ABCM Symposium Series in Mechatronics - Vol. 4 - pp.120-126

ACTIVE CONTROL SYSTEM TO STABILIZE SUSPENDED MOVING VEHICLES IN CABLES

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Abstract. *During the last decades, many researches and studies have been done about suspended vehicles like in chair lifts, cable cars, carrying and assemblies of parts in the industry. Suspended vehicles behave like a pendulum and they are susceptible to the action of external forces which cause oscillations and unwanted swing at the vehicle that may affect function and security of the vehicle. For several applications it is important to keep the physical stability of suspended vehicles (or part of them), such as in autonomous robots for inspection. In suspended systems it is very difficult to apply external forces to correct its position due the swing; so, it was proposed a new stabilizing system for suspended vehicles based on the conservation of energy and quantity of motion. Using only internal components of the suspended vehicle, the mass of the system was separated in two parts: an active mobile part that stabilizes a fixed part such as the structure of the vehicle. In this work, it is described an active system for swing control on suspended vehicles, able to soften the effects of external forces that can dangerously damage the performance of the vehicle. An autonomous off-board microcontroller with feed-back program was assembled to stabilize the structure of the vehicle by using an inclination sensor attached to it. A DC motor is used to move the mobile part of the suspended vehicle to correct the equilibrium of the vehicle's structure. The microcontroller program based on proportional-derivative control system was implemented and tests were performed on a prototype vehicle. A good performance of the system was obtained with an efficient and fast stabilization of the prototype structure under the action of external forces, such as wind forces.*

Keywords: *suspended moving vehicles, stability control, active suspension, feed-back control*

1. INTRODUCTION

The use of suspended vehicles is a fact since many centuries ago, one of the first data related to the use of suspended vehicles reports about the use of them to transport of stones for building a Chinese fortress in 400 b.C, another data reports the use of suspended vehicles in transport of people and loads throw gorges in Japan in 200 b.C. During many years the use of suspended vehicles was limited just for transport of loads and people to places with difficult or impossible access by land vehicles. During the last decades, the suspended vehicles and the available technological resources have been presenting a constant evolution; this fact has been making a suitable environment to development of suspended vehicles able to perform a wide range of activities. An interesting application of suspended vehicles is their use in activities related to inspection and maintenance of power transmission lines.

Nowadays, the inspection of power transmission lines is done manually by electricians who walk along to the length of the line to be examined, by using binoculars and, sometimes, thermal cameras. The electricians perform the visual inspection of the transmission lines and its components, looking for signals that can imply in futures failures. Such inspections have low degree of precision and reliability because it depends on the ability of the electrician.

Several times it is necessary that the electrician climb up the transmission towers or ride in gondolas suspended on the transmission line to perform inspection, with high risk to the electrician life and it need to be done with the transmission line turned off. Nowadays, turning off the transmission line is almost an impossible operation due to the crescent demand for energy and the big money related to energy distribution.

An alternative form to avoid turning off the transmission line and to ensure the safety of the electrician service is doing an aerial inspection. The energy company rent a helicopter to transport the electrician around the transmission line and the electrician film the line with a high resolution video camera, or with a thermal camera. This is an expensive solution, and the quality of the operation can't be ensured in bad climate conditions. Among the researches aiming the improvement of the inspection services in power transmission lines, the feasibility of using mobile robots to perform part or the whole inspection of transmission lines has an important place. The researches about this application have started in the beginning of the 80's.

In almost all of the suspended vehicles it is desirable a good physical stability to ensure safety and high quality of the inspection performed by the mobile robot. This fact shows the necessity of the studies concerned to mechanisms able to keep the physical stability of such mobile robots. Suspended vehicles behave like a pendulum and they are susceptible to the action of external forces which cause oscillations and unwanted swing at the vehicle.

In this work it is presented a study of an active stabilizing control system applicable on suspended vehicles, that do not make use of external forces.

