Design, Modelling and Simulation of Novel Hexapod-Shaped Passive Damping System for Coupling Cable Robot and End Effector in Curtain Wall Module Installation Application

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Abstract –

The application of robotics in the construction industry has been growing recently. However, it suffers from the lack of construction dedicated systems. The industry is characterised largely by designers and researchers scrambling to adapt systems from other industries and trying to apply them to the construction industry. In the application of Curtain Wall Module (CWM) installations, "HEPHAESTUS" is a European founded project that is engaged in designing a Cable Driven Parallel Robot (CDPR) automatic system capable of 1 mm positioning accuracy. It can perform other tasks such as drilling on the building by using a dedicated Modular End Effector (MEE). Conventional CWM installation from the outside of the building can be done in the case of 15 m/s wind but, to be competitive, the automatic cable robot system should be able to perform the task in similar outdoor situations. However, the cable robot – like other mechanical systems – has a specific stiffness which means that it could move slightly in the event of an external load such as wind, depending on the exerted load and stiffness. This movement should not be transferred to the final tool (e.g. the driller) while it's performing tasks on the building. To prevent or minimise the effect of the external load on the final tool in the chain of the mechanically connected system, a damping system should therefore exist. This paper introduces the novel hexapod-shaped passive damper. The damping system will be mathematically modelled and simulated using the Matlab Simscape software. The simulation results give logical consequences on the design. The designed damper and model can be used in other applications or dimensions with some simple modifications.

Keywords –

Construction robotics; Design; Modelling; Simulation; Passive damper; Hexapod; Cable robot; Façade installation

1 Introduction

The construction industry plays a crucial role all over the world. In many countries, it supports the economy, the development of other industries and helps maintain high employment rates [1], [2]. However, some tasks at construction sites involve dangers and risks and, in addition to this, need performance improvements. As a consequence of these challenges, the study of automatic construction robotics has recently been growing [3], [4] and [5].

The installation of a Curtain Wall Module (CWM) is one of such instances where high labour effort is required. This task involves several hazards for manual workers because it is performed on the outer edges and top floors of incomplete buildings. In addition, this operation is time consuming as it requires a lot of attention for completion. Therefore, automatic installation of curtain walls is required on grounds of safety and productivity [6].

This study is part of the HEPHAESTUS project [7], which was founded by the European Union. The focus of the project is on the installation of a Curtain Wall Module (CWM) as it is considered to be a high risk, yet critical, construction task [8]. The Cable Driven Parallel Robot (CDPR) moves on the face of a building and carries the CWM, while the Modular End Effector (MEE) works on the CDPR platform to set the brackets which are needed in advance for the installation of the CWM [9].

Excessive vibration from the CDPR caused by live loads like wind load could prevent the MEE from functioning properly while performing tasks such as drilling. Therefore, a damping system is necessary. A damping system is crucial because, when the frequency of vibrations from external forces is the same as the natural frequency of the structure, the structure may collapse like the Tacoma Narrows Bridge in 1940. Globally, there are many different kinds of damping systems. For example, a Tuned Mass Damper (TMD) consists of a mass, a spring and a viscous damper, and is used to reduce the amplitude of vibration of a structure caused by environmental forces or other factors. The largest and heaviest TMD is situated in the Taipei 101 skyscraper in Taiwan [10], [11]. There are other ways to classify damping systems: passive, semi-active and active [12]. The passive damper does not need an energy input, i.e. electricity. On the other hand, the active damper has actuators that require a high quantity of energy to function. The semi-active damper has variable dampers that require less energy than the active damper. The passive damper is less efficient than the active damper; however, it is cheaper and less complex. An example of an active damper that is in use is an active stabiliser for the CDPR which was developed by (Lesellier et al, 2018)e [13].

A hexapod-shaped spring-damper was applied in this paper as a passive damping system, which is represented by the Stewart Platform [14]. A hexapod is a 6-DOF robotic parallel manipulator. Although it is light and compact, it has a large payload. A hexapod is used in many other fields of study [15] such as milling machines, flight simulators or in medical science.

In this paper, first the design of a hexapod-shaped spring-damper between a cable robot and an MEE is proposed and modelled. Next, the analysis of the kinematics and dynamics of that model and simulation in Matlab® is presented. Finally, a conclusion is derived from the results that were obtained.

