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Response of Passive Exoskeleton to Torso Load under Natural Gait

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Abstract. Torso loads is the most common load form of daily life. Backpacks carried daily and radiation protection clothing worn by some specific workers belong to the category of torso load. When this kind of load is worn and walked by human body, it will fluctuate with the height of human centroid. For walking, what is done in this direction is useless. Under certain circumstances, such as marching, it is often required to walk with a large amount of load for a long time and the external environment cannot provide a sustainable energy supply. For the sake of to reduce the extra work required by load fluctuation in walking in passive condition, this paper first calculates the curve of human centroid change of natural gait, and obtains that the extra work required by unit mass in one gait cycle change are 0.72 J. After that, the spring mass damping model is established, and the change curve of human centroid is taken as the system input, and the energy reduction and shock absorption ability of exoskeleton models with different natural frequencies under the premise of a certain load mass is obtained, at the same time, the load weight ratio curve and theoretical energy reduction efficiency curve required to achieve energy reduction effect under different damping ratios are drawn. That provides theoretical basis of designing structural stiffness and damping for related research, and has high application value.

Keywords: passive exoskeleton, torso loads, shock absorption, natural gait

1. Introduction

Walking with torso load is very common to daily life, such as students carrying schoolbags to school, doctors wearing protective clothing to work, and soldiers carrying equipment to March. Long-term weight-bearing walking will not only increase physical fatigue and reduce the exercise state of human body, but also easily lead to stress fracture of lower limbs, joint pain of lower limbs, back muscle pull-up, lumbar disc herniation and other injuries [1-4]. In order to reduce the fatigue of human body, reduce the risk of injury and improve the sports performance, the current research mainly focuses on the following two directions.

One line of research is to boost the body of an active exoskeleton that provides extra power. A representative example is that in the beginning of 2020, the food delivery group Ele announced the exoskeleton that it is trying to study with Aoshian Intelligence [5]. The exoskeleton is currently targeted at people of normal building who is 1.7 to 1.8 meters tall. The full-body exoskeleton is designed to have a dead weight of 16 kilograms and a rated load of 50 kilograms. The whole skeleton has 12 degrees of freedom to reflect flexibility, among which 4 degrees of freedom are actively driven. Different from traditional industrial robots, some "joints" need to coordinate the flexible movement of human body. When working, the force is transmitted to the ground through the whole skeleton. No matter how heavy the device is or how heavy the object is, the person mainly bears the operating force. The shoulder bears 5-10 kilograms of force, just like carrying the weight of a laptop computer. However, the company said that there is no timeline for the landing of the exoskeleton. Due to the high cost of the exoskeleton, there is still a lot of testing space before it is officially put into actual take-out use. It will not be fully putting into operation for the time being, but will continue to explore.

Another line of research is to transfer the weight of the load directly to the ground via passive exoskeletons. One of the most representative is the UORISE ultraliet exoskeleton launched by Canadian Mawashi Company. The exoskeleton system uses biomechanics and human sports load management to transfer 50% to 80% of the weight carried by soldiers to the ground through mechanical levers, which can assist soldiers to carry equipment up to 54kg on the battlefield [6]. The interference degree for soldiers' movement is less than 1%.

Both the focus on the research direction is focused on the human body normal action of the influence of as small as possible at the same time to effectively the gravity of the load to the ground, but for such load can't be ignored: under the body's natural gait, the body center of mass is not along a straight line parallel to the ground, but there are some ups and downs [7]. The contact point of this kind of load and the human body is in the torso, and there is no contact with the ground and the lower limbs of the human body. So, the load also rises and falls with the height of the body's center of mass during walking. However, for walking, the work in this direction is useless, that is, when the human body is carrying the load of the torso, in addition to the work required for the load to move along the walking direction, it also needs to provide additional work to make the load rise and fall [8-9]. If we try to reduce this part of extra work in the design of assisting mechanism such as exoskeleton, the overall assist effect of exoskeleton will be significantly improved [10]. In order to achieve this purpose, this paper established the center of mass of the body of the natural gait trajectory, a center of mass movement cycles is calculated in the size of the extra work, according to the actual situation after the torso load model is simplified to single degree of freedom model, and then on the basis of the model, calculate the centroid movement for the input to the human body, different displacement output curves of stiffness and damping of the system. Finally, some suggestions for the design of the exoskeleton structure are putting forward, which provides some reference and help for the related research.

