A NOVEL AMBULANCE STRETCHER BASED ON PARAL-LEL MECHANISM AND ITS VIBRATION ISOLATION PER-FORMACE ANALYSIS

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The recumbent patients on the ambulance stretcher experience multi-dimensional excitations due to road roughness. In order to isolate the multi-dimensional vibrations validly, a novel ambulance stretcher based on 4-PUU parallel mechanism is proposed. Firstly, the kinematic and dynamic equation are deduced by geometric relation and Lagrange equation respectively. Subsequently, the vibration isolation performance is investigated in time and frequency domain. Further, selecting RMS value as the index of vibration isolation performance, the index with geometric parameters uncertainties, mass uncertainty and spring uncertainty is discussed. Simulations results demonstrate the stretcher system can isolate the multi-dimensional excitations in supine patients sensitive frequency range effectively. The RMS values show different characteristics with uncertainties because of altering Jacobin matrix of the stretcher.

Keywords: ambulance stretcher, parallel mechanism, multi-dimensional vibration isolation, uncertainties.

1. Introduction

The supine patients transported by ambulances are often in serious conditions. Obviously, such patients are extremely sensitive to the vibrations caused by road roughness, which may lead to the patients suffer secondary injuries. Ambulances are usually converted by trucks, thus the suspension systems can't adapt to road condition automatically [1]. Because of the cost, the active or semi-active ambulance suspensions have not been used widely. By solving this problem frugally, the approach taken to reduce the vibrations experienced by recumbent patients has focused on the stretcher system [2].

Generally, the ambulance stretcher can be divided into passive stretcher, active stretcher by whether the system has power source respectively. Several scholars have investigated the active control stretcher systemic [2-5]. Ranie. et al. proposed a novel pneumatic stretcher which can isolate the vibrations in pitch and vertical directions effectively [6]. However, the active or semi-active stretcher require energy input, and the actuators are expensive in manufacturing. Thus, such stretcher systems are difficult to be used widely due to the cost. When the springs and viscous dampers are installed on the stretchers, no complicated power supply and control systems are required, so the passive stretchers are cheap and reliable generally. Xu. et al. introduced a double-stage wire rope vibration absorber with long and short springs, which can isolate the vibration in vertical and pitch directions validly [7]. Niu. et al. investigated an ambulance stretcher by applying spring and metal rubber structure, the vibrations from the vehicle floor to the patient were reduced by 17%-45% through the experiment [8]. Bruzzone. et al. proposed a parallel mechanism as the main structure of the stretcher, but the isolation capability wasn't addressed [9].
In general these papers mainly focus on the vibration isolation performance in vertical and pitch directions. Actually, when the ambulance was driven on the road, many phenomena, e.g. speed up, turn around, brake, are quite common. The patients will suffer from the vibrations in horizontal, longitudinal, vertical, and pitch directions. The recumbent patients are sensitive to the horizontal vibration frequency range 1-2Hz and longitudinal vibration frequency range 8-10Hz [10], respectively. When the patients expose to the sensitive frequency, the resonance of the thoracic cavity and abdominal cavity will occur, which will bring some serious injuries to the patient laying on stretchers.

In order to isolate the multi-dimensional vibrations validly, a 4-PUU parallel mechanism is proposed as the main structure of the stretcher system, the vibration isolation performance is investigated with considering the geometric parameters uncertainties, the mass of moving platform uncertainty and stiffness of spring uncertainty, respectively.

2. Kinematic and dynamic analysis of 4-PUU stretcher system

2.1 Model of 4-PUU stretcher system

For the 4-PUU stretcher system, the fixed platform experiences the multi-dimensional excitations, connecting to the floor of the ambulance and the moving platform connects to the supine patients. The schematic and configuration of 4-PUU mechanism is shown in Figure. 1. The limbs of the 4-PUU mechanism have the same configurations. For each limb, from the fixed platform to the moving platform, is consisted of prismatic pair, universal joint, universal joint, respectively. The rotation axes of two universal joints in each limb locate in x-y plane, one axis is along x axis direction, the other deviates from y axis direction. Thus, the motions around y axis and in z axis direction aren't existed. The second universal joint is connected with the moving platform in points Ci (i=1,2,3,4). The shapes of fixed platform and moving platform are rectangle with the length 2d1x2d2, 2d3x2d4, respectively. A fixed Cartesian frame O-xyz is assigned in the central point O of the fixed platform. A moving Cartesian frame P-xPyPzP is established in the central point P of the moving platform. The lengths of link BiCi and prismatic pair AiBi are a and li, respectively, where i=1,2,3,4. θ means the angle around x axis. Four groups of springs and dampers are arranged in prismatic pairs AiBi, the ambulance stretcher based on 4-PUU mechanism is obtained.

