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Optimal Design of Passive Control of Space Tethered-Net Capture System

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ABSTRACT The space tethered-net is an important tool for space debris capture. But its rebound movement limits its effective working distance. To solve this issue, a passive control method using “Energy dissipation band (EDB)” is proposed in this paper. A semi-spring damper model of the EDB is first built and verified by the tests, and then the strengths of the bands are optimized with Radial Basis Function assisted optimization method with Batch infill Sampling criterion (RBFBS). Simulation results show that this passive control method can significantly increase the effective work distance of the space tethered-net, and RBFBS algorithm is able to optimize the strengths of the EDBs effectively and efficiently. This paper provides a new idea for the optimal design of the space tethered-net, which can be applied to the future flexible capture tasks.

INDEX TERMS Control design, dynamics, optimization, optimal control, simulation, space technology.

I. INTRODUCTION

As one of the main means of Active Debris Removal (ADR) [1], the space tethered-net capture system is characteristic of low weight, small volume, wide coverage and high fault tolerance. The working process of the tethered-net system is shown in Figure 1. Firstly, the tug-satellite is maneuvered to a certain place which is close to the target. Secondly the tethered-net is released and the target is captured. Thirdly the target is transported to the grave orbit, and then the tug-satellite returns to the standby orbit and prepares for the capture task of the next target.

With the progress in space science and technology, growing attentions have been paid to the flexible tethered-net system. In 2012, the European Space Agency (ESA) developed a space environment cleaning plan and restarted the space debris active removal project under the project code of e.Deorbit [2]. The parabolic flight test was performed in 2014 [3] and a subsequent space experiment was carried out in 2018 [4]. Momentum Exchange / Electrodynamic Reboost (MXER) project, which is supported by National Aeronautics and Space Administration (NASA), envisioned the use of tether systems to provide propulsion without using propellant [5]. The Electro Dynamic Debris Eliminator (EDDE) project of the Defense Advanced Research Projects Agency (DARPA) plans to launch 12 spacecrafts carrying 2400 electromagnetic networks [6]. The idea of using a spaceflight to construct a large spatial structure is derived from the concept of Furoshiki satellite system proposed by Nakasuka et al. [7], and in order to verify the Furoshiki satellite system, University of Tokyo and Kobe University conducted the first Furoshiki test in 2006 using the sounding rocket S-310-36 [8], [9].

A lot of efforts have been made in terms of tethered-net dynamics. Hobbs et al. analyzed the influence that different structure within the tether do to the elastic and fatigue fracture properties [10]. Benvenuto et al. of Milan Institute of Technology in Italy developed a multi-body dynamics simulation tool for the space tethered-net capture system, which analyzed the unfolding, closing and dragging process of the rope network [11]–[13]. Combined with 3D motion reconstruction technology, the simulator was verified using ground test results [14], [15] and microgravity test results [16]. Medina et al. of Spain’s GMV company organized a parabolic flight microgravity verification test of the tethered-net system simulator [17]. Zhang Qingbin et al. systematically designed the space tethered-net system with a number of ground tests, and built the rigid-flexible-coupling dynamic model of the
space tethered-net system [18]–[23]. Shan Minghe et al. have provided a comprehensive study on a model for the tethered-net based on absolute nodal coordinates formulation (ANCF) [24]. Yu Yang et al. of Tsinghua University applied the absolute node coordinate method and lumped mass method to study the characteristics of the movement of the regular quadrilateral space tethered-net [25], [26]. Zhao Guowei et al. of Beihang University established a quality ball-rod model of tethered-net and developed a C++ language solver, enabling the successful launch simulation of police cyber guns [27]. Guo Jifeng et al. of Zhejiang University developed the prototype of tension control robot of the space tethered-net [28].