2. Trajectory of torso load center of gravity in natural gait

Ideally, the connection between the torso load and the torso can be considered rigid, and the load is in direct contact with the torso, not with the lower extremities, ground, and other parts of the torso. Then the motion of the center of mass is the same as the motion of the body's own center of mass. Numerous studies have shown that for normal gait, the changes of centroid trajectory and angles for each joint can be regarded as mainly occurring in the sagittal plane. Assuming that the angle between the torso and the ground is always 90° in a gait cycle, then the change in the height of the centroid is only related to the angle of the lower limb joints. If the change in the height of the sole of the foot is ignored, then the change in the height of the centroid M of the human body is shown in Fig. 1. The figure shows the first half of the gait cycle with the right leg as an example, where the blue curve indicates that the right leg is the supporting leg, and the yellow curve indicates that the supporting leg is transformed into the left leg. Due to the symmetry of the gait, the height change of the centroid in the second half of the gait cycle is exactly the same as that in the first half[11].

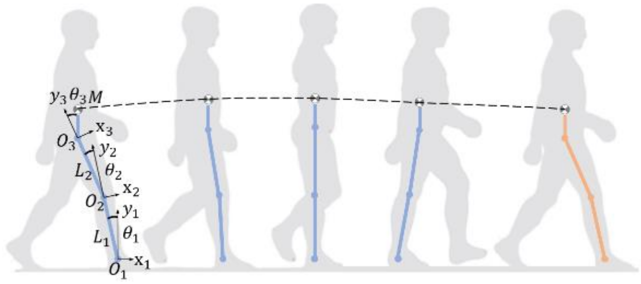

Fig. 1: Schematic diagram of height change of human center of mass.

In Fig. 1, L_1 is the foot coordinate system, L_1 is the length of the leg, θ_1 is the rotation angle of the y axis of the θ_1 coordinate system to the leg, and the counterclockwise direction is positive. θ_2 is the knee joint coordinate system, L_2 is the thigh length, θ_2 is the rotation angle of the y axis of the θ_2 coordinate system to the thigh, and the counterclockwise direction is positive. θ_3 is the hip joint coordinate system, θ_3 is the rotation angle of the y axis of the θ_3 coordinate system to the torso, and the counterclockwise direction is positive. H is the distance between the hip joint and the center of mass of the human body. Ignored the height of the foot, the distance between the center of mass M and the ground H is:

$$\mathrm{H} = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) + \mathrm{h} \tag{1}$$

The height of the experimenter in this model is 1.80m, and the actual measurement of L1, L2 and H are 0.396m, 0.371m and 0.121m respectively. The θ_1 and θ_2 are measured by the lower limb joint angle measuring device made by the laboratory. The above variables are put into Equation (1) to obtain the change of H of the centroid height, as shown in Fig. 2. For the sake of to demonstrate the periodicity of the centroid height curve,

Figure 2 shows the centroid height change in a complete gait cycle during two walking steps. Where the ordinate is the height of the center of mass in meters, the abscissa is the percentage of the gait period. The red curve in the figure is the height change curve of the center of mass. It can be seen from the diagram, in the double support phase, the center of mass is low, with the right leg into single support phase, when the leg unbend, completely centroid peaks, as compared to the lowest point, the center of mass increased by 4 cm, height mass center after began to decline to double support phase, reached its lowest point, into the left leg after single support phase, center of mass to rise again. In a complete gait cycle, there are two complete cycles of centroid height change, that is, the frequency of centroid height change is the same as the gait frequency, which is 2Hz.