![Figure 1: Schematic of 4-PUU parallel mechanism.](image)

The degrees-of-freedom of the stretcher system can be calculated by G-K formula [11] with correction coefficient, which is four, i.e., the translations in x, y, z directions and rotation around x direction.

2.2 Kinematic equation of the stretcher

The kinematic equation can be deduced by geometric relation. Considering position of moving platform, the coordinates of points BiCi can be expressed as BiPi, BiO and CiP, CiOi in moving Cartesian frame and fixed Cartesian frame, (i=1,2,3,4), respectively. The coordinate of Ci is

\[ \mathbf{C}_i = \mathbf{T}_z \mathbf{C}_{Pi}. \]

(1)
where $C_m = [x_m, y_m, z_m, 1]^T$, $(m = O, P)$, $T_x$ is rotational transfer matrix around $x$ axis,

$$T_x = \begin{bmatrix} 1 & 0 & 0 & x_p \\ 0 & \cos \theta & -\sin \theta & y_p \\ 0 & \sin \theta & \cos \theta & z_p \\ 1 & 0 & 0 & 1 \end{bmatrix}. \tag{2}$$

In the fixed Cartesian frame, the length of the link $B_iC_i$ can be obtained by geometric relation,

$$a^2 = (B_{\alpha i} - C_{\alpha i})^2. \tag{3}$$

Equation (3) above has eight group solutions for the length of links $l_i$. So as to ensure the moving platform upwards like Figure. 1, the inverse kinematics can be described as,

$$\begin{align*}
l_1 &= -\sqrt{D_1 + D_2} - d_3 \sin \theta + z_p, \\
l_2 &= -\sqrt{D_1 + D_2} + d_3 \sin \theta + z_p, \\
l_3 &= -\sqrt{D_1 + D_2} + d_3 \sin \theta + z_p, \\
l_4 &= -\sqrt{D_1 + D_2} - d_3 \sin \theta + z_p, 
\end{align*} \tag{4}$$

where $D_i$ is given by

$$D_1 = a^2 - (d_2 - d_3 - x_p)^2, D_2 = -(-d_1 + d_3 \cos \theta - y_p)^2, D_3 = a^2 - (-d_2 + d_4 - x_p)^2,$$

$$D_4 = -(-d_1 - d_3 \cos \theta - y_p)^2. \quad \text{Because of } \dot{\mathbf{l}} = J^{-1}[\mathbf{v}, \mathbf{\theta}]^T, \text{the inverse Jacobin matrix can be expressed as,}$$

$$J^{-1} = \begin{bmatrix} \sqrt{a^2 - D_1} \sqrt{-D_2} & 1 & \frac{d_3}{\sqrt{D_1 + D_2}} - d_4 \cos \theta \\ \sqrt{a^2 - D_1} & \sqrt{-D_2} & 1 & \frac{d_3}{\sqrt{D_1 + D_2}} + d_4 \cos \theta \\ \sqrt{a^2 - D_1} & \sqrt{-D_1} & 1 & \frac{d_3}{\sqrt{D_1 + D_4}} - d_4 \cos \theta \\ \sqrt{a^2 - D_1} & \sqrt{-D_1} & 1 & \frac{d_3}{\sqrt{D_1 + D_4}} + d_4 \cos \theta \\ \frac{a^2 - D_2}{D_2 + D_3} & \frac{-D_2}{D_2 + D_3} & 1 & \frac{d_3}{\sqrt{D_2 + D_3}} - d_4 \cos \theta \\ \frac{a^2 - D_2}{D_2 + D_3} & \frac{-D_2}{D_2 + D_3} & 1 & \frac{d_3}{\sqrt{D_2 + D_3}} + d_4 \cos \theta \end{bmatrix}. \tag{5}$$

### 2.3 Dynamic equation of the stretcher

In view of coupling, the dynamic equation of the stretcher characterizes non-linear. The solution is complicated, therefore, some conditions should take into account to simplify the dynamic equation. Firstly, considering the stretcher vibration amplitude being slight, the gravity potential energy can be ignored. Secondly, comparing with the mass of moving platform, the mass of links is negligible. Comparing with viscous damping, the structural damping is so tiny that it can be ignored in the formulation. The Lagrange equation with damping energy is expressed as follows,

$$\frac{d}{dt} \left( \frac{\partial T_E}{\partial \mathbf{\dot{X}}} \right) - \frac{\partial T_E}{\partial \mathbf{X}} + \frac{\partial U_E}{\partial \mathbf{X}} + \frac{\partial D_E}{\partial \mathbf{X}} = \mathbf{\Gamma}. \tag{6}$$

where $T_E$ is kinematic energy, $U_E$ is elastic potential energy, $D_E$ is damping energy, respectively. $\mathbf{X}$ denotes generalized coordinate of stretcher system, $\mathbf{\Gamma}$ is generalized force vector.