With a lot of ground tests and simulations, it is found that after being deployed to the maximum area, the tethered-net will quickly re-contract. This issue essentially limits the effective working distance of the tethered-net. To minimize or even eliminate the rebound movement, researchers have tried many different methods. For example, Huang Panfeng et al. of Northwestern Polytechnical University established a space rope robot system based on active maneuvering unit, and proposed the net retention control strategy based on the Leader-Follower method [29]–[35]. Zhai Guang et al. of Beijing Institute of Technology investigated the control scheme based on tether tension and proposed an integrated control scheme by introducing the thrusters into the system [36].

Most of the control methods above are active pattern with significant complexity. In this paper, we propose and optimize a novel passive control method based on EDB, as will be seen, it is easy to implement.

In this paper, the gradient of the optimized objective is unavailable, and the simulation of the space tethered-net is very computationally expensive, which takes an average of 5 minutes for each evaluation. Therefore, this optimization problem cannot be directly solved by the commonly-used evolutionary algorithms (EA) [37], [38] and the traditional derivative-based optimization algorithms [39], [40]. In this paper, we employ a radial basis function assisted optimization method with batch infill sampling criterion for solving this computationally expensive optimization problem in an effective and efficient way.

This paper is organized as follows. Section II introduces the passive control mechanism. Section III establishes the “semi-spring damper” model of the EDB, and verifies the model with on-ground tests. Section IV builds the “semi-spring damper” model of the whole tethered-net. Section V introduces the evaluation index of the space tethered-net’s work effectiveness and the RBFBS algorithm. Section VI conducts the simulation experiments and analyses, and Section VII concludes the work and discusses the future work.

II. PASSIVE CONTROL MECHANISM
A tethered-net system must be compactly stored in a launch vehicle [21], as shown in Figure 2. Once this system begins to work, the pilot masses fly outwards with an angle of $\alpha$ and speed of $v_0$.

In the working process of the traditional tethered-net, the area increases gradually before reaching its maximum. Then the rebound motion will occur, which leads to a rapid reduction of the area. This phenomenon seriously limits the effective working distance of the tethered-net. Therefore, based on the experience of the passive deployment control of the parachute, this paper proposes a passive control method based on EDB, which disposes EDB between every adjacent knots on the contour lines of the space tethered-net.

The working mechanism of the EDB is shown in Figure 3. When the distance of the adjacent knots is larger than the preset starting length, the stitches of the EDB begin to stretch. Meanwhile, the knots at both sides of the band are subjected to symmetrical opposite forces. The prototype of Energy dissipation band is shown in Figure 4.

Figure 5 is a quadrilateral tethered-net used in this paper. It is composed of contour lines, diagonal lines, pilot risers and inner lines. Figure 6 is an illustration of the tethered-net with the EDBs installed.
The length of the band at time $t$ is set as $L_{AB}(t)$. The preset starting and ending length of the band are set as $L_0$ and $L_{Nξ}$, respectively. Then, the working process of the EDB can be described in more detail as: when $L_{AB}(t)$ is longer than the preset initial length $L_0$, the first stitch starts to stretch; when $L_{AB}(t)$ is equal to $L_0 + a\%l_{s\text{max}}$, the second stitch starts to stretch; once $L_{AB}(t)$ firstly stretches to $L_0 + l_{s\text{max}}$, the first stitch breaks. And so forth, when $L_{AB}(t)$ is equal to $L_0 + (k - 1) \times a\%l_{s\text{max}}$, the $k$-th stitch begins to stretch; once $L_{AB}(t)$ firstly stretches to $L_0 + (k - 1) \times a\%l_{s\text{max}}$, the $k$-th stitch breaks. What is more, each stitch is elastically deformed before its breaking.

Based on the descriptions above, each stitch can be simulated by a “Semi-spring damper model”, which is a combination of a damper and a spring which has forces on both ends when being pulled but no force when being pressed. As can be observed in Figure 3, an EDB with $Nξ$ stitches can be equivalent to a combination of $Nξ$ semi-spring dampers $S_j$, which have different original lengths $l_{0j}$. Figure 7 shows the mechanical model of an EDB, where $L_k$ equals to $L_0 + k \times l_{s\text{max}}$.