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2. PREVIOUS WORKS

Several mobile robots supported by cables were developed with different moving mechanisms and different principles of operation. The majority of the studies aim to build full autonomous robots, such as reported by Sawada et al. (1991) and Aoshima et al. (1989). Their robots moves autonomously by mean of wheels, and has a mechanism to transpose all the obstacles in the transmission line. Tsujimura et al. (1996) reports a mobile robot designed to be applied in power transmission lines, using a kind of legs to move and transpose the obstacles on the cable. Zhu et al. (2006a, 2006b, 2006c, 2006d, 2006e) report a study showing a mechanism based on a centroid system. This system makes easier the transposition of obstacles just with one motor unit.

In the case of mobile robots for inspection of transmission lines, the performance of the operation depends on the quality of the images caught by the camera of the robot. Such quality of the images is directly related with the moving velocity and stability of the robot; if these facts are not observed, the application of suspended robots for the inspections in high power transmission lines can become impracticable. Even in systems where the swing does not disturb the robot operation, high oscillation can collapse the system.

Searching for reference works about stability of suspended mobile robots, it is observed that only few works present a detailed study on how to keep the robot stability. Many of them just mention the swing problem and the influence of the wind on suspended robot, but do not present a solution or mechanism to keep the robot stability.

Nishihara et al. (1992) describes some theoretical analysis of passive and active mechanisms based on the principle of gyroscopic moment to stabilize suspended bodies. Matsuhisa et al. (1995) describes a theoretical analyses of passive mechanisms based on mass-spring systems to stabilize ropeway carriers, that can be applicable to any suspended body. Kanki et al. (1994) describes an active device to control the vibration in gondolas, the device is also based on the principle of gyroscopic moment.

3. PROPOSED MECHANISM

In suspended systems it is very difficult to apply external forces to correct its position due the swing, so the first requirement to develop a mechanism to keep the physical stability of suspended vehicles is to applies an actuation method for stabilization of the vehicles structure using only internal elements of the vehicle. By using the principles of conservation energy and quantity of motion it was proposed an idea to separate the mass of the suspended vehicle in two different parts: a fixed mass such as the structure of the vehicle and another mobile mass composed by the heavy battery, as schematically suggested in figure 1.

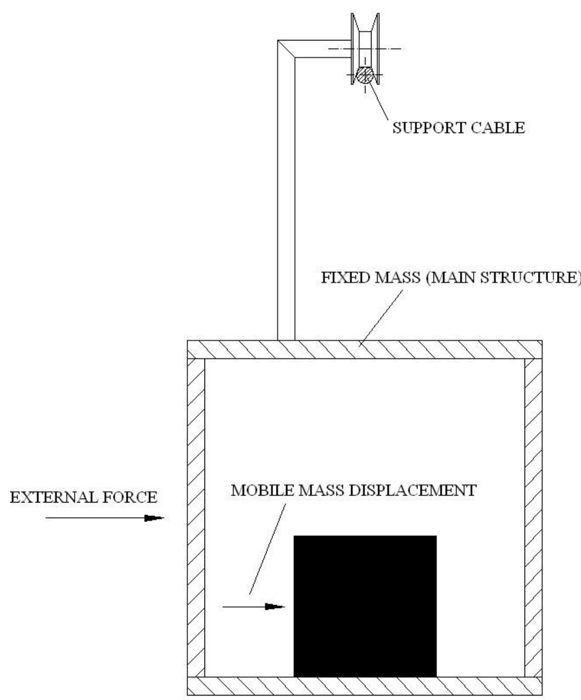

Figure 1 – Operation principle of the proposed mechanism

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In a system the quantity of motion $\vec{Q}$ is defined like:

$$\vec{Q} = m \cdot \vec{v} \tag{1}$$

Where, m and $\vec{v}$ are respectively mass and velocity of the system. In a system with many different parts the quantity of motion is defined like:

$$\vec{Q}_{sistema} = m_1 \cdot \vec{v}_1 + m_2 \cdot \vec{v}_2 + ... + m_n \cdot \vec{v}_n \tag{2}$$

Without any disturb the structure keep its work position, i.e., vertically under the cable, however when an external force acts on the system it provide energy to the vehicle structure moving it laterally. If the vehicle system is divided in two different parts, it is possible to transfer all the energy applied on the system to the mobile mass keeping the main structure of the vehicle stable.

