A Practical Development of the Suspender Device that Controls Load Rotation by Gyroscopic Moments

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Abstract

In the transportation of construction material using tower cranes, the hanging loads are frequently rotated by external disturbances. This lowers the efficiency and the safety of this kind of work. For the purpose of reducing load rotation and dangerous works, a suspender device activated by a gyroscope has been developed. This device controls load rotation via two different modes of the gyroscopic moment. In the active control mode, the load turns in high response to commands issued by the controller and can be correctly set in position at the desired angle. In the passive control mode, the load can be kept in position regardless of crane movement or outer disturbance. As a result of applying the suspender device to construction work, the cycle time for load transporting is effectively reduced and shortening of construction period is carried out. The operations are preciously regulated by wireless remote control, and dangerous manipulation works are drastically reduced. This device generates no noise and guarantees a comfortable and safe construction environment.

1.Introduction

Most building materials and components, such as steel beams and precast concrete panels are generally conveyed using tower cranes. The number of cranes at each construction site is limited, and the operation efficiency of each crane influences the speed of construction. The load on a crane can move freely in the horizontal plane because cable is not restricted and this is no torsional resistance. Thus, the load is easily rotated by external disturbances, such as wind and inertia reactions accompanied by crane boom slewing and movement of the crane itself. Once load rotation takes place during transportation, the load can not be mounted at the setting position by suppressing the rotation, and then transportation has to be temporarily interrupted. In fact, at several construction sites, including high-rise buildings and buildings facing the sea where strong winds often occur, transportation is frequently delayed. In the worst conditions, the work is discontinued all day. Using conventional methods, load rotation had been eliminated by pulling assistant ropes hooked to the load, but these additional operations are dangerous and time-consuming work. Thus, there has been a strong demand for construction site operators to find a way to suppress load rotation.

In the past, several types of suspender devices were developed to control load rotation in Japan. The torque source of these came from wind force, which was generated by actuating large scale axial fans installed on each side of the suspender beam. Load rotation was controlled by regulating the flow rate by opening a valve and the direction of the fans. But angular velocity of the load gradually increased with time. Manual responses to load rotation were so slow, and it was very difficult to master the fluent operation of this device. Further, as the power generator for fan is noisy, the work environment and the surrounding area was affected by this.

Under these circumstances, the conventional fan device far from satisfactory and technical improvements are required. As a result, a unique type of suspender device utilizing gyroscopic moment has been developed and applied to actual construction work. This device is called GYAPTS. (GYroscopic APplication To Suspender). Gyroscopes have been widely used in the control of machine such as vibration stabilizer and angular orientation sensor. In construction field, the gyroscope have been to vibration isolation system of the building or tower. Our co-authors has applied it to vibration control of load gondola [1]. However, the gyroscope has not been to the control of load rotation before.

In this paper, the outline of GYAPTS and its use in construction work is described. The result of a work study and its operation efficiency are also explained in detail.

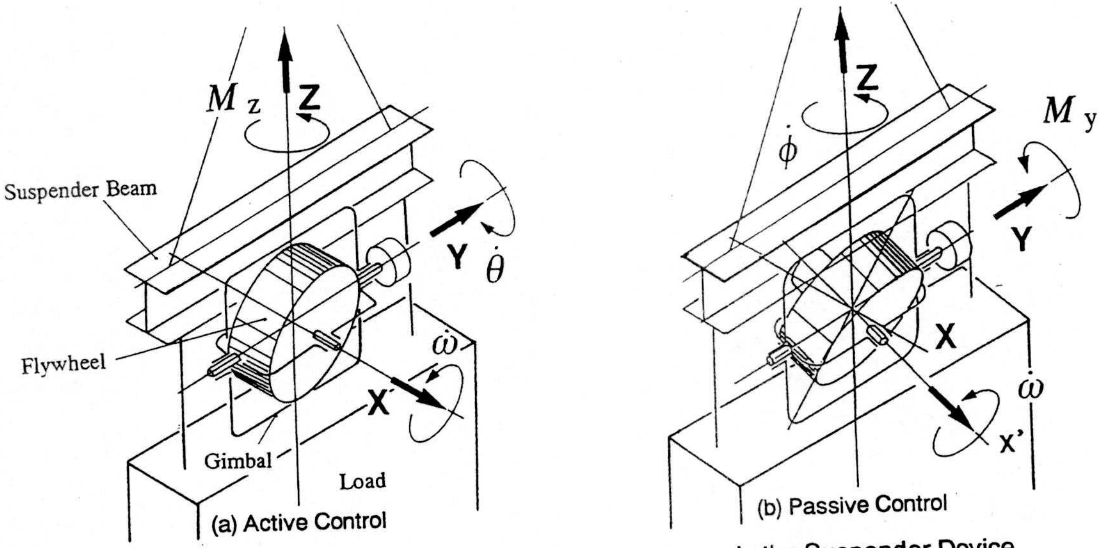


Figure 1 A Schematic Mechanism of the Gyroscope in the Suspender Device

2. Outline of GYAPTS

2.1 Mechanism of the gyroscopic moment and its dynamic behavior

A schematic mechanism of the gyroscope used in this suspender device is indicated in Figure 1. The load is hung in the vertical direction and it moves in a horizontal plane. The axis of the flywheel and its right angle axis to the gimbal frame in the gyroscope are assumed to be the x and y axis respectively.