As the latter stitch begins to stretch when the length of the previous stitch grows to $a\%$ of the maximum stretch $l_{s\text{max}}$, the maximum stretch of each stitch can be obtained by

$$l_{s\text{max}} = \frac{L_{Nξ} - L_0}{a\% (Nξ - 1) + 1} \quad (1)$$

Secondly, once $L_{AB}(t)$ stretches to $L_k$ the first time, $S_j$ become invalid. So the original length of the $k$-th semi-spring damper can be expressed as

$$l_{0j} = L_0 + (k - 1) \times a\%l_{s\text{max}} \quad (2)$$
The sign function here is

$$
\text{Sign}(x) = \begin{cases} 
1 & x > 0 \\
-1 & x \leq 0 
\end{cases}
$$

(3)

To characterize whether the stitch has been broken, we introduce the history function $\delta_k(t)$. When the $k$-th stitch breaks, the value of $\delta_k(t)$ is 0, otherwise is 1. Thus, the force of a stitch acting on both ends can be given by

$$
f_k = \left\{ \begin{array}{ll}
K_s (L_{AB}(t) - l_0k) [\text{sign}(L_{AB}(t) - l_0k) + 1] / 2 \\
-L_{AB}(t) C_s \end{array} \right. \delta_k(t)
$$

(4)

where $K_s$ and $C_s$ are the stiffness and damping of the stitch measured by experiment.

The resultant force at the ends of the semi-spring dampers is obtained by

$$
F_{SLD} = \sum_{k=1}^{N_k} f_k
$$

(5)

So far, in the case of knowing the preset starting and ending length $L_0$ and $L_N$, the stiffness $K_s$, damping $C_s$, the ratio $a\%$ of each stitch and the current length $L_{AB}(t)$ of that EDB, the value of the resultant force $F_{SLD}$ on the ends of the EDB can be obtained.

**B. TEST AND SIMULATION VERIFICATION**

A picture of the test system is given in Figure 8. It consists of a motion table, sensors, fixtures, display consoles, data processing equipment, and so on.

The forces that the energy dissipation band acts on the both ends are related to the density and the strength of the stitches. And the values can be measured by a mechanics test as shown in Figure 9.

In the tests, $L_0 = 6.5\, \text{mm}$, $L_N = 0.1134$, $N_k = 16$, $a\% \approx 30\%$. The curve of the forces changing with distance is shown by the solid line in Figure 10.

The stiffness and damping coefficients can be obtained from tests as shown in Figure 11 and Figure 12 [23]. The test results are listed below: the linear stiffness $K_s$ is about 628.7N/m and the damping $C_s$ is about 0.923 ($\text{N} \times \text{s})/\text{m}$.

Substituting the values of stiffness and damping into Equation 5, the curve of the forces changing with distance is shown by the dotted line in Figure 10.

As can be noticed in Figure 10, the test and simulation result are in good agreement. The average force values of the simulation and test are respectively 4.82N and 4.69N, which are really close. Furthermore, the Pearson correlation coefficient of the two cures is 0.60, also demonstrating the good agreement between the simulation and experiments. Above all, the correctness of the mechanical model of the EDB is proved.

**IV. DYNAMIC MODEL OF THE SPACE TETHERED-NET WITH EDB**

After discretizing the tethered-net into several tether segments (can only be pulled but cannot be pressed), each segment is also equivalent by a semi-spring damper. The mass
of the tether segment is concentrated at the two ends (i.e. the tether knot), and the internal force and the external force are equivalently applied to the tether knots. After adding the energy dissipation bands, the equivalent dynamic model is shown in Figure 13. The number of knots on the outer edge of the tethered-net is \( N \), the total number of tether knots is \( n \), and the mass of arbitrary knot is \( m_i \) (\( i = 1, 2, \ldots, n \)).