In the majority of the applications of suspended vehicles, it is not necessary to stabilize the whole vehicle, in other words, it is enough to stabilize just part of the system which perform the main function for which the vehicle has been designed to. As an example, in suspended vehicles applied for inspection of power transmission lines, only part that support the cameras/thermal cameras and moving/transposition mechanisms need to be stable relative to the object that is inspected or relative to suspended cable.

Most of mobile robots applied for inspection and maintenance of transmission lines are designed to perform the operations autonomously. So it is necessary to board and energy source on the robot such as a battery. The size and weight of the battery are directly proportional to the amount of electric and electronic equipments boarded and the desired autonomy of the robot. In several mobile robots the weight of the energy source means about 50% of the total weight of the robot. Concerned to this, it was proposed to use the battery of the robot as a mobile mass of the stability mechanism, and keep the robot structure as a fixed mass.

To implement the proposed solution, the battery was installed in a mobile platform built on the main structure of the robot as schematically represented in fig. 2.

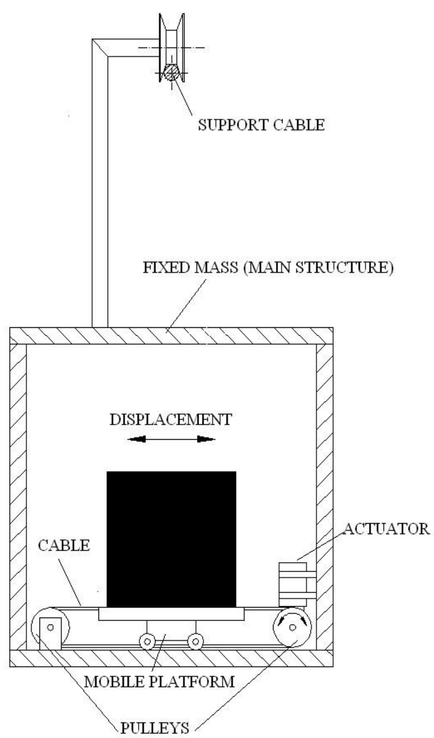

Figure 2 – Scheme of the robot structure with a mobile platform

To move the mobile platform it was necessary an electric actuator, such as stepper motor, servo motor or DC motor. In this work it was used a Mabuchi DC motor with a 1/50 reduction gearbox, suitable to give torch and velocity

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necessary to the system. To convert the rotary actuator to a linear motion of the mobile platform, it was designed a system of pulleys and cables as shown in fig. 2.

3. CONTROL SYSTEM

To keep the stability to the robot structure, an inclinometer was used as a sensor to measure the inclination of the main structure relative to the horizontal plane or vertically under the supported cable. A 900-Series Biaxial Clinometers by Applied Geomechanics Incorporated, with 0.01 degree resolution was fixed on a vehicle structure as shown in fig. 3.

