Dynamic Characteristic Analysis of Large Space Deployable Articulated Mast

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Abstract

Equivalent continuum beam model and finite element model of space deployable articulated mast are developed. Dynamic characteristics of the mast without and with tip load are analyzed based on two models respectively. Frequencies and mode shapes of the mast are calculated and simulated by Euler beam theory and finite element simulation, and theoretical solutions are compared with simulation results. Influence of mast structural parameters on mast natural frequencies is analyzed, the sensitivities of mast bending, torsional, axial frequencies to structural parameters are calculated. The measure for improving mast dynamic characteristic is proposed through sensitivity analysis.

1. Introduction

Space deployable masts are widely used to deploy and support flexible solar array, magnetometer, deployable antenna, photometer, gravity gradient boom, interferometer and other optical instrument. Space deployable masts are classified into Bi-stem, telescoping mast, coilable mast, articulated mast and inflatable mast as in [1]. Advantages of the articulated mast are superior stiffness, high dimensional stability, high deployment reliability and high positioning accuracy. So it can be used to support and position high accuracy exploration instruments such as synthetic aperture radar, space telescope and deployable antenna and so on. The Able Deployable Articulated Mast has been used in the Shuttle Radar Topography Mission successfully in February 2000, the ADAM mast supported Interferometric Synthetic Aperture Radar to digitally survey the Earth’s surface from space. Its fully deployment length is 60
meters which has been the longest space deployable structure of space exploration applications. The height of mast retraction stack is 1.44 meter, the packaging efficiency is 4.9 percent as in [2].

Performance of space deployable articulated mast is sufficiently dependent upon its dynamic characteristics [3], fundamental frequency is the most significant performance metrics for determining stability of the mast. This paper focuses on the natural frequencies of the mast, and dynamic model of articulated mast is developed to analyze mast dynamic characteristic. Influence of structural parameters on mast frequencies is analyzed by calculating sensitivities of frequencies to structural parameters.

2. Dynamic modeling of deployable articulated mast

2.1. Deployable articulated mast

Space deployable articulated masts usually are designed as truss structures which constructed by numbers of basic repeated deployable bays as in [4]. The basic deployable mast bay is a composite structure composed of longerons, battens, spheric hinges or pin joints, diagonal cables and latch mechanisms as shown in Fig.1. The joint or hinge permits the mast bay to retract or deploy, four longerons are used in the mast bay which determines the cross-section of the mast is quadrangular, three longerons can also been used in the mast bay and corresponding cross-section is triangular.

2.2. Equivalent continuum beam model

As shown in Fig.2, the space deployable articulated mast extends out from the shuttle or satellite, the root of the mast connects with the spacecraft that is assumed to be cantilevered from the spacecraft and the tip of the mast supports a load.

Due to the mast is large complex beam-like structure composed of identical repeated bays, it can been represented by equivalent continuum beam model, according to [5] the equivalent stiffness of mast with four longerons can been expressed as:

\[
\begin{align*}
EI &= 2E_iA_iR^2 \\
GJ &= 4E_iA_iR^2 \sin \gamma \cos^2 \gamma \\
GA &= 4E_iA_i \sin \gamma \cos^2 \gamma \\
EA &= 4E_iA_i
\end{align*}
\]

(1)
where, $E_L$, $E_D$, are elastic modulus of longeron and diagonal cable, and $A_L$, $A_D$ are cross section areas of longeron and diagonal cable respectively, $\gamma$ is angle between batten and diagonal cable, $R$ is radius of mast.

The line density of the mast is equivalent as:

$$\bar{m} = 4(\rho_A A_L \frac{l_B}{l_l} + 2 \rho_D A_D \frac{l_D}{l_l} + m_j + m_z) \quad (2)$$

where, $\rho_A$, $\rho_B$, $\rho_D$ are density of longeron, batten and diagonal cable respectively, $l_B$, $l_D$, $l_l$ are length of batten, diagonal cable and longeron, $A_B$, $A_D$ are cross-section areas of batten and diagonal cable, $m_j$, $m_z$ are mass of joint and latch.

Based on Euler beam theory, the fundamental frequency of cantilevered mast without tip load is:

$$f = \frac{3.516}{2\pi} \sqrt{\frac{EI}{\bar{m}L^2}} \quad (3)$$

The fundamental frequency of cantilevered mast supporting a tip load can been expressed as:

$$f = \frac{1}{2\pi} \sqrt{\frac{3EI}{m_{tip} + 0.24m_{mast}L}}$$

where $m_{tip}$ is the tip load mass, $m_{mast}$ is the mast’s own mass, $L$ is full length of the mast.

2.3. Finite element model

The finite element models of the cantilevered mast with and without tip load are developed in order to simulate dynamic behavior of the mast system as shown in Fig.3. All freedom of bottom side of the mast is constrained.

Joints are assumed to be perfect and rigid in the simulation model because there is prestress in diagonal cable, joint is pressed between contact surfaces. The longerons and battens are simulated by beam elements. The diagonal cables are simulated by link elements which only stand tension and assigned the initial strain to simulate the force of prestress in the cables. The mass of the joints, latches and tip load are simulated using lamped mass elements. The natural frequencies and mode shapes of the mast can been simulated by this model.