The earth’s center of mass is taken as the coordinate origin to build the geodetic coordinates system \( O - XYZ \) (right-handed coordinate system), the \( OX \) axis points to the 0° longitude line and the \( OZ \) axis points to the geographical north pole. At the moment of launch, the position of the center point of the tethered-net is taken as the coordinate origin to build a rectangular coordinate system \( o - xyz \) (right-handed coordinate system), the \( ox \) axis points to a net corner and the \( oz \) axis is the direction in which the tethered-net is deployed. The radius vector of \( O \) to \( o \) is \( R \). The tether segment model is shown in Figure 14. The radius vector of the arbitrary knot \( i \) and \( j \) (\( j = 1, 2, \ldots, n \)) in the \( o - xyz \) coordinate system are \( r_i \) \( (r_{ix}, r_{iy}, r_{iz}) \) and \( r_j \) \( (r_{jx}, r_{jy}, r_{jz}) \), respectively.

The force acting on the point \( i \) is divided into several external forces and internal forces. The internal forces are provided by the semi-spring dampers connected to the point \( i \). The external force is simplified to gravity. For the knots with EDB attached, the external force should also contain the force provided by the bands. The internal force that acts on the knot \( i \) is given by

\[
F_i^a = \sum_{j=1}^{p_i} e_{ij} F_{ij}^a
\]

where \( p_i \) is the number of knots connected to knot \( i \). \( e_{ij} \) is the segment vector pointing from knot \( i \) to knot \( j \). \( F_{ij}^a \) is the force of segment \( ij \) acting on the knot \( i \), and its value can be obtained by

\[
F_{ij}^a = \begin{cases} 
  k_{ij}(l_{ij} - l_{ij}^0) + c_{ij}l_{ij} & l_{ij} > l_{ij}^0 \\
  0 & l_{ij} \leq l_{ij}^0
\end{cases}
\]

where \( k_{ij} \) and \( c_{ij} \) are the stiffness and damping of the tether segment respectively, and they also can be measured by the tests shown in Figure 11 and 12.
The force the space environment act on the knot is \( G_i^e \), and it can be expressed as
\[
G_i^e = G_{\text{earth}} \times m_i \frac{\mathbf{R} + \mathbf{r}_i}{(\mathbf{R} + \mathbf{r}_i)^3 \cdot \| \mathbf{R} + \mathbf{r}_i \|} \quad (8)
\]
where \( G \) is the gravitational constant, \( m_{\text{earth}} \) is the mass of the earth. If any energy dissipation constant are attached to knot \( i \), the force of the bands acting on the knot is written as
\[
F_{ikSLD} = \sum_{k=1}^{q_i} e_{ik} F_{ikSLD}
\]
where \( q_i \) is the number of bands that attached to knot \( i \), \( F_{ikSLD} \) is the force value that the \( k \)-th band acting on knot \( i \).

Above all, the dynamic function of arbitrary knot \( i \) yields
\[
m_i \mathbf{r}_i = F_i^a + G_i^e + F_{iSLD}
\]
Matrix form of (10) is
\[
\mathbf{mR} - \mathbf{F}^a - (\mathbf{G}^e + \mathbf{NF}_{SLD}) = 0
\]
where,
- \( \mathbf{m} = \text{diag} \left( m_1, m_2, \ldots, m_n \right) \)
- \( \mathbf{F}^a = \left[ \left( \sum_{j=1}^{k_1} e_{ij} F_{ij}^a \right) \left( \sum_{j=1}^{k_2} e_{ij} F_{ij}^a \right) \cdots \left( \sum_{j=1}^{k_n} e_{ij} F_{ij}^a \right) \right]^T \)
- \( \mathbf{G}^e = [ G_1^e, G_2^e, \ldots, G_n^e ]^T \)
- \( \mathbf{F}_{SLD} = \left[ \sum_{j=1}^{q_1} e_{ij} F_{iSLD} \sum_{j=1}^{q_2} e_{ij} F_{iSLD} \cdots \sum_{j=1}^{q_n} e_{ij} F_{iSLD} \right]^T \)
- \( \mathbf{N} = \left[ N_1, N_2, \ldots, N_n \right]^T \)

In which \( \mathbf{N} \) is a Boolean matrix, and if \( i \)-th knot is attached by EDBs, \( N_i = [1 \ 1 \ 1]^T \).