The kinematic energy, elastic potential energy, and the damping energy are respectively given by,
where $X = [x_p, y_p, z_p, \theta]^T$ is the displacement of the moving platform, $M = \text{diag}(m_p, m_p, m_p, I_x)$ is inertia matrix of moving platform, $m_p$ is the mass of the moving platform, $I_x$ is the moment inertia around $x$ axis, $K = G \text{diag}(k) G^T$ is the stiffness matrix, $k$ is the spring stiffness, $C = G \text{diag}(c_i) G^T$ denotes damping matrix, $c_i (i = 1, 2, 3, 4)$ is the viscous damping coefficient of four dampers respectively, and $G = J^{-1}$ is the force Jacobian matrix.

Substituting Eq. (7) into Eq. (6), the dynamic equation of stretcher system can be yielded as follows,

$$MX + CX + KX = \Gamma.$$  \hspace{1cm} (8)

### 2.4 Road profile and state-space equation of the stretcher

Recumbent patients on ambulance stretcher experience multi-dimensional stochastic excitations because of road roughness, the road random excitation is,

$$\dot{q} = -2\pi n_0 q + 2\pi n_1 w \sqrt{G_q} v.$$  \hspace{1cm} (9)

where $q$ is road roughness amplitude, $G_q$ is random road roughness coefficient for different road, here defining the ambulance driven on road of B class, $v$ denotes the vehicle velocity, $n_0$ is lowest cut-off frequency, $n_1$ is reference spatial frequency, $w$ denotes white Gauss noise with zero mean.

In order to analyze the isolation performance in time and frequency domain, the state-space equation of stretcher system is deduced with stochastic road excitation. Defining $Z = [X, \dot{X}]^T$, substituting $Z$ into Eq.(8) yields,

$$\dot{Z} = AZ + B\ddot{q}(t).$$  \hspace{1cm} (10)

where $\ddot{q}(t)$ is acceleration of road excitation, $A$ is system matrix, $B$ is input matrix, which are,

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ G \end{bmatrix}. \hspace{1cm} (11)$$

Defining $T = [\theta_{a,4}, I_{a,4}]$ and conducting Fourier transformation on Eq. (10), the displacement solution of moving platform in frequency domain can be described as,

$$X(\omega) = \frac{1}{j\omega} T(j\omega I - A)^{-1} Bq(\omega).$$  \hspace{1cm} (12)

where $q(\omega)$ is road roughness amplitude in frequency domain, $j = \sqrt{-1}$.

### 3. Simulation analysis

The vibration isolation capability, the vibration isolation performance with parameters uncertainties are addressed in this section, respectively. The parameters using in simulation are given by Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>The mass of moving platform, $m_p$</td>
<td>48.75/kg</td>
</tr>
<tr>
<td>The inertia moment of moving platform, $I_x$</td>
<td>1.02/kg\cdot m\cdot s^{-2}</td>
</tr>
<tr>
<td>Stiffness of spring, $k$</td>
<td>1e4/N\cdot m^{-1}</td>
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<tr>
<td>Viscous damping coefficient, $c_i (i = 1, 2, 3, 4)$</td>
<td>30/N\cdot m\cdot s^{-1}</td>
</tr>
<tr>
<td>Length of fixed platform, $d_i$</td>
<td>0.22/m</td>
</tr>
</tbody>
</table>

Table 1: Parameters in simulation.
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<thead>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Length of fixed platform, $d_2$</td>
<td>0.2/m</td>
</tr>
<tr>
<td>Length of moving platform, $d_3$</td>
<td>0.25/m</td>
</tr>
<tr>
<td>Length of moving platform, $d_4$</td>
<td>0.25/m</td>
</tr>
<tr>
<td>Length of link $B.C_i$, $a$</td>
<td>0.2/m</td>
</tr>
<tr>
<td>Lowest cut-off frequency, $n_0$</td>
<td>0.011/m$^{-1}$</td>
</tr>
<tr>
<td>Reference spatial frequency, $n_1$</td>
<td>0.1/m$^{-1}$</td>
</tr>
<tr>
<td>Random road roughness coefficient, $G_q$</td>
<td>64e-6/m$^3$</td>
</tr>
<tr>
<td>The ambulance forward velocity, $v$</td>
<td>16.67/m$^{-1}$</td>
</tr>
</tbody>
</table>

3.1 Vibration isolation in time and frequency domain

According to the values in Table 1, the natural frequencies of the stretcher system are calculated as $f_{n1}=0.015$Hz, $f_{n2}=1.20$Hz, $f_{n3}=4.58$Hz, $f_{n4}=7.84$Hz, which directions are along $y$ axis, $x$ axis, $z$ axis and around $x$ axis respectively. The supine patients are sensitive to frequencies from 1~12Hz, the second to forth order natural frequencies are in the sensitive frequency range exactly. Therefore, four dampers $c_i$ are installed on the prismatic joints $l_i$ respectively, for isolating the vibration validly. Defining the recumbent patients experience compound excitations, which directions are along $x$, $y$, $z$ axis and around $x$ axis, analyzing the vibration isolation performance of stretcher system in time domain and frequency domain.