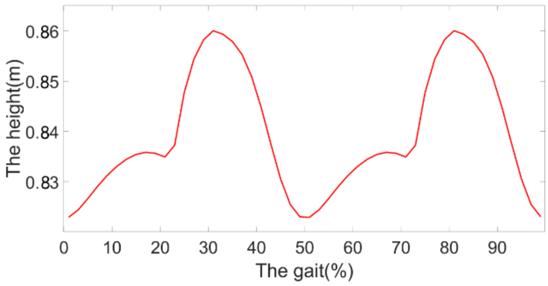

Fig. 2: Height change of center of mass of human body

The normal walking speed of human body is 1.1m/s-1.5m/s. Assuming the speed is 1.3m/s, the energy required to reach the speed per unit mass is as follows:

$$W_v = \frac{1}{2}mv^2 = 0.845J \tag{2}$$

Taking the lowest point of the centroid motion trajectory calculated above as the zero gravitational potential energy point, the additional work done by the unit mass in a period of changing the height of the centroid is:

$$W_{body} \approx mg\Delta h = 0.36J \tag{3}$$

Ignored other frictional costs, most of the work done during walking is used to raise the center of mass of the torso load, assuming that the speed of the body remains constant after the start of walking. This also illustrates the importance of reducing the extra work in this part.

3. Analysis of exoskeleton trunk load model

3.1. Frequency domain analysis of torso load model

Based on the assumptions of the previous section, a load-bearing exoskeleton system is introduced. It is assumed that the exoskeleton system is rigidly connected to the torso, and its motion trajectory is consistent with the motion trajectory of the human body's own center of mass. The load mass of the torso is M, and it is connected with the exoskeleton system through an elastic element and the damping element, so the system can be simplified into a single-degree-of-freedom vibration model, as shown in Fig. 3. Where M is the mass of the load of the torso, k and c are the stiffness and damping of the exoskeleton system, O is the contact part between the exoskeleton system and the human body, q is the input of the system, namely the height of the center of mass of the human body, and z is the output, which is the height displacement of the load.

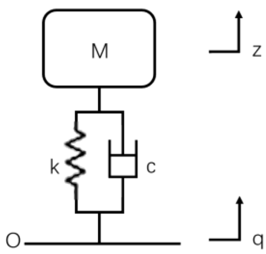

Fig. 3: Single degree of freedom vibration model

The motion equation of the system is as follows:

$$M\ddot{z} + c(\dot{z} - \dot{q}) + k(z - q) = 0 \tag{4}$$

Let z_0 and q_0 be the amplitude of the output input harmonic quantity; φ_1 and φ_2 are the phase angles of output and input harmonic quantities. Then the frequency response function is:

$$\mathrm{H(j\omega)}_{z-q} = \frac{z_0}{q_0} e^{j(\varphi_2 - \varphi_1)} = |\mathrm{H(j\omega)}|_{z-q} e^{j\varphi(\omega)} \tag{5}$$

Set $\mathrm{z = z_0} e^{j\omega t}$ and $\mathrm{q = q_0} e^{j\omega t}$, and carry out the Fourier transform of (3) to get:

$$\mathrm{H(j\omega)}_{z-q} = \frac{k + jc\omega}{(-M\omega^2 + k) + jc\omega} = \frac{1 + (2j\zeta\lambda)}{1 - \lambda^2 + 2j\zeta\lambda} \tag{6}$$

Where $\omega_0 = \sqrt{\frac{k}{M}}$ is the natural circular frequency of the system, $\lambda = \frac{\omega}{\omega_0}$ is the frequency ratio, and $\zeta = \frac{c}{2\sqrt{Mk}}$ is the damping ratio. Equation (7) is the amplitude frequency characteristic of the system.

$$|\mathrm{H(j\omega)}|_{z-q} = \sqrt{\frac{1 + (2\zeta\lambda)^2}{(1 - \lambda^2)^2 + (2\zeta\lambda)^2}} \tag{7}$$

Assuming that the load of the torso is 20kg, according to the actual situation, the deformation range of the exoskeleton after carrying the load is 4-20cm, then the stiffness range of the exoskeleton system is 1000-5000N/m. It is assumed that the stiffness is 5000N/m, then the natural frequency of the system is:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{M}} = 2.51Hz \tag{8}$$

The amplitude-frequency characteristic curves with damping ratios of 0, 0.25 and 0.5 are shown in the logarithmic coordinate system respectively.