V. OPTIMIZATION
Exploratory simulation results shows that if the strength of the energy dissipation band is different, the deploy performance of the space tethered-net is also different. So as to keep the tethered-net mouth open as long as possible, it is necessary to optimize the strength of the EDBs.

A. PERFORMANCE INDEX
To quantitatively describe the effectiveness of the deployment performance of the tethered-net, we will define a performance index: ‘effective working distance’. Before introducing this performance indicator, the definition of the “expanded area ratio (w)” is present firstly. \( w \) is the ratio of the area \( S_t \) (the polygon formed by the lines connecting Neighboring pilot masses, as shown in Figure 15) to the area \( S_0 \) (the original area of the net).
\[
w = S_t / S_0
\]
(12)

Then, the “effective working distance” is defined as the forward distance when \( w \) is larger than 0.6 (industrial requirement) during the unfolding process of the tethered-net. Figure 16 is the illustration of the effective flight distance, wherein the effective flight distance \( d_e \) is equal to \( d_b - d_a \).

B. OPTIMIMAL INDEPENDENT VARIABLES AND OBJECTIVE FUNCTIONS
The number of knots on each contour line of the tethered-net is \( N_\lambda \). The number of energy dissipation bands on each outer edge is \( N_\lambda - 1 \). The stiffness \( K_\lambda \) of the band \( \psi_i (i = 1, 2, \ldots, \lambda - 1) \) at different positions is used as an optimization variable here. As the four pilot mass are launched with the same velocity and angle, the bands on the four contour lines are symmetrically mounted in this manuscript, i.e. \( \psi_i = \psi_{4-i} (i = 1, 2, \ldots, \lambda - 1) \). Therefore, the optimization independent variable is given by
\[
X_{\text{op}} = \left[ \begin{array}{ccc} k_1^1 & k_2^2 & \cdots & k_{\lambda-1}^{(\lambda-1)/2} \\ \vdots & \vdots & \ddots & \vdots \\ k_{\lambda}^{1} & k_2^{2} & \cdots & k_{\lambda}^{\lambda/2} \end{array} \right] \quad \lambda \text{ is odd}
\]
\[
X_{\text{op}} = \left[ \begin{array}{ccc} k_1^1 & k_2^2 & \cdots & k_{\lambda}^{\lambda/2} \\ \vdots & \vdots & \ddots & \vdots \\ k_{\lambda}^{1} & k_2^{2} & \cdots & k_{\lambda}^{\lambda/2} \end{array} \right] \quad \lambda \text{ is even}
\]
(13)
The objective function is given by
\[
\min (-d_e)
\]
(14)
Equation (13) and (14) are respectively the optimized independent variables and objective function. And the optimization work can be performed with RBFBS algorithm.
C. INTRODUCTION OF RBFBBS ALGORITHM

Calculating the objective function value (14) for each set of design parameters can be very time-consuming. To resolve it in a more efficient way, we propose a RBFBBS algorithm [41], in which a computationally cheap RBF model is used to approximate the original optimization method. And then a batch infill criterion including both a bi-objective-based and a single-objective-based approach is used for sampling. We will introduce the RBF model and the batch infill sampling criterion before providing a completed introduction of RBFBBS algorithm.