When a high spinning flywheel is turned around the y axis through the gimbal frame, an amplified moment M_z is generated around the z axis as shown in Figure 2 - (a). M_z is the gyroscopic moment obtained, as shown by equation (1). Where I_x and $\dot{\omega}$ represent the inertia moment and angular velocity of the flywheel, and $\dot{\theta}$ is the angular velocity of gimbal frame.

$$M_z = I_x \cdot \dot{\omega} \cdot \dot{\theta} \tag{1}$$

To control this active moment in this device, the load is correctly set in position at a desired angle.

On the other hand, as indicated in Figure2-(b), when the load is rotated around the z-axis at an angular velocity $\dot{\phi}$ representing an external disturbance such as wind, the gyroscopic moment M_y is generated around the y axis. Where M_y is represented by;

$$M_y = - I_x \cdot \dot{\omega} \cdot \dot{\phi} \tag{2}$$

As M_y acts negatively around the y axis, an other gyroscopic moment opposing the external disturbance is also generated instantly by M_y. Therefore, the load resists external disturbance and the current angle of the load can be preserved. By controlling this passive moment, the load is automatically kept in position regardless of any disturbance.

The behavior of load rotation with the gyroscope has been analyzed by numerical simulation in order to obtain values for its basic parameters and characteristics. Each axial Euler's equation of motion for gyroscope taking the inertia moment of the load into consideration is given in equations (3) ~ (5).

$$I_x \ddot{\omega} - I_y \dot{\theta} \dot{\phi} \cos\theta = 0 \tag{3}$$

$$I_y \ddot{\theta} + I_x \dot{\omega} \dot{\phi} \cos\theta = M_y + C_1 \dot{\theta} + K_1 \theta \tag{4}$$

$$I_z \ddot{\phi} + I_y C_2 \dot{\phi} - I_x \omega \theta \cos\theta = M_z + K_2 \phi \tag{5}$$

where I is the inertia moments for each axis, C is a constant value which is proportional to angular velocity, K is a constant value which is proportional to the angle, M_y is control torque and M_z is the external disturbance force.

Two case simulations using gyroscopic moments were carried out; that is, orientation control at a desired angle and preservation control at the current angle. The results of the numerical simulations and experiments are as follows:

(1) Orientation control:

As shown in Figure 2, by giving a constant torque M_y at time=0, a gyroscopic moment is generated in the device. Then the load begins to rotate at an angular velocity and the gimbal frame turns and rests at an angle.

When the load arrived at desired angle, the torque in the flywheel is zero. Then the flywheel is turned inversely by the gyroscopic moment accompanied with load location, and the load stops moving instantly. In the experimental result, as frequent twisting of the cables, which is imparted

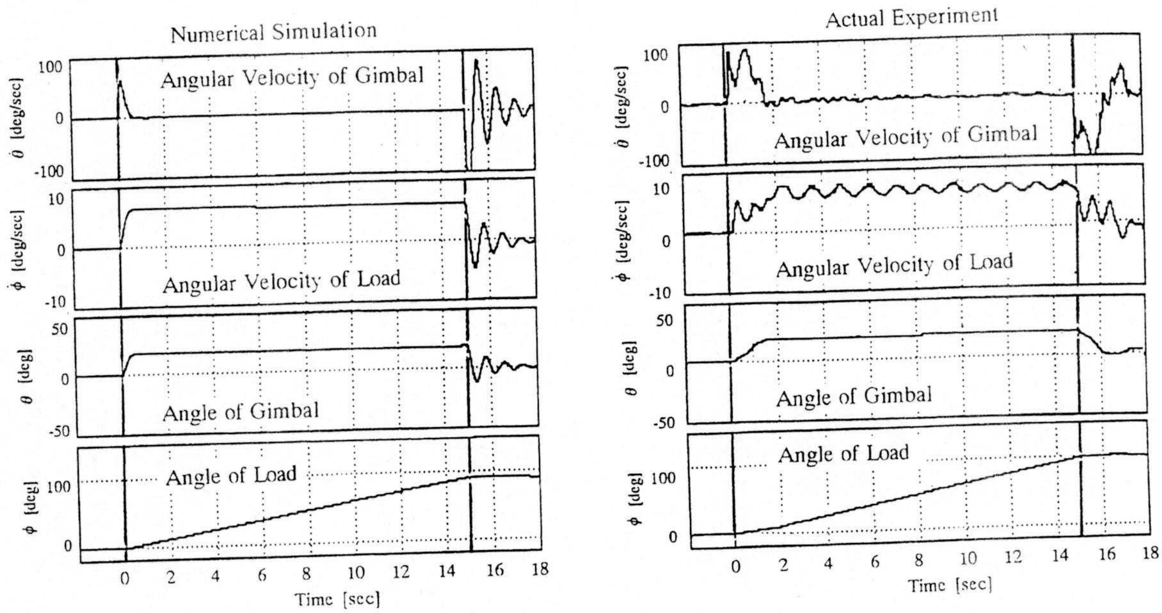


Figure 2 The Behavior of the gyroscope and the load with angular Orientation Control

gyroscopic moment is occurred, and small waves of angular velocity were observed. The angular velocity of the load corresponded to that simulated. The response to starting and stopping the load rotation is extremely sharp.