2 Passive Damper Design

In the application of the HEPHAESTUS project, a fully constrained cable-driven parallel robot (CDPR) [8] exists on one end and on the other end there is a Modular End Effector (MEE) [9] which is gripped to the side of the building when in operation. Between these two mechanical components, there is a passive damper that was designed as shown in Figure 1.

For the tasks of the MEE to be performed with precision on the building, it is required that its base remains stable throughout the duration of the task.

Figure 2 shows the connection in a simplified manner, for example, the CDPR connection to the building and the ground are shown with just one connection and spring whereas, in reality, it consists of 6-9 cables providing the stiffness and damping in six dimensions including three translational and three rotational. As demonstrated in [16] and [17], studies have been carried out in this area. On the design of the CDPR, the stiffness could be one of the design parameters. Put simply, the higher stiffness means stronger cables, motor and gearboxes, which is one of the design constraints.

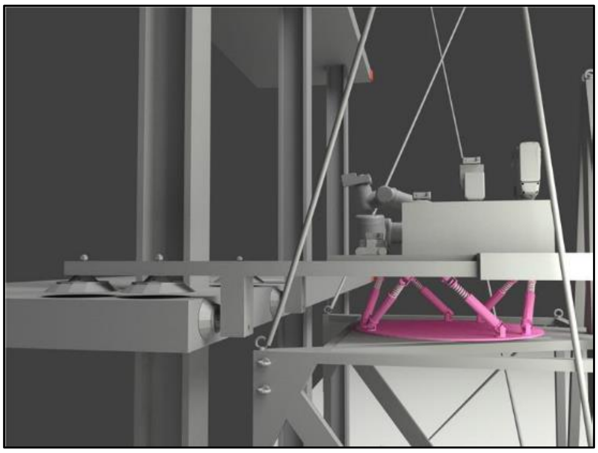

Figure 1. Hexapod-shaped damping system between the MEE and CDPR

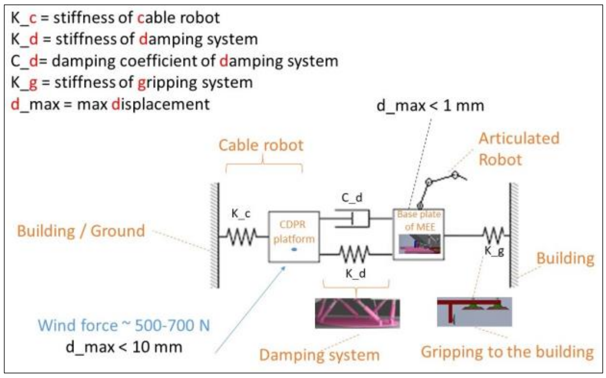

Figure 2. The chain of systems mechanically coupled

For the application of the HEPHAESTUS project, it is considered that the maximum displacement of the CDPR platform is less than 10 mm in the case of a wind force of 700 N which is caused by a 15 m/s wind speed on the CWM with a size of 150×350 cm. The relationship between these parameters can be seen using the following equation from [18]:

$$\boldsymbol{F}_W = \boldsymbol{p}_d\, A = \frac{1}{2}\rho v^2 A \qquad (1)$$

where $\boldsymbol{F}_W$ = wind force (N), A = surface area (m^2), $\boldsymbol{p}_d$ = dynamic pressure (Pa), ρ = density of air (kg/m^3), and v = wind speed (m/s). ρ is equal to 1.2 kg/m^3at 20° C. $\boldsymbol{F}_W$ is an estimation of the force, caused by the pressure acting on a surface. The surface slows the air and the dynamic energy in the wind is transformed into pressure. Here, the drag force is not considered.

This research focuses solely on the damping system of the chain shown in Figure 2. The final goal of the design is to keep the maximum displacement of the MEE base to less than 1 mm, while keeping the displacement of the “connection point of MEE and

CDPR" other end to a maximum of 10mm. To do so, a model of the damper is required, which is the main subject of this paper. The model is generic, which means that the dimensions (size of the linear cylinder as well as the diameter of the upper and lower plate of the damper) and physical characteristics (mechanical properties e.g. damping and spring coefficient of each linear axis) could be adjusted based on the output requirements which is the maximum displacement.