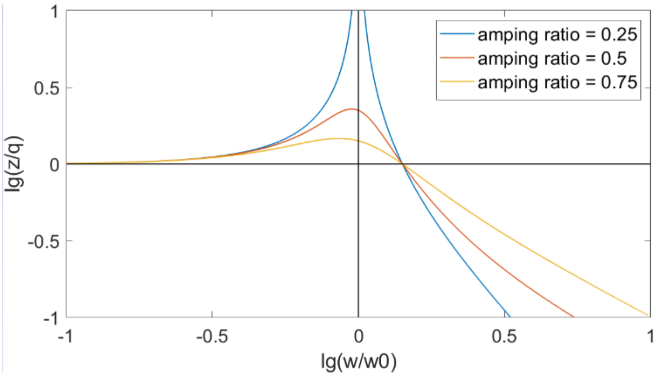

Fig. 4: Amplitude-frequency characteristic curve in log-log coordinate system

As can be seen from Fig. 4, for this system, when the input is in the low frequency band, $0 < \lambda < 0.75$, the output amplitude of the system is approximately equal to the input amplitude, and the damping coefficient of the system has no obvious effect on the amplitude gain. When the input is in the resonance section, $0.75 < \lambda < 1.41$, the output amplitude of the system is obviously larger than the input amplitude. The system gains the input amplitude, and the smaller the damping coefficient of the system, the more obvious the amplitude gain. When the input is in the high frequency band, $1.41 < \lambda$, the system suppressed the input amplitude, and the smaller the damping coefficient of the system, the more obvious the amplitude suppression was.

From the analysis in the previous section, it can be obtained that the frequency of the height change of the center of mass of the torso load is about 2Hz, that is, the external input frequency is 2Hz, then the vibration input is in the resonance section of the system. For the sake of to reduce the response to the torso load to the input amplitude, the damping ratio of the whole system should be increased, but the output amplitude will not be lower than the input amplitude, indicating that the additional work done by the torso load is greater than the additional work done by the center of mass of the body. Since the gait frequency of walking generally does not change, that is, the input frequency is stable at 2Hz, for the sake of reduce the extra work done by the torso load, the natural frequency of the system should be as low as possible when designing the relevant system, so that the final frequency ratio falls in the high frequency band.

3.2. Time domain analysis of trunk load model

Simulink was used to build the above physical model for simulation verification, as shown in Fig.5. The input is the change rate of the human body centroid height obtained in the second section after deriving from time. Through the ideal speed source input system, the final output is the change height of the load centroid of the exoskeleton system. Firstly, the output curve of the torso load model is assumed to be 20kg with a stiffness of 5000N/m and a damping ratio of 0.25,0.5 and 0.75, as shown in Fig.6.

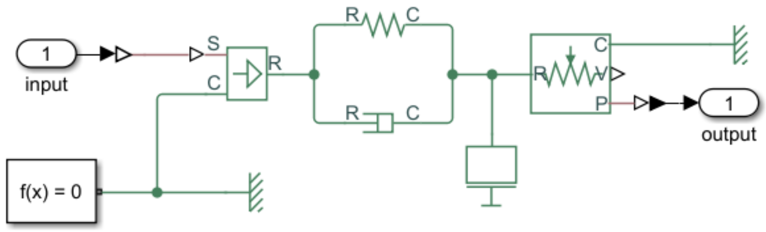

Fig. 5: torso load model

According to the analysis in the previous section, the system is currently in the resonance section. Under the three damping ratios, the output amplitude of the system is obviously larger than the input amplitude, and with the increase of the system damping ratio, the output amplitude becomes smaller and smaller, but ultimately it is greater than the input amplitude. For the sake of reduce the extra work done by the torso load, the stiffness of the system is changed to 1000N/m without changing the load, then the natural frequency of the system is f_0=1.13Hz. At this moment, the frequency ratio of the system is λ=1.78, which is in the high frequency band. At this moment, the damping ratio is 0.25, 0.5. The output curve of the 0.75 torso load model is shown in Fig.6. The output amplitude of the system under three damping ratios is all smaller than the input amplitude, and the output amplitude becomes smaller and smaller with the decrease of the damping ratio.