(2) Preservation control:

With a free rotating load, in which the gyroscopic effect is excluded at the initial stage, when the passive gyroscopic moment acts on the load at ϕ =0, the behavior of the load is shown in Figure 3. The load stops rotating suddenly and the current angle is preserved. At the same time, the gimbal frame turns a lot and the external disturbance is absorbed by the resistance accompanying with the gimbal turn. These passive moments against external disturbances act on the load successively as far as the angle of gimbal is limited. In GYAPTS, as the resistance capacity absorbed by the external disturbance is designed to be magnified, the current angle of the load is sufficiently preserved during transportation.

From these numerical and experimental studies, we conclude that gyroscopic moments can be used effectively in load rotation control, and then the suspender device, GYAPTS, which we developed.

2.2 Specifications and Characteristics of the suspender device

In this development case, we consulted employees at several construction sites where load rotation was a problem, and as a result produced a practical suspender device. The content of GYAPTS is as follows;

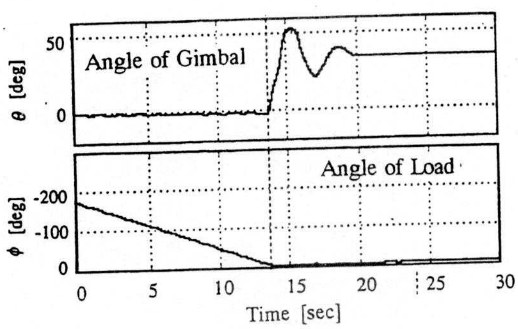


Figure 3 The Behavior of the gyroscope and the load with angular Preservation Control

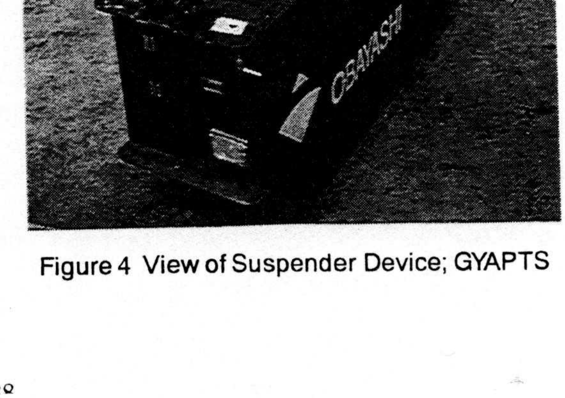


Figure 4 View of Suspender Device; GYAPTS

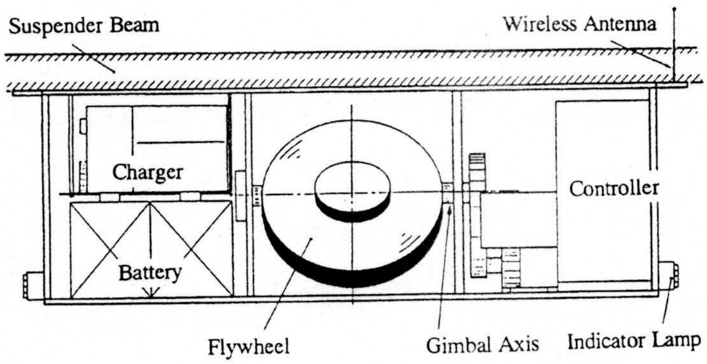


Figure 5 Inner Structure of GYAPTS

Table 1 Specifications of GYAPTS

Type	06	25
Device Form (Length) (Wide) (Height)	 1.4 m 0.5m 0.5 m	 1.80m 0.73m 0.75 m
Weight	400 kg	1,100 kg
Rorating Drive	Gyroscopic Moment	
Inertia Moment	6 ton m^2	25 ton m^2
Angular Velocity	90 deg / 15sec	
Power Supply	DC12V 2 sets	DC12V 4 set

(1) Appearance and inner structure:

The suspender device, GYAPTS, is box-like in shape as shown Figure 4 and it is fitted on a beam or the load itself. Figure 5 shows the inner structure of the suspender device. From herein the gyroscopic moment is generated. A large scale gyroscope, as an actuator, is installed in the center part and the axis of the gimbal frame is combined with the torque motor thought a chain. The spinning motor of the flywheel and the torque motor, which are exclusive motors, were developed especially for this device. The control system and power supply components are set on each side of the actuator.

(2) Specification and type of GYAPTS:

By investigating several kinds of building material of different shape, weight and inertia moment used at construction sites, two types of suspender device have been produced according to the magnitude of the inertia moment of the load which it is designed to control. With these devices, 6-type or 25-type, the rotation control of most building material can be realized sufficiently. Specifications of the device are presented in Table 1.