1) RBF MODEL

The RBF model is one of the most popular techniques to interpolate scattered data. Suppose that \( f = f(x) \), \( x = (x_1, \ldots, x_d)^T \in \mathbb{R}^d \) is a real-valued function that we intend to approximate, and \( d \) is the number of variables of \( f \). A RBF model can be expressed in the following form: [42]

\[
    s(x, c) = \sum_{k=1}^{K} w_k \varphi(\|x - x_k\|)
\]

where \( W = (w_1, w_2, \ldots, w_K)^T \) is the weight vector and \( \| \cdot \| \) represents the Euclidean distance. The points \( \{x_1, \ldots, x_K\} \) are the centers of the RBF model, \( \varphi(r, c), r \geq 0 \) is a real-valued basis function. In this paper, the following multiquadric function is employed as the basis function:

\[
    \varphi(r) = \sqrt{c^2 + r^2}
\]

where \( r \) is the inputted parameter of the basis function, and \( c \) is a parameter affecting the shape of the surface.

Assume that all points in the training dataset \( D = \{x_i, f(x_i), i = 1, 2, \ldots, N\} \) happen to be the centers, to get the weight vector \( W \), the following interpolation condition needs to be satisfied:

\[
    f(x_i) = s(x_i, c), \quad i = 1, 2, \ldots, N
\]

It can be written in a matrix form as:

\[
    \Phi W = F
\]

where \( \Phi_{ij} = \varphi(\|x_i - x_j\|, c), i, j = 1, 2, \ldots, N, F = (f(x_1), f(x_2), \ldots, f(x_N))^T \). Finally, the weight vector \( W \) can be obtained by solving the above linear equation system as:

\[
    W = \Phi^{-1} F
\]

In this paper, the RBF model is implemented by the Matlab SURROGATES tool-box [43].

2) BATCH INFILL SAMPLING CRITERION

Based on the surrogate model \( s(x, c) \), we want to find a batch of new samples for simulation. These new samples should be able to balance exploration and exploitation adaptively. To this end, we combine a bi-objective-based and a single-objective-based sampling approach. First, a bi-objective and a single-objective optimization problems are defined below:

\[
    \min \{ f_1(x), f_2(x) \} \quad (20)
\]

\[
    \min f_1(x) \quad (21)
\]

where \( f_1(x) = s(x, c) \), \( f_2(x) = -\min_{x_i \in D} \|x - x_i\| \), and \( D \) is the dataset that saves the previously evaluated solutions.

The bi-objective optimization problem (20) minimizes the predicted objective function value and maximizes the distance to the previously evaluated solutions. For this problem, we can employ well-developed multi-objective evolutionary algorithms (MOEAs), such as non-dominated sorting genetic algorithm - II (NSGA-II) [44] and the multi-objective evolutionary algorithm based on decomposition (MOEA/D) [45–47], to get the non-dominated front (NF) and corresponding non-dominated set (NS). In this paper, we choose NSGA-II since the magnitudes of these two objectives are different. Moreover, in NSGA-II, we use differential mutation DE/rand/1 and binary crossover to generate offspring [48]. After getting the non-dominated front NF and NS, the slope(\( x_i \)), \( x_i \in NS \), is calculated as

\[
    \text{slope}(x_i) = \frac{f_2(x_{i1}) - f_2(x_i)}{f_1(x_{i1}) - f_1(x_i)}
\]

where \( x_{i1} \) represents the solution in NS that has a minimum \( f_1 \) value.

In the bi-objective-based sampling approach, the point \( x_{i1} \) and the solution \( x_i \) with maximum slope value are selected for simulation. A simple illustration for the selection of these two points is shown in Figure 17, in which \( x_1 \) and \( x_3 \) are selected. For the single-objective-based sampling approach, Jingqiao’s adaptive differential evolution (JADE) algorithm [49] is employed to solve the problem (21). In this way, we can get a quasi-optimal solution \( x^* = \arg \min s(x, c) \). Finally, in each iteration of RBFBBS, three new points \( \{x_{i1}, x_i, x^*\} \) are selected for RBFBBS, three new points are selected for expensive computer simulation.