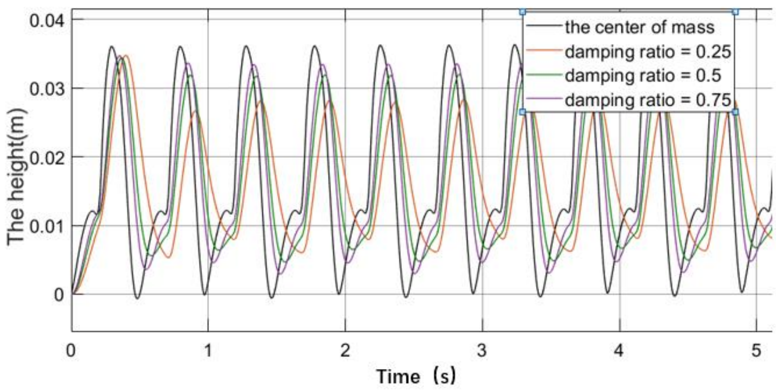

Fig. 6: Output curve of torso load model.

3.3. Analysis of energy reduction effect of exoskeleton

As in the second section, the lowest point of each curve in Fig. 6 was taken as the zero gravitational potential energy point. Assume that the load was 20kg, and calculate the extra work done in a cycle of changing in one gait of mass. As can be seen from Table Ⅰ, when the load is carried directly on the body without passing through the exoskeleton system, the additional work required is 14.4J. When the natural frequency of the designed system is high, the change frequency of the height of the center of mass of the human body is always in the resonance band of the system. At this time, the extra work done by the system for the trunk load is greater than the extra work done by the human body. Therefore, such a system needs additional power sources to reduce the fatigue of the human body carrying the load. When the natural frequency of the designed system is low, the change frequency of the height of the center of mass of human body is usually in the high frequency band for the system. For the torso load, the extra work done by the system is less than the extra work done by the body, so such systems can reduce fatigue without the need for a power source, but care needs to be taken in the ratio of the load mass to the overall system mass. The natural frequency of the system is F_0 = 1.13Hz, the load mass is 20kg, and the damping ratio of the system is ζ = 0.25. It is assumed that the change of the center of mass of the exoskeleton system is consistent with that of the human body, and the change of the center of mass of the load conforms to the change curve of the shock absorption by the exoskeleton. It can be calculated from the table that the mass of the passive system needs to be less than 8.9kg. For the sake of to reduce the sense of fatigue of the human body carrying the load, otherwise the extra work caused by the system mass will be greater than the extra work reduced.

Table 1: Additional work required for different torso load systems

Exoskeleton natural frequency(Hz)	Damping ratio	Extra work required by exoskeleton(J)	All the extra work the body does(J)
2.51	0.25	26	14.4
	0.50	19.6	
	0.75	17.2	
1.13	0.25	7.0	
	0.50	8.8	
	0.75	9.9	

In order to further to explore the relationship between passive exoskeleton properties and energy-saving effect, it is calculated that when the load is 0-50kg and the exoskeleton damping ratio is 0.25, 0.50 and 0.75 respectively. In order to achieve energy-saving effect, the exoskeleton must be less than the maximum mass of, as shown in the Fig.7. It is known from the previous analysis in this chapter that the frequency of trunk load height change is about 2Hz. In order to achieve the purpose of energy saving and shock absorption, the ratio of external input frequency to the natural frequency to exoskeleton system needs to be in the high frequency band. Therefore, in order to reduce the natural frequency of exoskeleton, the stiffness of exoskeleton related mechanisms should be as small as possible under a certain load. It is assumed that when the exoskeleton reaches a stable state under static load, the corresponding spring displacement reaches the designed maximum displacement of 0.2m, and the stiffness of the exoskeleton is calculated. Under these three damping ratios, if you want the exoskeleton to achieve the effect of energy saving and shock absorption in the walking state, the load to weight ratio of the exoskeleton should be at least greater than 2. If the damping ratio is 0.75, the load to weight ratio of the exoskeleton should be at least 3, and under the determined load mass, the exoskeleton mass of the corresponding damping ratio needs to be less than the curve in the figure to achieve the effect of energy saving and shock absorption.