(3) Selection of GYAPTS

The type of GYAPTS used should be determined by the inertia moment of the load. The load, in which aspect ratio is large, as in a steel beam, is calculated with a simplified equation (6). Where W and L represent the weight and length of the load.

$$I_z = W \cdot L^2 / 12 \tag{6}$$

Figure 6 indicates the relationship between load characteristics and the inertia moment. In this range of inertia moments, the device type needed can be determined easily. The vague standard, which was only based on weight, used in the conventional suspender device has been greatly improved. If the inertia moment of the load is

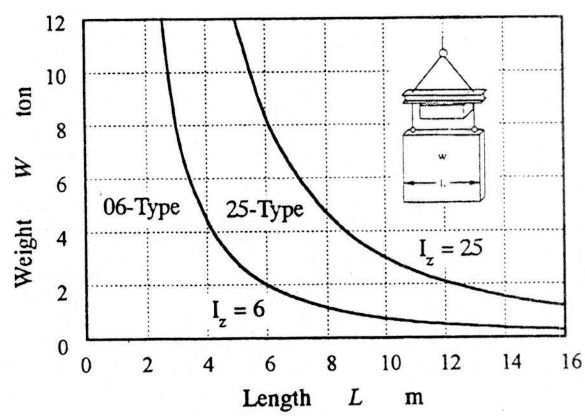


Figure 6 The Standard Inertia Moment for GYAPTS

below the standard inertia moment curve for each device, the angular velocity of the load is regulated at a rate of 90 degrees per 15 second. This rate is equivalent to walking pace, and is not dangerous. If the inertia moment is more than that of the standard inertia moment curve, only the angular velocity is less than the normal angular velocity.

(4) Control mode of operation

This device can be operated by two methods by using wireless remote controls.

During manual operation, three modes with gyroscopic moments can be selected as follows;

a. Active control mode: the load is forcibly rotated and oriented at the desired angle.
b. Passive control mode: the load is maintained at the current angle.
c. Free control mode: by releasing the gyroscopic effect, the control of the load is left to the operator

During automatic operation, the load can be kept in position despite of the external disturbance via feedback control, in which the variation angle from the angle set is determined by the angular orientation sensor.

(5) Power supply system

As this device uses little power, a storage battery can be used as the main power supply. By recharging batteries after work daily, the suspender device can be continuously operated everyday. Noise and air pollution are serious problem with the power generators in conventional devices, both of which are improved by the use of gyroscopic moments.

(6) Safety indication

In either the active or passive control modes, safe lamps are blinked. These interval of light express the condition of each control mode.

3. Application conditions of GYAPTS at construction sites

3.1 Typical operation methods

This device, introduced to actual construction sites, has been used in the transportation and of several construction materials. A flow chart of the typical methods of GYAPTS operation is indicated in Figure 7. By selecting the operation method according to the weather conditions either normal wind or strong wind, work efficiency can be improved considerably.

(1) Normal wind operation

a. Stock yard stage: with active control, the angle of the suspender is oriented to that of the load.
b. Transportation stage: with passive control, the load is constantly kept at the current angle despite external disturbance
c. Workshop stage: active control again, the angle of the load matches the mounted angle. Next, with free control, the operation of the load is left to the worker and then the setting work is done.

(2) Strong wind operation

a. Stock yard stage: equivalent to normal wind operation
b. Transportation stage: in the joint control free and active modes, load rotation is suppressed as much as possible. Because the consumption of the gyroscopic moment is so huge during strong wind, it is necessary to save it until the next stage.
c. Workshop stage: with active control, the angle of the load matches the mounting angle. Next, push the passive control switch and the load is set at that angle. Preservation of angular orientation guarantees faster and safer building construction

Figure 8 shows an example of mounting work for aluminum curtain wall acted on by strong wind, which frequently occurs during the construction of high-rise buildings. By following the strong wind operating procedure mentioned above, efficient work was carried out.