In the following sections, the mathematical model of the design, together with the dynamic model and simulation in the Matlab® Simscape™ program, are explained.

2.1 Mathematical Modelling

Mathematical modelling of hexapods has been performed in previous researches. Forward kinematics and inverse kinematics have also been studied, as can be seen in [19] and [20]. Although there are researches about the dynamics of the active hexapod e.g. [21] and [22], few studies exist that focus primarily on the dynamics of the passive hexapod. In the passive hexapod model, the following equation can be established:

$$\boldsymbol{f} = -\boldsymbol{K}(\boldsymbol{l} - \boldsymbol{l}_r) - \boldsymbol{C}\dot{\boldsymbol{l}} \quad (2)$$

where, $\boldsymbol{f}$ is the 6×1 vector of forces exerted at the bottom of the strut from each strut; $\boldsymbol{K}$ and $\boldsymbol{C}$ are the 6×6 matrices containing the stiffness and damping of each strut respectively; $\boldsymbol{l}$ is the 6×1 vector of the strut lengths; $\boldsymbol{l}_r$ is the constant 6×1 vector of the relaxed strut lengths.

Then, the force P and the moment M about the tool point position are given by:

$$\begin{bmatrix} P_x \\ P_y \\ P_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = -\begin{bmatrix} u_{1x} & u_{2x} & u_{3x} & u_{4x} & u_{5x} & u_{6x} \\ u_{1y} & u_{2y} & u_{3y} & u_{4y} & u_{5y} & u_{6y} \\ u_{1z} & u_{2z} & u_{3z} & u_{4z} & u_{5z} & u_{6z} \\ J_{1x} & J_{2x} & J_{3x} & J_{4x} & J_{5x} & J_{6x} \\ J_{1y} & J_{2y} & J_{3y} & J_{4y} & J_{5y} & J_{6y} \\ J_{1z} & J_{2z} & J_{3z} & J_{4z} & J_{5z} & J_{6z} \end{bmatrix} \boldsymbol{f} \quad (3)$$

where, $\boldsymbol{u}_i = [u_{ix} \quad u_{iy} \quad u_{iz}]$ is the unit vector of the ith strut; $\boldsymbol{J}_i = \boldsymbol{u}_i \times \boldsymbol{b}_i$; $\boldsymbol{b}_i$ is the vector from the centre of the base body to the attachment point of the ith strut. Figure 3 shows a schematic of a mathematical model of the hexapod described above.

This Mathematical model relates the forces $\boldsymbol{f}$ at the bottom of each strut to the forces P and the moments M at the centre of the top plate (tool point position). The mathematical model is introduced here to give the reader an understanding of how the dynamic system works within the theoretical framework of the paper.

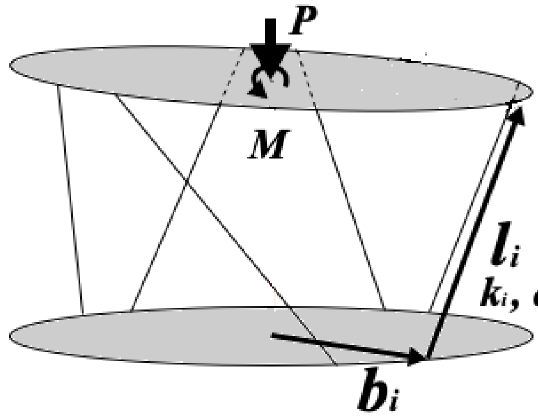

Figure 3. The mathematical model of the hexapod

2.2 Simscape™ Model in Matlab®

For simulation by the Simscape™ environment of Matlab® software, the CAD model in AUDODESK® INVENOR® software is first created and then imported to Simscape Multibody™. The relation and assembly constraints were carefully selected to automatically drive to a Simscape™ proper joint. The material and weight of the physical part were selected so as to resemble stainless steel, the material that the component will most probably be made out of. Once they are all imported, the Simscape™ model was edited to most closely resemble what the system is like in reality. Figure 4 shows the first level of the multibody diagram.