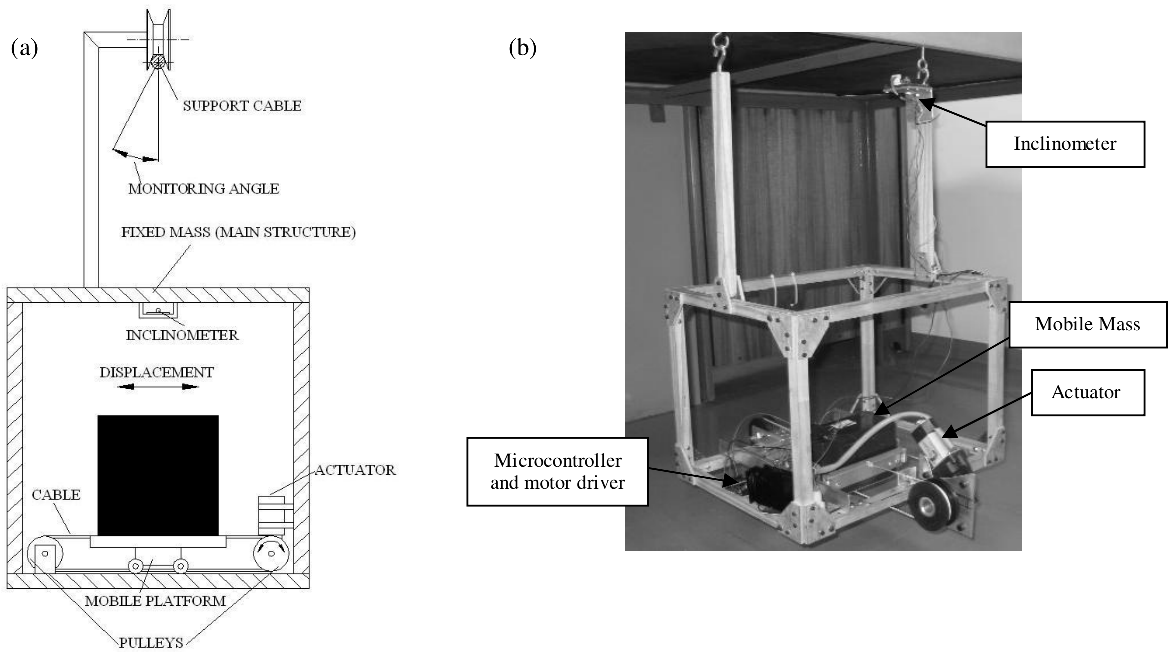

Figure 3 – (a) Installation scheme of the inclinometer with the monitoring swing angle. (b) Prototype of the robot structure built to perform study of the stability system.

The figure 3 shows the prototype of the robot built to study the performance of the proposed stability system. The Arduino Diecimila (ATMEL ATMEGA168 based) an off-board microcontroller, was used to collect data from the inclinometer and drive the mobile platform in an active feed-back system.

The proposed stabilization mechanism for the suspended robot can be resumed by two single steps: measure the deviation of the structure from its working position, i.e., vertically under the suspended cable; and drive the moving platform, with the heavy battery fixed on it, to the opposite side of the structure deviation. Moving the heavy battery will force the main structure to move in an opposite side as action-reaction mechanism to recover the main structure to its original position. The figure 4 shows a flowchart illustrating the operation principle of the control system.

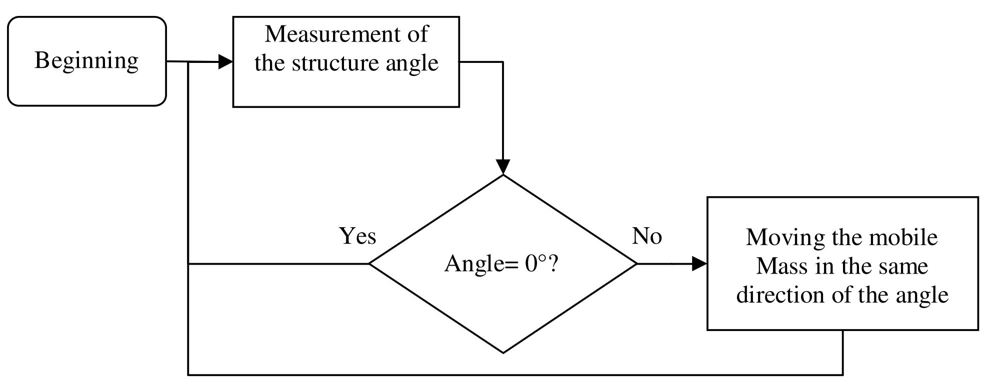

Figure 4 – Flowchart of the system operation

A digital control was implemented by using the PID concept, but in the present work only a proportional-derivative parameters were used. The block diagram of the control system is illustrated in the fig. 5.