![Velocity response of moving platform in x and y directions.](image)

Figure 2: Velocity response of moving platform in $x$ and $y$ directions.

Figure 2 depicts the velocity response of moving platform in $x$ and $y$ directions under compound excitations in time domain. It shows that the stretcher system has a fine vibration isolation performance along $x$, $y$ axis, the amplitude of velocity response fluctuates nearby zero. The velocity responses in other directions aren't given due to the length of paper and they have the same characteristics.

![Displacement of moving platform with different stiffness of spring.](image)

Figure 3: Displacement of moving platform with different stiffness of spring.

As the stiffness of spring increasing, the natural frequencies also increase. The formants are deviating with augmenting of stiffness. These results are quite similar to the single degree of freedom.
system. The displacement in other directions aren't given because of the length of paper and they have the same characteristics.

Figure 4: Displacement of moving platform in frequency domain.

Figure 4 describes the output displacement of moving platform in x, y, z and around x directions in frequency domain. From Figure 4, the conclusions can be drawn, (1). When the viscous damping coefficients $c_1, c_2, c_3, c_4$ are all zero, the resonance peaks of the stretcher system are excited. The frequencies of the formants are equal to the natural frequencies. (2). Because of the influence of viscous damping coefficient, the formants are offset comparing with the non-damping formants. (3). By applying the dampers on the prismatic pairs gradually, the vibration isolation performances are getting better. The first formant is reduced slightly. The second and third formants are weakened significantly, the forth resonance peak is inhibited completely. Considering the sensitive frequency range of supine patients, the ride comfort is enhanced validly.

### 3.2 Vibration isolation performance influenced by uncertainties of geometric parameters

The geometric parameters of the stretcher system can't be so precise in manufacturing process, i.e. uncertainties exist. Root-Mean-Square (RMS) value is selected as the index of vibration isolation performance. Defining the uncertainties of geometric parameters $a, d_1, d_2, d_3, d_4$ are $\varepsilon = [-2\%, 2\%]$, investigating the isolation capability in each direction of the stretcher system.
Figure 5: Vibration isolation performance with geometric parameters uncertainties.

Figure 5 demonstrates the displacement RMS values of moving platform in each direction with geometric parameters uncertainties. Due to uncertainties, Jacobin matrix altered, furthermore, the vibration isolation capability changed. It shows clearly that, the RMS value around x axis is most sensitive to the geometric parameters uncertainties, however, the RMS value in z axis direction is most insensitive to the geometric uncertainty. These results imply the vibration isolation capability in vertical direction is stable but susceptible to interference in pitch direction under geometric parameters uncertainties. Parameters uncertainties can enhance or reduce vibration isolation capability in each direction. The uncertainties of parameters $d_4, a, d_3, d_1$ contribute mostly in improving vibration isolation performance in x direction, y direction, z direction and around x direction respectively.

3.3 Vibration isolation performance influenced by uncertainties of mass and spring

Generally, the mass of moving platform is totally different by virtue of carrying the recumbent patients. The spring can't be linear strictly. We assume the mass-changing range of moving platform is [40kg,120kg] and the stiffness-changing range is [5e2,5e4]. The RMS values with mass-changing and stiffness-changing are discussed.

Figure 6: Vibration isolation performance with uncertainties of mass and spring.

Figure 6 depicts the RMS value in each direction with mass changing of moving platform and stiffness-changing. It presents as the mass, stiffness increasing, the RMS value enhancing, decreasing in all directions respectively. It implies that the vibration isolation capacity is going worse as the mass increasing. Larger stiffness of spring can improve the vibration isolation capability obviously.

4. Conclusion

A novel ambulance stretcher based on 4-PUU mechanism is proposed. The kinematic and dynamic equation are deduced. Through simulation, the stretcher system can isolate the vibrations along x, y, z axis and around x axis in recumbent patients sensitive frequency range effectively. The vibration isolation performance with geometric parameters, mass and spring uncertainties are ad-
dressed. Due to parameters changing, the Jacobin matrix is altered, therefore, the vibration capability is changed. The vibration isolation capability show different characteristics in each direction due to uncertainties, it can be improved by adjusting geometric parameters.

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REFERENCES