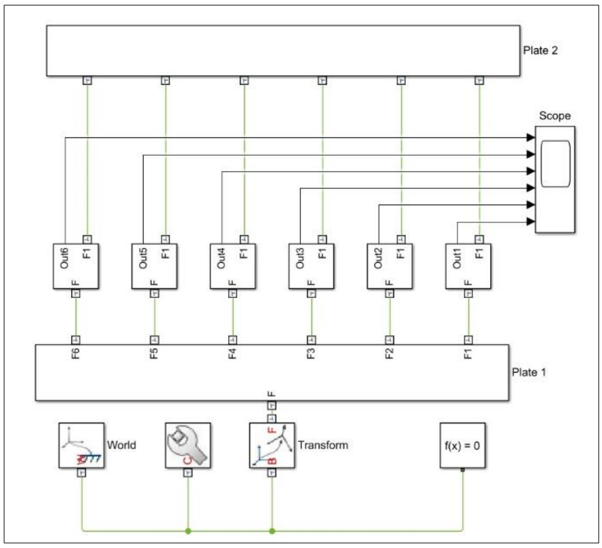

Figure 4. The first level of the multibody diagram

As shown in Figure 4, there are two plates which have between them six spring-damper cylinders. A scope module is also inserted to show the result of the simulation which is, in this paper, the position of each cylinder. Although several results could be extracted from this model, e.g. the force on each cylinder and the speed of each of them, their positions in this model are shown as an illustration. It would be possible for one to extract more results from this model.

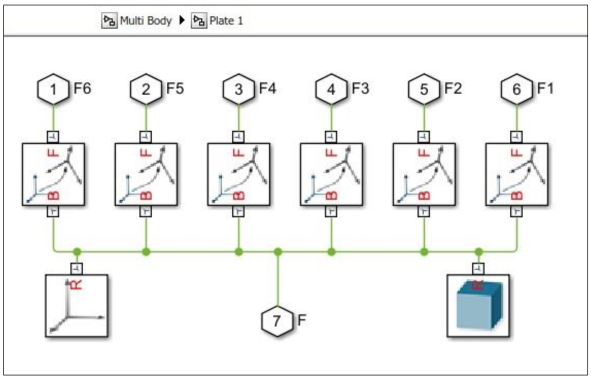

Figure 5. The lower plate of the multibody diagram

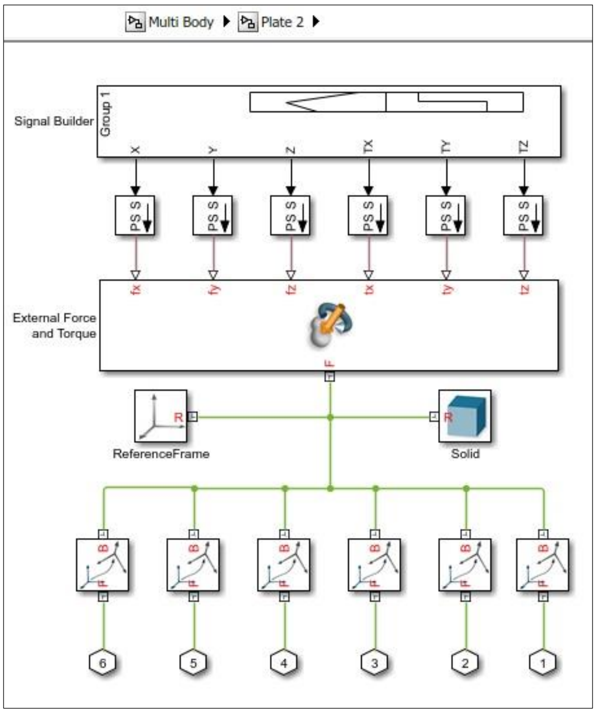

Figure 6. The upper plate of the multibody diagram

In this model, it is considered that the lower body is fixed, as shown in Figure 5, and that the upper body is free to move. Sample forces and torques are applied on the upper body in all directions. The diagram of the upper plate is shown in Figure 6. The purpose of this model is to provide a demonstration on how the model works in general.