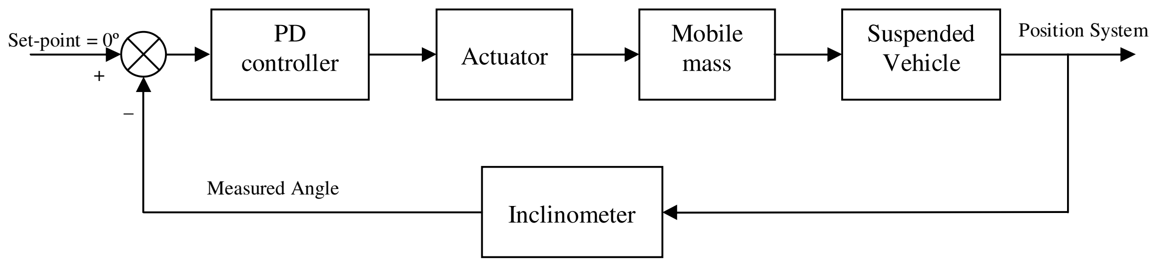

Figure 5 – Block diagram of the control system

The proportional gain of the controller acts in the system forcing the signal of the actuator be proportional to the structure angle deviation. Its contribution to the system is described like:

$$MV = Kp \cdot e \tag{3}$$

Where MV is the manipulated variable, in this system it is the displacement of the mobile mass; Kp is the proportional gain and e is the error, that is the difference between the working angle (set-point) and measured angle, then when the error is 0 the mobile mass does not move. To get a faster response of the system, the controller action must consider, beyond the position of the system, how the system is moving, i.e., how fast the structure is going toward to the desired position or far away from the desired position. The derivative controller consider this aspect, and its contribution to the system is described like:

$$MV = Kp \cdot e_{current} + Kd \cdot \left(e_{current} - e_{previous}\right) \tag{4}$$

Where Kd is the derivative gain, $e_{current}$ is the current difference between the set-point and measured angle and $e_{previous}$ is the $e_{current}$ measured one cycle before in a feed-back system. The controller parameters, proportional and derivative gains, where gotten experimentally. It was applied specific disturbances on the prototype, like a lateral force, and the oscillation behavior was collected by the clinometer and analyzed graphically to find the better parameters for stabilization.

4. EXPERIMENTS AND RESULTS

To find the best parameters for the proportional and derivative gains, several disturbance were applied to the system and different gains fixed to observe the oscillation behavior. With the best adjusted controller parameters achieved, a disturbance like a constant applied lateral force to the structure was graphically recorded to show the performance of the active stabilization system proposed compared to the system oscillation with stabilization turned off.

The figure 6 shows the two graphs of the system behavior for a step like force applied: first of them with the active stabilization control turned off and the second one with the active stabilization system turned on. In both graphs, two horizontal lines delimit the area where the system is considered stable, i.e, small deviation of the vertical position that does not disturb the operation of the suspended vehicle.

In this example, with the active control system turned off the robot oscillation takes about 160 seconds to reach the stable region and with the stabilization turned on it takes 21 seconds to reach the stable region. Comparing the times where each oscillation reach the stable area, the active stabilization system proposed is 8 times faster then the system without control.

For the disturbance where the external force is applied slowly, such as action of the wind, the main structure of the robot keep its original position and only the moving battery is dislocated from its original position to compensate the external force. So, for a small force, i.e., within the zone where the dislocation of the moving battery can cancel the external force, the main structure of the robot behaves as system with infinite rigidity.