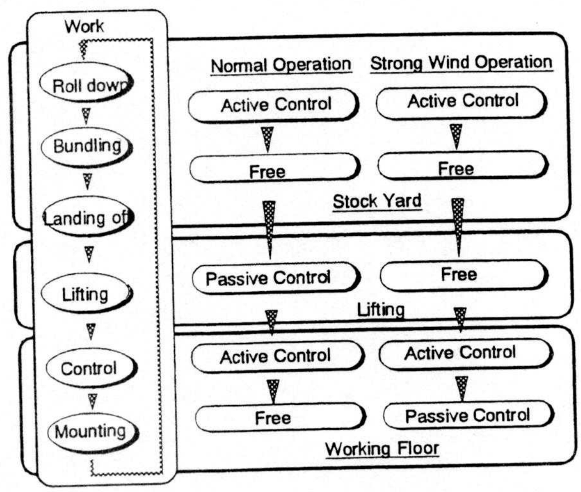


Figure 7 The Typical Method of GYAPTS operation

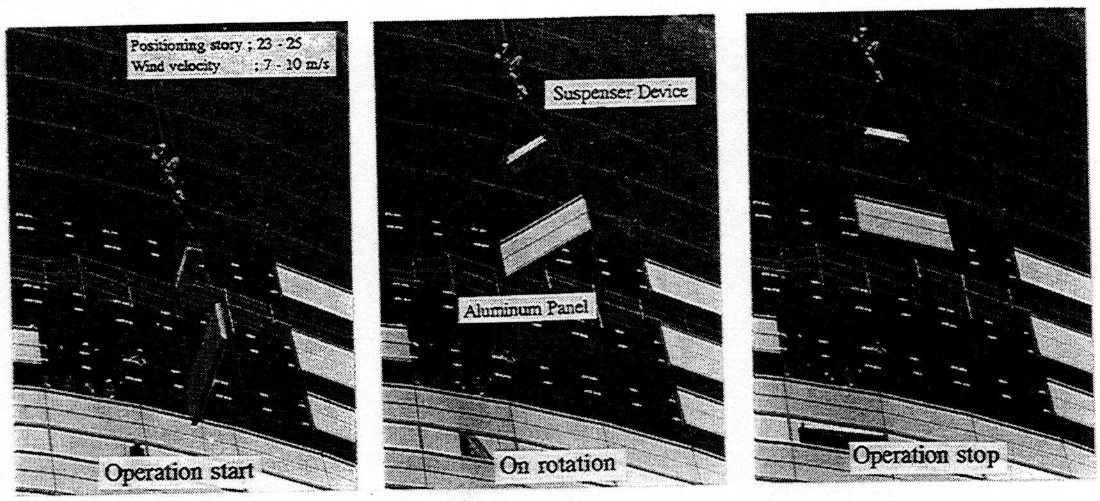


Figure 8 An Example of Mounting Work for Aluminum Curtain Wall

3.2 Application condition by using GYAPTS

It has been three years since the GYAPTS was developed, and more than 30 sets of GYAPTS have been applied to more than 20 construction sites. The work conditions and the execution records of this device at major sites are shown in Figure 9 and Table 2, respectively.

Evaluation of these results showed that, the cycle time for the transportation and mounting of the load was effectively reduced, as was the work period. The operating conditions were preciously regulated by wireless remote control, thus the amount of dangerous manipulation work was drastically reduced.

Table 2 The Execution Records at Typical Site

Site	Example 1	Example 2 (Ref.[2])
Period	1994. 8 - 1995. 10	1995. 12 - 1996. 8
Place	Osaka City, Japan	Chiba City, Japan
Length	256 m	85 m
Load	Aluminum Curtain Wall ($I_z = 6$)	PCa.Floor Slab and Balcony ($I_z = 18$)
Site Condition	High-rise Building Facing to the sea Strong wind	Automated Construction System for RC-building Strong Wind
Numbers	25-type, 2 sets	25-type, 3 sets

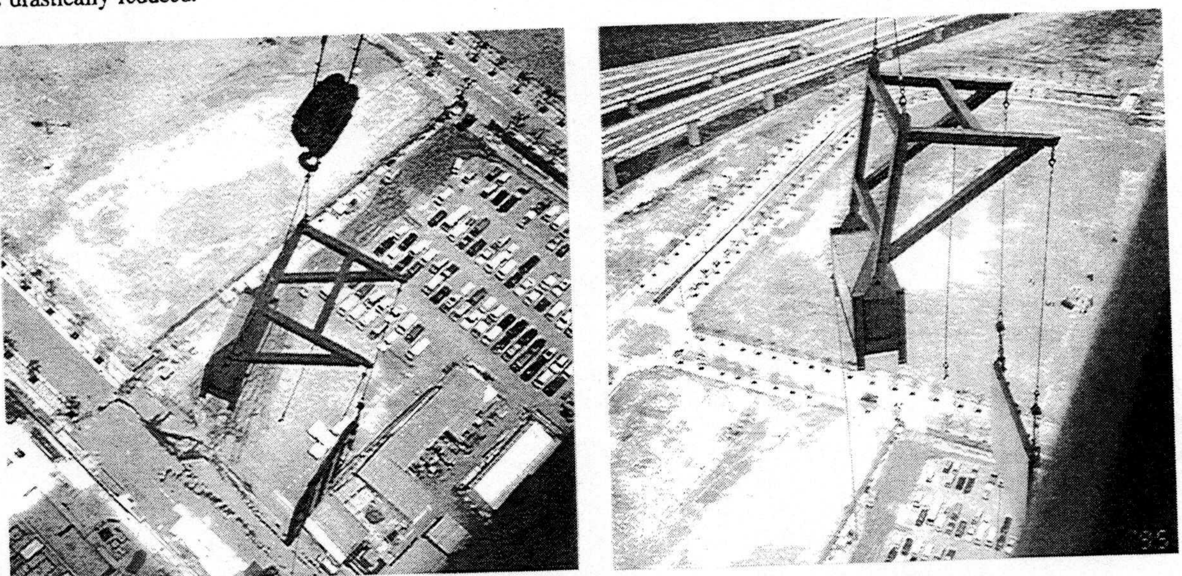


Figure 9 The Work Condition using GYAPTA at Actual Construction Site (Example 1)