Each of the spring-damper cylinders is modelled in Simscape™ with a set of revolute joints and one cylindrical joint as shown in Figure 7. In the properties of the cylindrical joint, the spring and damping coefficient, together with the equilibrium point of the cylinder, could be identified. In this example, the spring factor or stiffness of the damping system is considered to be 31,200 N/m and the damping coefficient of each cylinder is considered to be 2,250 N.s/m which is in the same range of suspension systems as automobiles, which are also considered in [23]. Automobiles are chosen since they are widely used and show that the model works with any conventional spring-damper system. The value is also not unlike off-road motorbike damping systems, which is another example of equipment that is widely used [24].

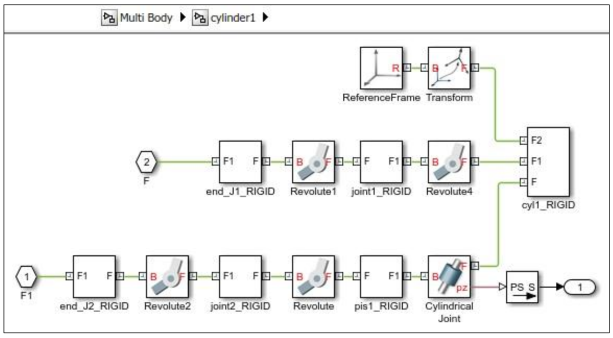

Figure 7. The cylinder level of multibody diagram

The characteristics of the sample damper are shown in Table 1 and the details of the simulation parameters are explained in the simulation results section. As previously explained, the dimensions and mechanical properties could easily be changed in the model, and the dynamic behaviour of the new model could then be established. For future development in the HEPHAESTUS project, the CDPR should be added to one plate on one end and, on the other end, the system that grips to the building.

Table 1. Damper characteristics

Property of item	Nomenclature	Value
Upper bound of cylinder movement	l_0	0.04 m
Lower bound of cylinder movement	l_m	-0.04 m
Spring factor of each cylinder	31,200	N/m
Damping coefficient of each cylinder	2,250	N.s/m

2.3 Simulation Results

For the simulation, one set of sample forces and torques is applied on the upper plate (representing, for example, the wind load applied to the CDPR and the effect it has on the damping system) since the lower plate is considered fixed to the ground (which represents the MEE gripped to the building). These loads are chosen for illustration purposes only; one can edit the input in the model and analyse the simulation results for specific loads. The applied forces are shown in Figure 8.

For the Y axis, a load of 700 N calculated using equation 1 is considered, even though in reality, by using the CDPR, not all of this wind load will be transferred to the MEE.

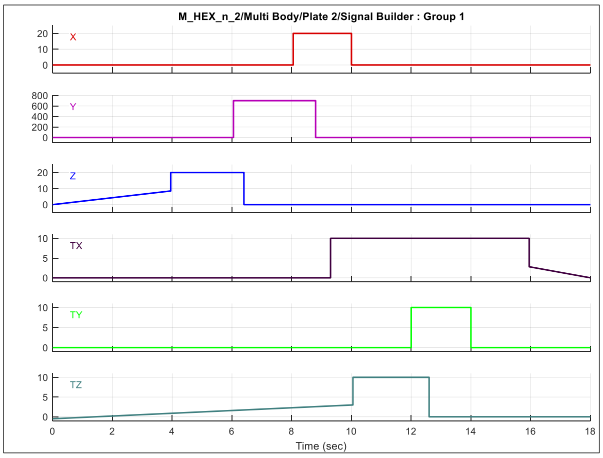

Figure 8. Input forces [N] and torques [N.m] signals

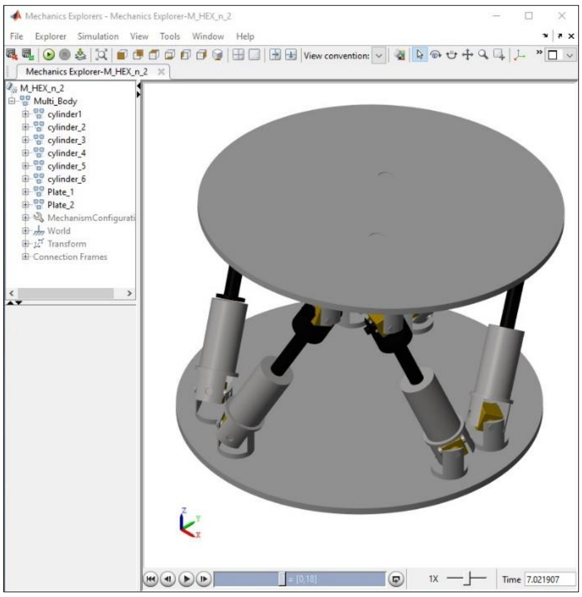

Figure 9. Mechanics explorer windows showing the simulation at the moment: time = 7.02 s