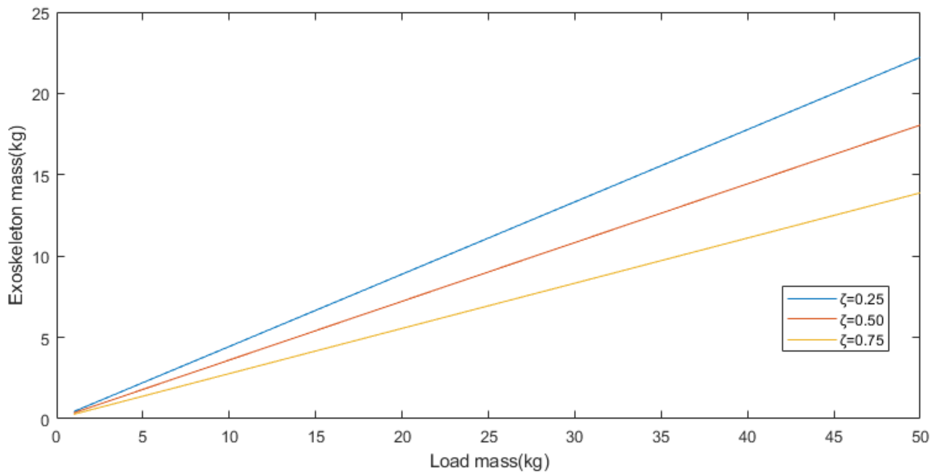

Fig. 7: Load exoskeleton mass curve under different damping ratio

The Fig.8 shows the load to weight ratio that the exoskeleton needs to achieve in order to achieve the effect of energy saving and shock absorption with the change of the damping ratio of the exoskeleton system, and the maximum energy-saving efficiency of the natural gait load that the exoskeleton corresponding to the damping ratio can achieve under ideal conditions. At present, the weight-bearing ratio of passive exoskeleton is generally between 2-5. Taking the damping ratio of 0.25, 0.50 and 0.75 as examples, in order to achieve the effect of energy saving and damping, the load self weight ratio should at least reach more than 1.95, 2.55 and 3.24, and under ideal conditions, the maximum energy-saving efficiency can reach 51.4%, 39.2% and 30.1%.

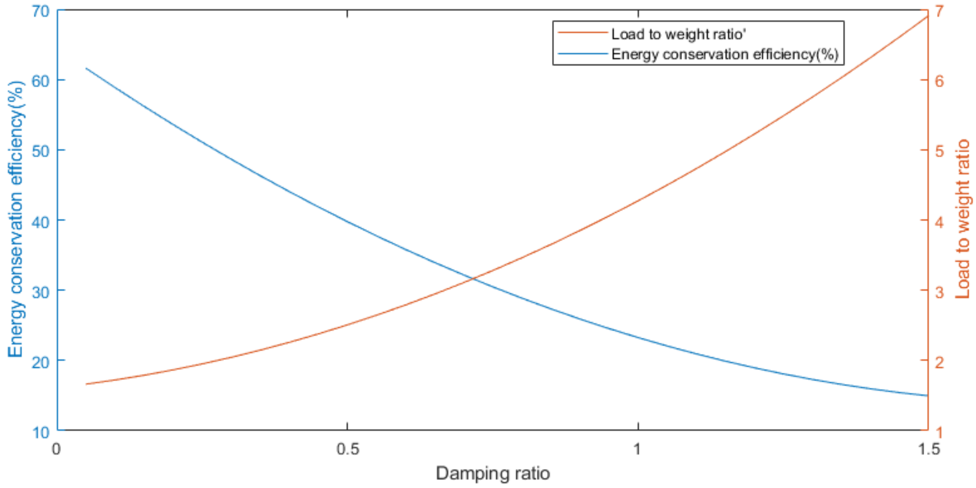

Fig. 8: energy conservation efficiency and load to weight ratio

4. Conclusion

In this paper, the trajectory of human centroid motion is obtained through calculation, and the additional work consumed by unit mass in a cycle of human centroid change is 0.72J. Exoskeleton spring quality damping model is established, through the centroid trajectory as the input, explores the different system natural frequency of the output performance. The results show that when the input frequency and the ratio of the system's inherent frequency of resonance period, then the system need external energy input, can reduce the fatigue of the body bearing to load if the ratio of the input frequency of the natural frequency of the system is in the high frequency band, the fatigue of the human body can be reduced only when the ratio of the whole system mass to the load mass is within a certain range. At the same time, the load weight ratio curve and theoretical energy reduction efficiency curve required to achieve energy-saving effect under different damping ratios are drawn the calculation flow and results in this paper provide the method and theoretical basis for the design of the stiffness and damping of the whole machine.

5. References

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