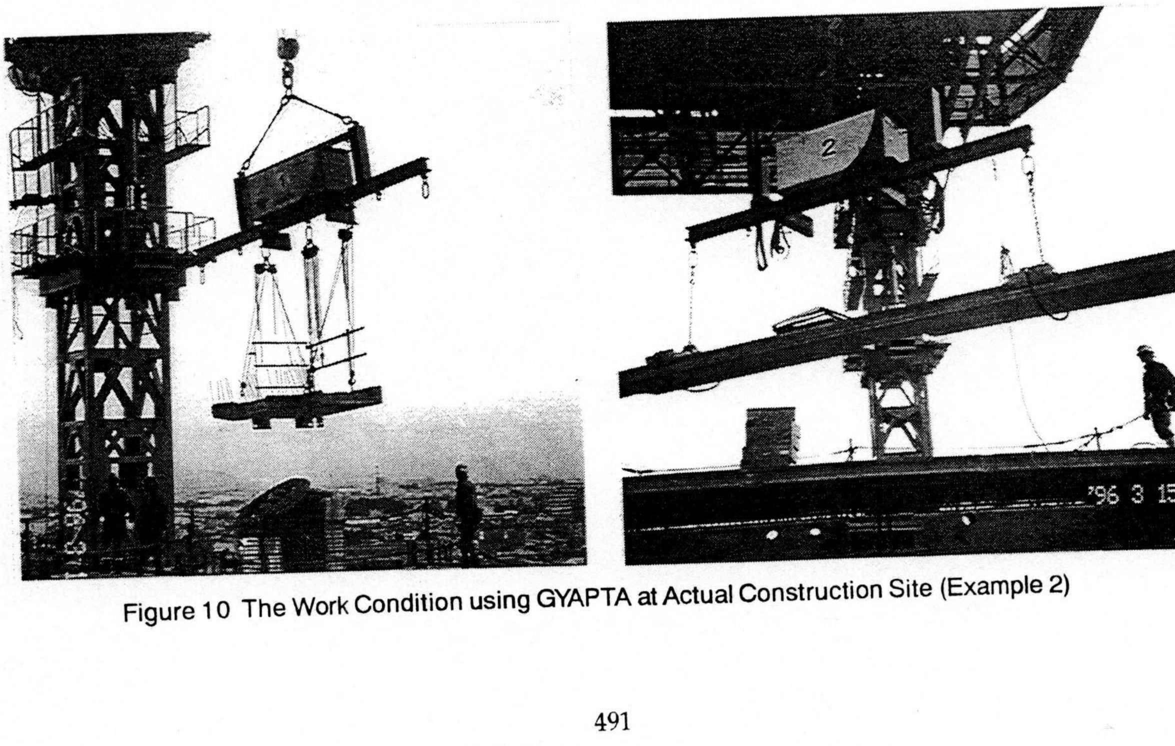


Figure 10 The Work Condition using GYAPTA at Actual Construction Site (Example 2)

4. Operation Efficiency of GYAPTS and a work study of the use of GYAPTS

In order to improve the efficiency of GYAPTS and for it to be a useful suspender device in construction work, working conditions with GYAPTS were analyzed from the following points;

a. Device performance
b. Productivity improvement
c. Reduced construction time
d. Work environment safety

The construction site investigated work study is shown in Figure11. The reasons why GYAPTS was introduced to this site are as follows;

(1) The construction site was next to the sea and strong winds of more than 10 m/s were frequently generated. Rotation and swinging of the load was dangerous

(2) Due to the positioning of the tower crane at the center of constructing building, which is semi-circle in sharp, the load was predicted to rotate during transportation along the circumference of building.

(3) PCa panels with balcony fixtures rotated easily, making it difficult to attach them to the building.

Because of these serious construction restrictions, the introduction of GTAPTS was vital at this site.

4.1 Device performance

At the construction site, the transportation and mounting work with GYAPTS was carried out by method of strong wind operation as mentioned in 3.1. The angular orientation of the PCa panels directly before mounting is indicated in Figure12. Without the gyroscopic effect byree control mode during transportation between the stock yard and mounted floor, the PCa panels were rotated

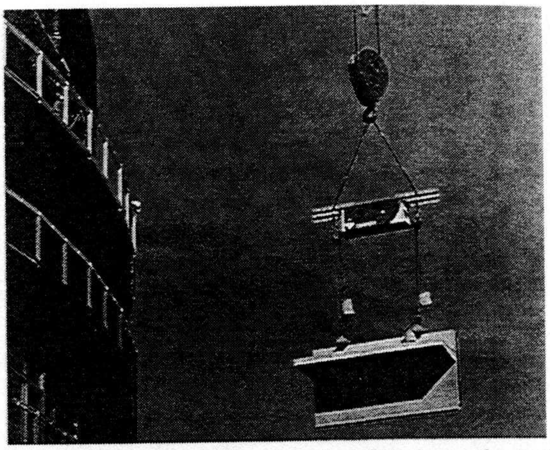


Figure 11 View of Construction Site Investigated Work Study

irregularly in varying directions depending on the strength and the direction of the wind.

The average angular velocity and average rotation time per 90 degrees, which were calculated from the angle and the time taken to rectify each load to the correct mounted angle, is shown in Table 2. Where the conventional method was used the amount of man power needed using assistant ropes and sticks as Figure 13-(a), and where the new method was used the amount of automated work with GYAPTS is shown in Figure 13-(b)

Table 3 Evaluation of Device Performance

Method	Angular Velocity deg/sec	Rotation time 90 deg/sec
Conventional	2.04	44.1
Original	4.91	18.3
Standard Value	6.00	15.0

