Dynamics analysis of planar linear array deployable structures with multiple clearance joints

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Abstract. The purpose of this paper is to investigate the dynamic characteristic of the scissor linear array deployable structure under the coupling action of clearance joints, where the kinematic model of the deployable structure with clearance is established according to the principle of the motion between joint elements. The normal and tangential contact forces between contact components are respectively described using the Flores contact force model and modified Coulomb friction model. In the sequel of this process, the impact forces between the connected components are converted to the mass centers of links connected by this clearance joint, and the converted contact force and additional torque were integrated to the generalized force in motion equations of the deployable structure, and then the effect of joint clearance is introduced to deployable system. The simulation results show that the dynamic characteristics of the mechanism are very sensitive to the clearance position, and the movement of a joint clearance will affect the movement of the other joint clearance, which shows that clearance joints in deployable structure have a strong dynamic interaction and all the joints should be modeled as real joints.

1. Introduction
The deployable structure has the characteristics of small volume and large space. Moreover, this structure can be expanded from the contraction state to the preset expansion state and keeps the stable configuration during the transportation, so it has been widely used in aviation, aerospace and construction fields [1-5]. Li et al [2] proposed a new inter-joint force model to predict the dynamics of planar linear deployable structure.

In the movement of the real mechanism, the joint clearance is inevitable. And it greatly affects the motion precision and stability of the structure. Yan et al [4] and Flores [5] investigated the influence of clearance on the structural dynamics, but the dynamic interaction between different clearance joints is not clearly stated. In reality, each joint in a multibody system has a gap, so the interaction of the clearances at different location must be considered.

Therefore, the clearances are introduced into the kinematic pairs at different locations for modeling the dynamics of deployable structure consisting of SLE. Also, the intra-joint forces between the contact bodies are evaluated using the Flores contact model and modified Coulomb law. In the sequel of this process, the resulting general forces are included into the motion equation of the system to model the contact impact process between the journal and bearing.
2. Equations of motion of planar deployable structure

The deployable structure consisting of two SLEs is presented in Figure 1, where each SLE is composed of two bars and can be rotated around the midpoint. Joints A and D are real joint, other joints are ideal joints. This structure has only one degree of freedom and is subject to a horizontal load at point F, 100 N.

\[
\begin{bmatrix}
M & \Phi_q \\
\Phi_q & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{\mathbf{q}} \\
\lambda
\end{bmatrix} =
\begin{bmatrix}
\mathbf{Q} \\
-(\Phi_q \dot{\mathbf{q}}) \dot{\mathbf{q}} - 2\Phi_q \dot{\mathbf{q}} - \Phi_{\dot{\mathbf{q}}}
\end{bmatrix},
\]

(1)

where \(M\) and \(\Phi_q\) are respectively the mass matrix and Jacobian matrix, \(\mathbf{q}\) is the generalized coordinate, the vectors \(\dot{\mathbf{q}}\) and \(\ddot{\mathbf{q}}\) separately the first and second derivatives of \(\mathbf{q}\) with respect to time, \(\mathbf{Q}\) and \(\lambda\) are the generalized force vector and Lagrange multiplier vector. In order to avoid the constraint violation, Baumgarte method is used where the violation parameters \(\alpha\) and \(\beta\) are taken as 5.

3. Modeling the revolute clearance joint

During the analysis, it is assumed that the revolute joint consists of two components, journal and bearing, shown in Figure 2.

The penetration \(\delta\) shown in Figure 2 can be obtained : \(\delta = e - c\), where \(c\) is the radial clearance size, \(e\) is the eccentricity between the centers of journal and bearing. Also, \(\delta\) can be used to determine the positional relationship between the connecting bodies. When \(\delta < 0\), it indicates that the contact bodies are in a free movement state. On the contrary, the contact deformation takes place between the connected components.

Compared with the Lankarani-Nikravesh model commonly used, Flores model broadens the application range of the Hertz law and has more stable dynamic solution, it has obtained good numerical results in the dynamic solution of soft materials and hard materials.
\[ F_N = K \delta^a [1 + \frac{8(1-c_r)}{5c_r} \dot{\delta}(-\dot{\delta})], \]

where \( \delta \) and \( \dot{\delta} \) are respectively the indentation depth and relative normal contact velocity of the contacting bodies. \( \dot{\delta}(-) \) is the initial impact velocity. \( K \) and \( n \) are respectively the contact stiffness parameter.

On the other hand, when different bodies where there are contacting surfaces have relative sliding motion the friction may likely appear in joints. In order to describe the friction phenomenon, the modified Coulomb friction model is utilized which effectively prevents the unstable numerical integration operation caused by the change of friction direction when the tangential velocity is near 0.

\[ F_t = -\mu_d c_d F_N v_t, \]

where \( F_N \) is the normal intra-joint force obtained from Equation (2), \( \mu_d \) and \( c_d \) denote the slide friction coefficient and dynamic modification coefficient, and \( v_t \) is relative tangential velocity.

4. Simulation and discussion

Figure 1 is used as an example to verify how the joint clearance affects the dynamic behavior of the deployable structure, where the bars in this structure have the same length and mass, 566 mm and 3.7 kg, and the endpoint F is subject to the horizontal load, 100 N. At the beginning of the simulation, the bearing and journal coincide, and the parameters required to solve the dynamic model are shown in Table 1.

A typical planar deployable structure as shown in Figure 1 is used as a demonstrative example to study the parametric effect of a revolute clearance joint on the dynamic response of the mechanical system. The bars in the SLE are of the same length and mass which are respectively 566mm and 3.7kg. The end F of bar 4 bears the horizontal constant force which is taken as 100 N, and the journal and bearing centers coincide. The parameters used for the numerical calculations required to solve the mechanism dynamics are listed in Table 1.

| Parameter                  | Value       |
|----------------------------|-------------|
| Bearing radius             | 10.0mm      |
| Poisson’s ratio            | 0.29        |
| Restitution coefficient    | 0.7         |
| Density                    | 7.8 g/cm³   |
| Young’s modulus            | 206.8 GPa   |
| Nonlinear power exponent   | 3/2         |

According to the initial parameters, Figures 3 and 4 show when the revolute joints A and D have different clearance sizes, the dynamic response of the center of mass of bar 1 with respect to the ideal mechanism. The clearance values of joints A and D in Figure 3 are 0.2mm and 0.5mm respectively, the situation in Figure 4 is just the opposite.

Figure 3 (1) Acceleration response (2) Impact force at the clearance joint. A=0.2mm, D=0.5mm
Figure 4 (1) Acceleration response (2) Impact force at the clearance joint. A=0.5mm, D=0.2mm

It can be seen from Figures 3 and 4 that as the clearance value increases in joint A, the dynamic characteristics of the center of mass of bar 1 change more obviously. Compared with Figure 3, the acceleration response and impact force amplitude in Figure 4 show a more pronounced high frequency oscillation, which indicates that the influence of the clearance coupling between the different joints on the dynamic performance of mechanical system cannot be ignored.

5. Conclusions
According to the simulations, it can be concluded that the coupling between the joint clearance at different positions is complicated, and the dynamic behavior of the mechanical system become irregular. For the deployable structure, when the revolute joints have different clearance values, the increase or decrease of the structural dynamic behavior is consistent with those of the clearance size at joint A. On the contrary, when the clearance size at joint D is increased, the dynamic behavior of this structure is suppressed, which indicates that the clearance in joint D is the main factor causing the nonlinearity of the deployable structure, and it should be analyzed in more detail in order to optimize the structure.

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Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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