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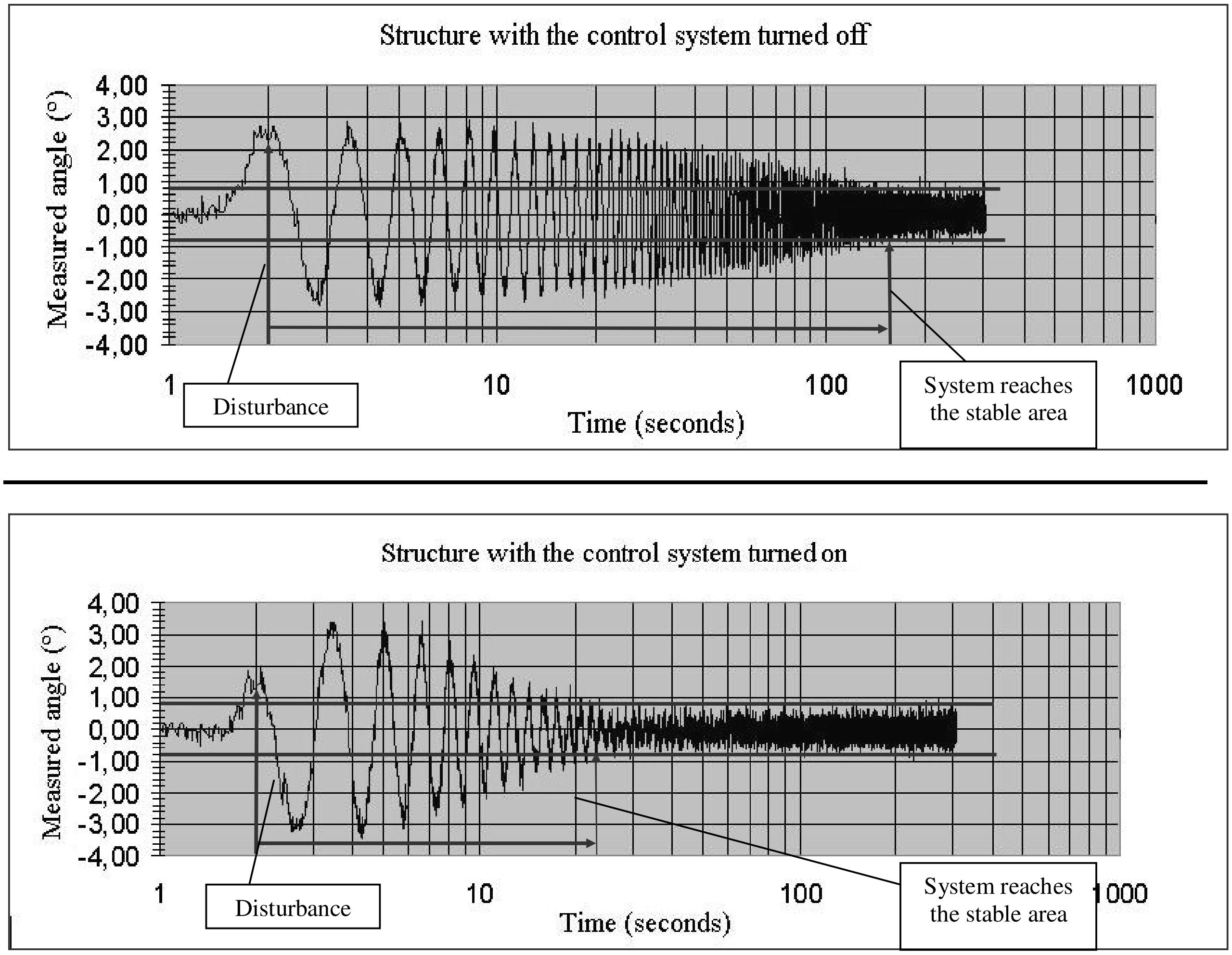

Figure 6 – Graphics of the oscillation disturbance behavior of the robot without and with active stabilization system.

5. CONCLUSION

The experimental results achieved with this active stabilization system, applied to robot suspended by cable, shows that is possible to compensate external forces and disturbances, for at least part of the robot, just managing internal components of the robot. The conservation of the moment applied in this work give good performance to the stabilization of part of the robot structure validating the initial proposed mechanism.

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