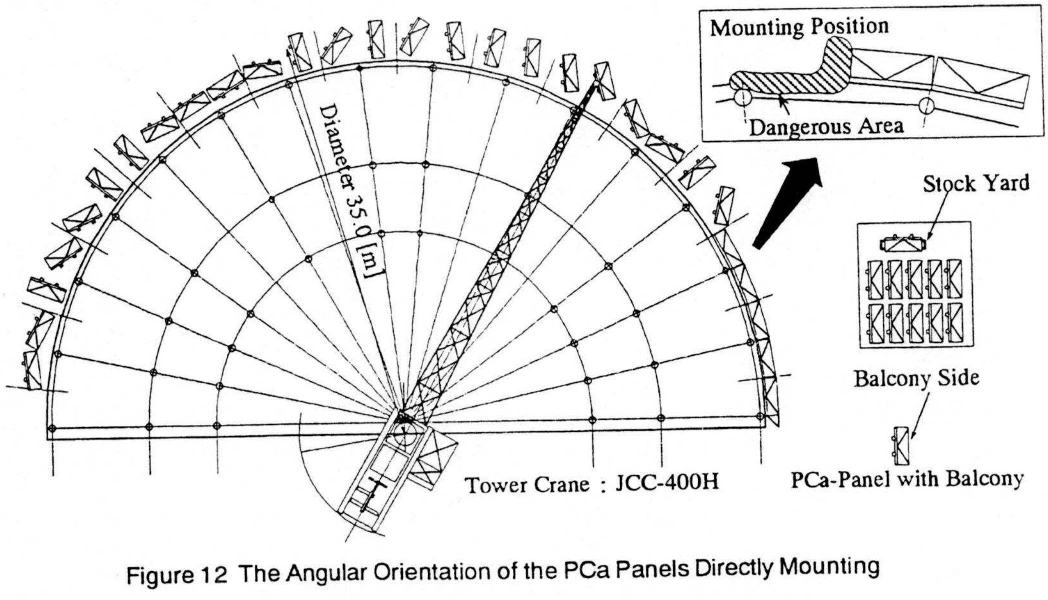
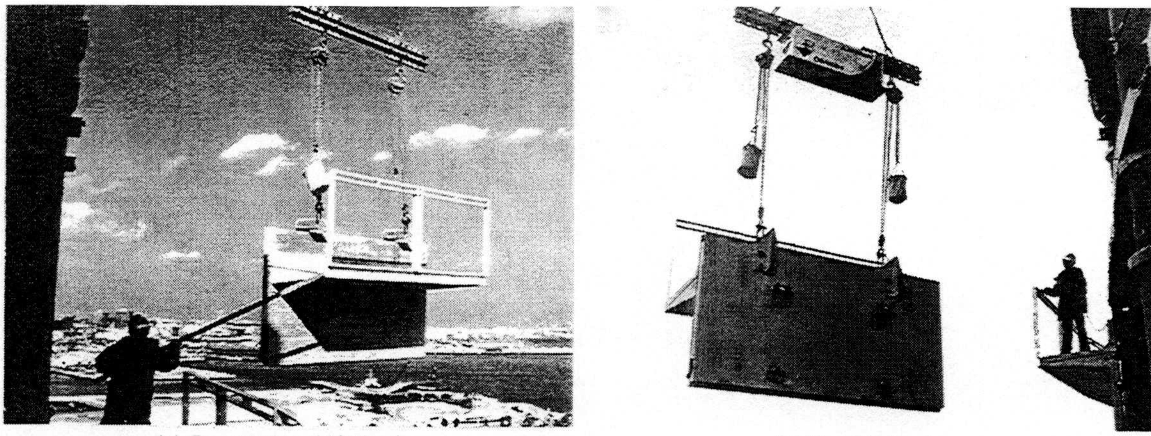


Figure 12 The Angular Orientation of the PCa Panels Directly Mounting



(a) Conventional Method (b) New Method

Figure 13 View of Construction Work for the Rotation Control

The rotation time of the new method was 40% that of the conventional method. This is because it took so much time and manpower when the PCa panel began to move and stop in the wind. But, with the new method, the amplified gyroscopic moment and its high responses acted on angular orientation effectively. In comparison of the standard angular velocity of GYAPTS, despite strong winds of more than 10 m/s, the operating efficiency of GYAPTS was recognized to be over 80 %.

4.2 Evaluation of the work study

The transportation and mounting work was divided up into stages, and the time spent on each was measured individually. Herein, we focused on mounting work included angular orientation work, initial mounting work and adjustment work.

(1) Productivity improvement

The amount of manpower, which is presented by the product working times and number of workers, was calculated for every work stage, and the ratio between the amount of manpower in each stage to the total amount of manpower in whole work is shown in Figure14. When comparing the ratios of the new method to those of the conventional method, the mounting work with GYAPTS was reduced by about 30% and that the total amount of manpower was also reduced about 10%. Figure 15 shows the actual data for each mounting procedure. With the conventional method, which is influenced by the wind, the amount of manpower were varied greatly. However, data using the new method was generally consistent. The time taken to complete the mounting work directly influenced the total time spent working, so that the reduction of the amount of manpower in the mounting work by GYAPTS contributes the raising productivity significantly. During the mounting of more than 500 piece of PCa panels, a consistent working will improve work efficiency and aid construction planing.

