation angle

1) Overview: In Section 5.2, we found that the period of the baby bouncer changes with variations in the baby's weight, and in Section 5.3, we found that matching the period of the device with that of the baby bouncer can produce larger rocking amplitudes. However, larger vibrations are not always ideal when using a baby bouncer. Excessive rocking could lead to accidents, and it would be beneficial if the intensity of the rocking could be adjusted based on the intended use, such as soothing a baby or helping a baby fall asleep. Therefore, this experiment investigated how the amplitude of the baby bouncer changes with variations in the device's rotation angle.

The amplitude of the baby bouncer was measured by analyzing video footage recorded during the experiments.

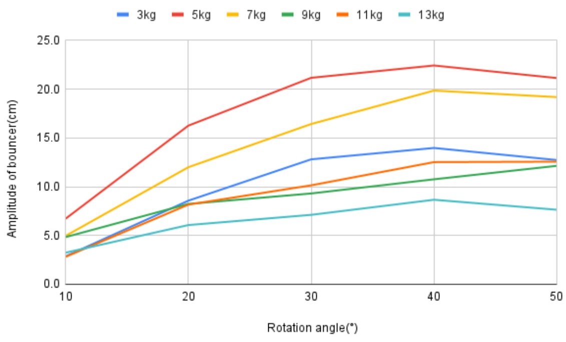

Fig. 8. Amplitude variation with baby weight and rotation period

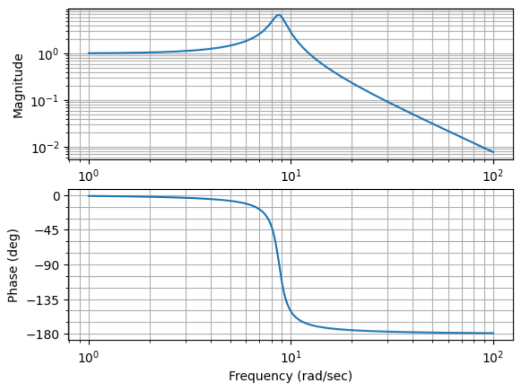

Fig. 9. Bode diagram with 5 kg/High and no external input

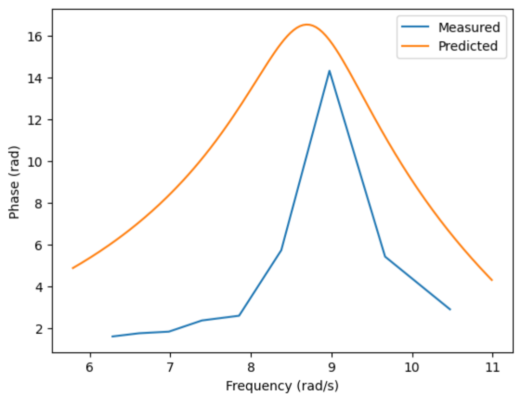

Fig. 10. Comparison of initial state response and frequency response

The conditions for this experiment were the same as those described in Section 5.3.

The inclination of the baby bouncer was set to High, and the period of the device was set to the value that produced the largest rocking amplitude for each baby weight, as determined in Section 5.3. The baby's weight was varied under six conditions (3 kg, 5 kg, 7 kg, 9 kg, 11 kg, and 13 kg), and the device's rotation angle was varied under five conditions (10°, 20°, 30°, 40°, and 50°). The endpoint of the rotation was fixed to the outer side of the device relative to the baby bouncer, while the starting point was varied.

A total of 90 amplitude measurements were conducted, with three trials performed for each condition. The results were averaged and compared across all conditions.

2) Results and Discussion: The relationship between the device's rotation angle and the baby bouncer's amplitude is shown in Fig. 8.

In general, increasing the rotation angle allows the baby bouncer to rock more, while decreasing the rotation angle reduces the rocking amplitude. These results indicate that adjusting the device's rotation angle can control the intensity of the baby bouncer's rocking.

E. Experiment 5: Estimation of resonance frequency of baby bouncer

1) Overview: In this experiment, we assume that the equation of motion of the baby bouncer can be expressed in terms of a second-order delay system and model it with unforced response. The maximum amplitude period of the baby bouncer is estimated and compared with the value obtained in Section 5.3 to determine if this value is accurate.