3) COMPLETED RBFBBS

The pseudo-code of the completed RBFBBS algorithm is provided in Table 1. In initialization, \( n_0 \) initial solutions

![Figure 17. Selection of two points from the non-dominated set, where \( x_{f1} = x_1 \) and \( x_5 = x_3 \).](image-url)
Algorithm 1 RBFBS

Input: The shape parameter c. The number of initial solutions $n_0$
1. Generate the initial training dataset $\mathcal{D}_I$
2. Set the current dataset $\mathcal{D} = \mathcal{D}_I$
3. while the stopping criterion is not satisfied do
4. Train $S(x, c)$ based on $\mathcal{D}$ and c
5. Get NF and NS of Eq. (12) by NSGA-II
6. Get $\{x_{f1}, x_s\}$ from NS
7. Get $x^*$ of Eq. (13) by JADE
8. Conduct computer simulation on $\{x_{f1}, x_s, x^*\}$
9. $\mathcal{D} = \mathcal{D} \cup \{x_{f1}, f(x_{f1}), x_s, f(x_s), (x^*, f(x^*))\}$
10. end while
Output: The best solution in the dataset $\mathcal{D}$

TABLE 1. Parameters of the space tethered-net.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot mass</td>
<td>1.0 kg</td>
</tr>
<tr>
<td>Launch angle</td>
<td>45°</td>
</tr>
<tr>
<td>Launch speed</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Length of the contour lines between two adjacent pilot masses</td>
<td>10 m</td>
</tr>
<tr>
<td>Density of contour lines, diagonal lines, and pilot risers</td>
<td>631.3 kg/m$^3$</td>
</tr>
<tr>
<td>Diameter of contour lines, diagonal lines, and pilot risers</td>
<td>3 mm</td>
</tr>
<tr>
<td>Density of inner lines</td>
<td>1288.9 kg/m$^3$</td>
</tr>
<tr>
<td>Diameter of inner lines</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

$X_I = \{x_1, x_2, \cdots x_{n_0}\}$ are generated in the entire search space by Latin hypercube sampling (LHS), and the initial training dataset $\mathcal{D}_I = \{(x_{f1}, f(x_{f1})), \cdots, (x_{n_0}, f(x_{n_0}))\}$ can be obtained by conducting expensive computer simulation on the initial solutions. After initialization, the algorithm goes into a loop of iterations until the stopping criterion is met. It should be pointed out that the batch infill sampling and the evaluation of batch samples can be realized in parallel. In our experiment, the shaper parameter $c$ is set to 0.8, and the initial solution size is set to 12. For JADE and NSGA-II, the population size and the maximal number of generation is set to 100 and 100, respectively, for DE operator, the scale factor and crossover rate are set to 0.5 and 0.9, respectively.

VI. SIMULATION AND ANALYSIS

A. SYSTEM PARAMETERS SETTING

In this paper, the tethered-net is assumed to be placed on geosynchronous orbit ($R = 42300$ km). The number of knots on each contour line is 10 ($N_k = 10$) and the number of stitches of a EBD is 10 ($N_e = 10$). The other parameters of the space tethered-net are shown in Table 1.

Besides, the linear density of the stitches is about $2.5 \times 10^{-5}$ kg/m. And the total mass of the stitches is about $5.0 \times 10^{-5}$ kg, which is small enough to be ignored when compared to the total mass 1.85 kg of the tethered-net.

B. ANALYSIS OF THE SIMULATION RESULTS

The trend of convergence of RBFBS on this design optimization problem are illustrated in Figure 18. The best solution found by RBFBS is $[0.50, 2.29, 7.67, 7.80, 4.91]$ and its objective function value is $-44.64$. Meanwhile, the objective function value is $-13.62$ when the space tethered-net is without passive control (i.e. $x = [0.0 0.0 0.0 0.0 0.0]$). And the curves of the expanded area ratio ($\omega$) varying with the flying distance and without and with optimal designed passive control are both given in Figure 19. Combining the figure and optimization results, it can be obtained that, under the working conditions of this paper, the effective working distance of the space tethered-net with optimal designed EDBs is 3.27 times of that without control, which proves the effectiveness of this passive control method.