![Fig. 3. Finite element model of the mast](image)

3. Dynamic analysis of deployable articulated mast

3.1. Dynamic analysis of mast without tip load

The simulation mast model contains 20 bays, and mast full length is 7300mm, mast radius is 560mm, cable prestress is 500N, longeron and batten diameters are both 16mm, cable diameter is 1.5mm, joint and
latch mass is both 100g, elastic modulus of longeron and batten is 70GPa, and cable elastic modulus is 210GPa. Bending, torsional, axial vibration frequencies of mast and corresponding mode shapes description are shown in Table.1, and mode shapes are shown in Fig.3, theoretical solution results of equivalent continuum beam model are compared with finite element model simulation results which match well each other, the equivalent continuum beam model overestimates mast stiffness compared with finite element model.

Table 1. First eight vibration frequencies and mode shapes of the mast(Hz)

| Mode | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| FEM  | 3.4380| 12.918| 17.379| 38.709| 49.790| 60.052| 64.363| 71.668|
| Equivalent Modal | 3.792 | 13.345| 19.633| 40.036| 45.269| 69.524| 66.727| 74.038 |
| Mode shape | Bending | Torsional | Bending | Torsional | Bending | Axial | Torsional | Bending |

Fig. 4. First eight mode shapes of mast

Synchronously, the first bending frequencies of the mast with different length are obtained from the finite element simulation and theoretical analysis. The results comparison is shown in Fig.5, theoretical results are closer to simulation results with the mast length increasing.

Fig. 5. Natural frequencies of the mast as a function of mast length
3.2. Dynamic analysis of mast with tip load

Dynamic of the 20-bay mast with tip load is analyzed, the same mast model and with tip load mass is 44Kg, bending, torsional, axial vibration frequencies of mast with tip load and corresponding mode shapes are shown in Fig.6. It is found through simulation that the motion of the tip mass diminishes and approaching a pinned end condition when the tip mass is larger, higher order frequencies will not change as much as first order. The fundamental frequency of mast with tip mass varies with ratio of tip mass to mast mass changing is shown in Fig.7, the simulation results match well with theoretical calculation results.

![Fig. 6. First eight mode shapes of mast with tip load](image)

![Fig. 7. Natural frequencies of the mast as a function of tip mass to mast mass ratio](image)
4. Influence of structural parameters on mast frequencies

Mast structural design parameters include mast diameter, longeron, batten and cable diameters, joint and latch mass, cable prestress. In order to analyze and compare influence of structural parameters on mast frequencies, the sensitivity of mast frequency to structural parameter is defined as:

\[
\eta(f_i/x_j) = \lim_{\Delta x_i \to 0} \frac{\Delta f_i}{f_i} / \frac{x_j}{x_i} (x_j \neq 0, f_i \neq 0)
\]  

(5)

where, \(f_i\) is the mast frequency of mode i, \(x_j\) is one mast structural parameter, \(\Delta x_j\) is change value of mast structural parameter, \(\Delta f_i\) is change value of mast frequency induced by \(\Delta x_j\).

Sensitivities of mast bending, tortional and axial frequencies to structural parameters are calculated and shown in Table.2. Mast diameter is not included because the scale of the mast is usually restricted before detail parameters designed. Negative delegates that mast frequencies decrease with structural parameters increasing.

| Parameter       | Bending  | Latch mass | Longeron diameter | Batten diameter | Cable diameter | Cable prestress |
|-----------------|----------|------------|-------------------|----------------|----------------|----------------|
| Joint mass      | -0.249   | -0.123     | 0.804             | -0.124         | 0.093          | 0.291\times10^{-3} |
| Latch mass      | -0.307   | -0.074     | -0.099            | -0.072         | 2.561          | -1.548\times10^{-7} |
| Longeron diameter | -0.249  | -0.124     | 0.840             | -0.119         | -0.105         | 0.167\times10^{-3} |
| Batten diameter | -0.123   | -0.074     | -0.099            | -0.072         | 2.561          | -1.548\times10^{-7} |
| Cable diameter  | -0.124   | -0.072     | -0.099            | -0.072         | 2.561          | -1.548\times10^{-7} |
| Cable prestress | 0.093    | 2.561      | -0.105            | 0.167\times10^{-3} |

Mast bending and axial frequencies are sufficiently sensitive to mast longeron diameter, while cable diameter affects on mast torsional frequencies sufficiently. The cable prestress has little influence on mast frequencies. Influence of longeron and diagonal cable diameters on every order frequencies of mast are shown in Fig.8 and Fig.9. The longeron diameter varies from 12mm to 16mm, first bending and axial frequencies increase 13.24% and 13.81% respectively. The cable diameters varies from 1.5mm to 4.5mm, first torsional frequency increases 164.18%. It is preferred to increase longeron cross-section area and cable diameters, decrease batten cross-section area and mass of joint and latch when design the mast.

Fig. 8. Influence of longeron diameter on mast frequencies

Fig. 9. Influence of cable diameter on mast frequencies
5. Conclusion

The dynamic model of space deployable articulated mast has been studied in this paper, equivalent continuum model and finite element model of the mast are developed respectively. Frequencies and mode shapes of the mast are calculated and simulated based on equivalent continuum beam model and finite element model. The results from theoretical solution and simulation match well, especially the mast length is longer. Influence of mast structural parameters on mast frequencies has been analyzed, mast bending and axial frequencies are sensitive to longeron diameter, while mast torsional frequency are sensitive to diagonal cable diameter. It is effective to increase longeron and diagonal cable diameters for improving mast frequencies and stiffness.

Acknowledgments

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