In the Matlab® Simscape™ model, under mechanism configuration, the linearisation delta is set to 0.001. "The linearisation delta specifies the perturbation value that is used to compute numerical partial derivatives for linearisation" [25]. The other solver configuration, the ODE solver, is set to "auto" mode in Matlab®, as this leads to the best matching results. g, the acceleration due to gravity, is considered as 9.80665 m/s^2 in the model configuration. In the solver configuration, filtering time is considered to be 0.001 s and consistency tolerance is considered equal to 1e-09.

As a visual result, in the *Mechanics explorer* window of Simscape™, the movement of the whole damper is also simulated. Figure 9 shows a screenshot of the *Mechanics explorer* windows at the moment: time = 7.02 s.

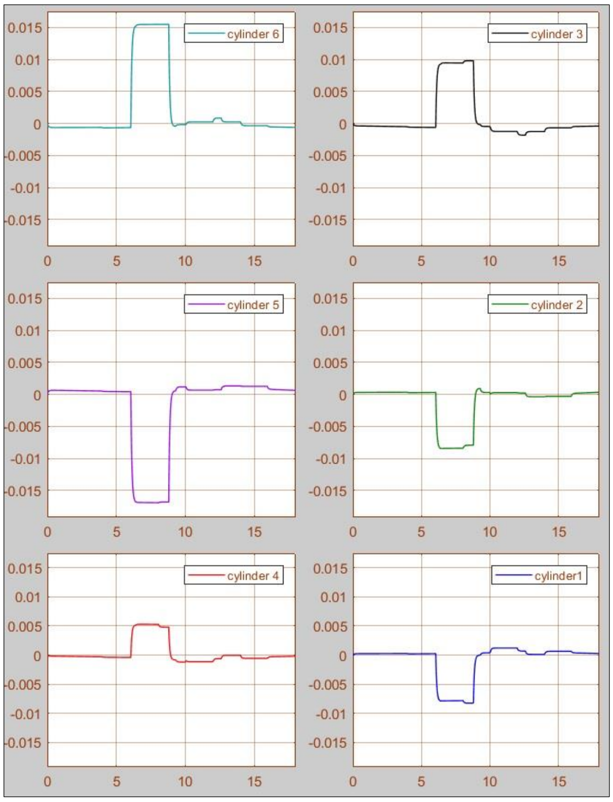

Figure 10. Output of cylinder position in Y axis [m] regarding the time in X axis [s]

As a result, the dynamic characteristics and movements of each cylinder could be drawn in a SCOOP module. It is possible to extract the forces and speeds on each joint. In this paper, only the position of each cylinder (spring-damper) is shown in Figure 10.

3 Conclusion

In this paper, a novel damper for passive damping of a Modular End Effector mounted on a CDPR has been introduced. If a MEE and CDPR are directly coupled, excessive vibrations from the CDPR (caused by e.g. wind) may render the MEE unable to effectively fulfil some of its tasks (e.g. drilling). This problem calls for the installation of a novel damping system to reduce these effects. The system consists of a hexapod-shaped spring-damper placed between a MEE and CDPR. A mathematical model and Matlab® Simscape™ model are introduced and a simulation has been performed. The displacement of each cylinder is shown; however, other output data such as the forces and speeds on each joint could be extracted from the model for analytical purposes, which are not shown in this paper.

Although the initial design was for the CWM installation application, the model is generic and the characteristics of the mechanical system can be chosen freely. This entails the system can be used in other applications as well.

For future development of the CWM installation with CDPR and MEE, one can add the CDPR stiffness model on top of this model. This approach will be explored together with some other partners of the HEPHAESTUS project. In addition, to make the dynamic model presented in this paper for the damper more precise, one could perform some laboratory tests to optimise the Simscape model; this will be carried in the next steps of the project.

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