The simulation is set to end when the expanded area ratio ($\omega$) decreases to 0.05. The shapes of the space tethered-net without and with the optimal designed passive control are shown in Figure 20, and the flying trajectories of the pilot masses are shown in Figure 21. As can be seen from the figures, in the case of without passive control, the space tethered-net rebounds immediately after expanding to its maximum area. But when the tethered-net is under optimal designed passive control, the speed of rebound movement significantly reduced. Also noticing that, the tethered-net can fly about 120 meters away with optimal designed passive control, which is almost 6 times of that without control. Besides, as can be obtained from the figures, the max expanded area ratio becomes smaller when the tethered-net is under passive control, which indicates that this pattern of control needs to be improved.

The pilot-mass velocity in the $o - xy$ plane and on the $oz$ axis are shown in Figure 22 and 23, respectively. As can be seen from Figure 22, without control, the velocity in the $o - xy$ plane decreases slowly at first, but sharply decreases to 0.0 m/s and increases to 11.20 m/s within a short distance. However, with optimal designed passive control, the velocity decreases from 14.14 m/s to 0.0 m/s in a more uniform speed,
and at last it increases to 1.03 m/s within a long distance. In addition, it can be seen from Figure 23 that, adding passive control or not, the velocity on the oz axis finally increases to about 12.5 m/s within about the same flight distance. So with the analyses above, it can be concluded that the optimal designed passive control with EDBs mitigates the rebound movement greatly but impacts the flying direction of the space tethered-net slightly.

The maximum internal forces of the tethered-net at each location during the flight distance are shown in Figure 24 and 25. And it can be seen from the figures that when the tethered-net flies to the distance of 11.1 m, the rapid rebound movement causes a large internal force of 565.9 N when without control. But with optimal designed passive control, that force disappears with the disappearance of the rapid rebound movement. And the maximum internal force during the flight becomes 443.2 N, which is 78.3% of that without control. Therefore, the optimal designed passive

\[ \text{Without control} \quad \text{With optimal designed passive control} \]

\[ \text{Without control} \quad \text{With optimal designed passive control} \]

\[ \text{Without control} \quad \text{With optimal designed passive control} \]

\[ \text{Without control} \quad \text{With optimal designed passive control} \]
control with EDBs can reduce the possibility of destruction of the tethered-net and lower the mechanical requirement of the materials used.

VII. CONCLUSION

A passive control method based on EDB is proposed to minimize the rebound movement of the space tethered-net during its deployment. And the strengths of the EDBs are optimized with RBFBS. In this paper, the passive control mechanism of the EDB is firstly introduced, and then “semi-spring damper” model of the band is established and verified by the tests. Secondly, the “semi-spring damper” model of the whole tethered-net is built and the evaluation index of the space tethered-net’s work effectiveness is introduced. Thirdly, RBFBS algorithm is used to optimize the strengths of the EDBs. And the characteristics of the space tethered-nets without and with optimal designed EDBs are comparatively analyzed. Simulation results show that the passive control method based on EDBs can effectively mitigate the rebounding movement and increase the effective work distance of the space tethered-net. Besides, it is proved that RBFBS can solve this problem in an effective and efficient way.

Simulation results show that the shapes of the tethered-net during the working process are still not that perfect. And the max expanded area becomes smaller when the tethered net is under this pattern of passive control. Therefore, in future works, the EDBs can be attached to all possible knots. And other methods such as changing the initial folding pattern, optimizing the topology of the tethered-net and so on can be used to optimize the deployment of the space tethered-net.

REFERENCES


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