To obtain the damping constant ξ and fixed angular frequency ω_n in Eq.(1), data were obtained with the external input set to 0.

The weight of the baby was set to 5 kg, the inclination of the baby bouncer to High, and the device was mounted at the top and center of the baby bouncer. To measure the angle change, Xsens dots were placed along the inclination of the baby bouncer near the safety restraints of the baby bouncer. At this point, the weight attached to the device was positioned inward most toward the baby bouncer. Once the baby bouncer was pushed with the hand, data was acquired for approximately 20 seconds, during which time the vibration decayed until the angle change could no longer be visually observed. The least-squares method was used to obtain ξ and ω_n, resulting in $\xi = 8.75$ and $\omega_n = 0.075$. The Bode plot is shown in Fig. 9.

2) Results and Discussion: The initial state response and frequency response are compared graphically. The frequency response corresponds to the amplitude obtained in Section 5.3. Since the amplitude was obtained in terms of length in section 5.3, it was converted from length to angular displacement using the cosine theorem. In addition, the horizontal axis, which was in units of time, was converted to angular frequency(Fig. 10).

It can be said that the values predicted by the initial state response from the Fig. 10 and the shape of the graph actually observed in the frequency response and the angular frequency at the apex are almost the same. However, there is an error. One possible cause is the difference in experimental conditions. Since the experiments were conducted on different days, the position of the babies may have been different. Therefore, we will conduct the experiment again on the same day under the same conditions. Compared to the initial state response, the frequency response showed extremely small values for angular displacements other than the apex. We would like to investigate the difference between the initial state response and the frequency response in detail in the future.

As a future prospect based on the experimental results, we would like to create a system to predict the period of the device so that it can accurately reproduce the movement of a specified amplitude using only the angular variation data. To this end, we will investigate the dependence on the baby's weight and position on the baby bouncer.

VI. LIMITATIONS AND FUTURE VISION

A. Limitations

There are two major limitations associated with using this device.

The first limitation is the use of high-output servo motors, which produce loud motor noise. Since the primary purpose of this device is to soothe the baby, the electronic noise generated by the motor may disrupt the baby's comfort. To address this issue, the use of low-output servo motors or alternative vibration-generating mechanisms will be considered in the future.

The second limitation is the size of the device. The device measures approximately 20 cm in size and weighs around 800 g. Although it is sufficiently lightweight and compact compared to automatic baby bouncers, one of the key advantages of using this device is the compactness of manual baby bouncers. Therefore, it is necessary to further reduce the size of the device to align with this benefit. Additionally, if the device can be stored without taking up much space while remaining attached to the baby bouncer, it would simplify both storage and installation, enabling the development of a more user-friendly system.

B. Future Work

This paper demonstrated the use of a device to automatically rock a baby bouncer. However, the period of the baby bouncer changes depending on the weight of the baby placed on it. As shown in Section 5.3, matching the period of the baby bouncer with the swinging period of the device controlled by the servo motor allows for larger rocking amplitudes. Additionally, Section 5.5 demonstrated that the rocking amplitude of the baby bouncer can be adjusted by changing the rotation angle of the device.

Based on these findings, it is considered that the device could be made more user-friendly and convenient if the servo motor's rotation cycle could be automatically adjusted to recognize the baby's weight and provide appropriate rocking accordingly. To develop a system capable of adjusting the rocking intensity to suit different usage scenarios, we will continue to investigate the effects of changing the device's rotation direction, weight distribution, and weight. Further analysis of the physical phenomena involved will also be conducted.

Although this experiment aimed to maximize the rocking amplitude of the baby bouncer, it is not always optimal to rock the baby bouncer extensively when soothing a baby. Excessive rocking may pose health risks to the baby and could lead to accidents, such as falling out of the bouncer. Therefore, future research will focus on developing a mechanism to control the rocking range of the baby bouncer, ensuring a comfortable and safe environment for soothing and caring for the baby.

VII. CONCLUSION

This paper proposes a small detachable device that can rock a baby bouncer. This device rocks the bouncer by the rotation of a servo motor. Through experiments in which the rotation period of the device was varied, it was shown that the baby bouncer can be rocked significantly by matching the period of the baby bouncer and the rotation period of the device, and the size of this rocking can be adjusted. In the future, control of the shaking and muffling and downsizing of the device will be considered.

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