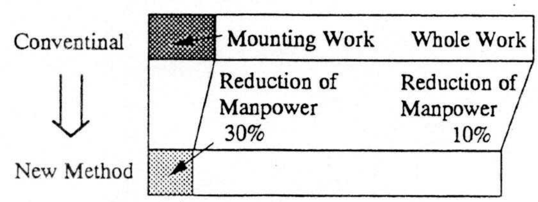


Figure 14 Comparison of Manpower by Conventional and New Method

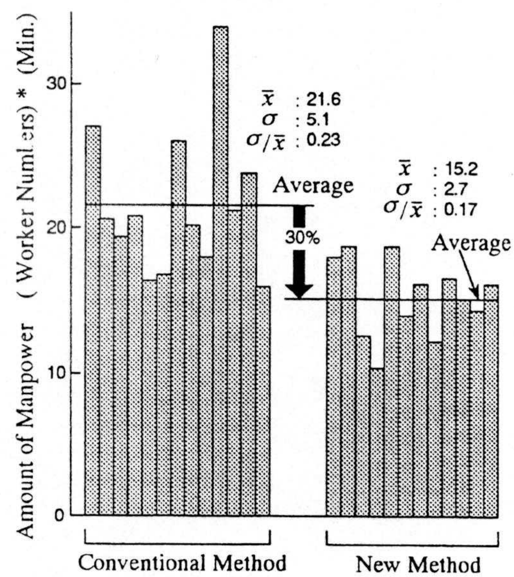


Figure 15 Actual Data of Each Manpower for Each Mounting Work

(2) Reduced construction time

The average amount of time spent on each mounting work, which is made dimensionless by the average amount of time spent on mounting work with the conventional method, is shown in Figure 16. The time spent on angular orientation work was reduced by half with the new method, and the time needed for the initial mounting work was

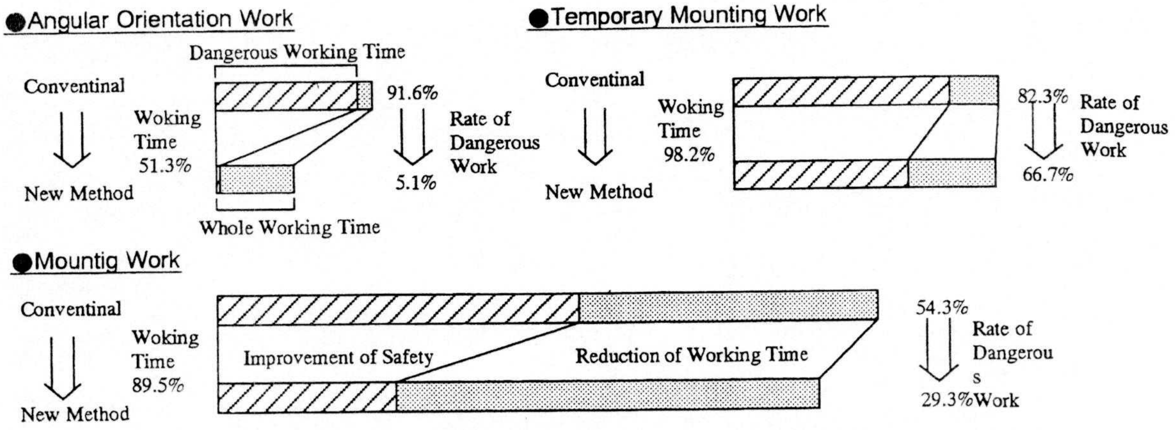


Figure 16 Evaluation of Working Time and Dangerous Working Time by Work Study

almost equal. This is because the initial mounting work depends on the movement of the crane itself. But, as the angular orientation of the load was preserved by GYAPTS during the initial mounting work, next the adjustment work was easily finished and its spending time was shorted. The whole mounting procedure was completed about 10% quicker.

(3) Safety improvement

In order to analyze the safety of mounting work with GYAPTS, dangerous work in the areas, represented by the oblique lines in Figure 12, have been defined. Dangerous work includes the following;

* Direct manipulation work to control the load
* Indirect manipulation work with assistant tools such as ropes or sticks to control the load

The ratio of dangerous working time to the total working time is shown in Figure 16. With the new method, the amount of danger time during angular orientation work was drastically reduced because the workers was rarely entered the dangerous area when operating GYAPTS with the wireless remote control at a distance. And the dangerous time during initial mounting work was also reduced by 15% due to the diminished the amount of manipulation work. Therefore, the total dangerous time during mounting work was shorted by about 25%, and then the safety of mounting work was improved considerably.

5. Conclusion

A suspender device which controls the load by gyroscopic moments has been developed and applied to actual construction work. To investigate the operation efficiency and work conditions , the work study was carried out. The results are summarized as follows:

(1) By analyzing the behavior of the gyroscope, the capabilities of GYAPTS have been explained in detail. A high response angular orientation and present angular preservation of the load could be realized despite the wind.

(2) This device is easily operated by wireless remote control without any special license. Due to its low power consumption and quietness , it is considered to be a most suitable device for construction work.

(3) Evaluation these results of applying the device during construction work at various sites, the cycle times for transportation and mounting work were effectively reduced and reduced construction time was almost accomplished.

(4) Operation efficiency of GYAPTS was recognized to be over 80 % during strong winds of more than 10 m/s. By using GYAPTS, the amount of the time spent on angular orientation work was decreased by 40% in comparison with the conventional method.

(5) By work study, the amount of manpower during the mounting work during and the whole work with GYAPTS was reduced by about 30% and 10% respectively. The total amount of dangerous time during mounting work was shorted about 25%.

Besides, considering that only one day of the mounting work with GYAPTS was interrupted by strong wind, reduced construction period is sufficiently carried out.

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References

[1] Kanki H., "Development of CMG Active Vibration Control Device for Gondola", Proceeding the First International Conference on MOVIC, 1992, pp 310 ~315.

[2] Wakisaka T., "Automated Construction System for High-rise Reinforced Concrete Buildings", Proceeding 14th international conference on ISARC, pre-print.