

涡轮泵转子的临界转速研究

(Ⅱ) 非均匀支承转子临界转速 的传递矩阵法*

何洪庆 张小龙 沈达宽 张哲文

(西北工业大学航天工程学院, 西安, 710072)

摘 要: 当支承的组合刚性沿圆周不均匀时, 可将其刚性分解到两个互相垂直的主平面中, 在主平面中具有最大和最小刚性。同时, 把转子振动时的受力和位移分解到主平面中, 用八阶矩阵分别建立轴、支承、盘的传递矩阵。然后根据具体的转子布局方案可导出临界转速和振幅计算方程。研究表明, 非均匀支承转子与均匀支承转子相比, 频率谱有质量差别, 前者可能出现的临界转速数增加一倍, 在刚性小的方向首先发生振动, 转子振动的轨迹为椭圆。

主题词: 液体推进剂火箭发动机, 涡轮转子, 转子速度, 传递矩阵法⁺, 数值仿真

分类号: V434.21

STUDY ON CRITICAL ROTATIONAL SPEED OF TURBOPUMP ROTORS (Ⅱ) TRANSFER MATRIX METHOD FOR NON-HOMOGENEOUS SUPPORT ROTORS

He Hongqing Zhang Xiaolong Shen Dakuan Zhang Zhewen

(Coll. of Astronautics, Northwestern Polytechnical Univ., Xi'an, 710072)

Abstract: If the complex stiffness of a support is non-homogeneous along circle, the stiffness may be resolved into two main planes vertical each other. There is maximum or minimum stiffness in the main planes. Simultaneously, the acting forces and displacements at vibration are also resolved into the main planes. The 8-steps transfer matrices are respectively built for shaft, support and plate. Then, the calculated equations of critical rotational speed and amplitude can be deduced according to the overall arrangement of rotors. Study specifies that the non-homogeneous rotor is essential distinct from the homogenous one in the frequency spectrum and the critical rotational speed of the former will increase twice. The vibration occurs first in direction of minimum stiffness and the trace of rotor vibration is an ellipse.

Subject terms: Liquid propellant rocket engine, Turbine rotor, Rotor speed, Transfer matrix method⁺, Numerical simulation

1 引 言

涡轮转子中, 转动部件沿圆周是均匀的, 即使有微小的不均匀, 经过静、动平衡, 还是均匀的。非均匀转子是指转子的支撑元件(如支承、壳体等)的刚性沿圆周不均匀的转子, 称

* 收稿日期: 1998-02-04, 修回日期: 1998-06-08

之为非均匀支承转子,其中支承和壳体为组合刚性。本文在均匀支承转子临界转速研究^[1]的基础上,用将参数分解到 xz 和 yz 两个主平面中的方法,建立了非对称支承转子转速的传递矩阵法。

2 自由振动时非均匀转子元件的传递矩阵

本文所用符号与系列论文之一^[1]相同,仅下标 x, y 分别表示两个主平面中的值。

经推导,在非均匀支承转子中,无质量轴的传递矩阵 $[a]_i$,以及由弹性元件和粘性阻尼并联构成的非均匀支承的传递矩阵 $[b]_i$ 分别为

$$[a]_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ l_i & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \beta_{xi} & v_{xi} & 1 & 0 & 0 & 0 & 0 & 0 \\ \gamma_{xi} & \epsilon_{xi} & l_i & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & l_i & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \beta_{yi} & v_{yi} & 1 & 0 \\ 0 & 0 & 0 & 0 & \gamma_{yi} & \epsilon_{yi} & l_i & 1 \end{bmatrix} \quad [b]_i = \begin{bmatrix} 1 & 0 & 0 & -K_{xi} & 0 & 0 & 0 & c_{xi}\Omega \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -c_{yi}\Omega & 1 & 0 & 0 & -K_{yi} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

式中

$$v_{xi} = \frac{l_i}{EJ_{xi}}\beta_{xi} = \epsilon_{xi} = \frac{l_i^2}{2EJ_{xi}}\gamma_{xi} = \frac{l_i^3}{6EJ_{xi}}, \quad v_{yi} = \frac{l_i}{EJ_{yi}}\beta_{yi} = \epsilon_{yi} = \frac{l_i^2}{2EJ_{yi}}\gamma_{yi} = \frac{l_i^3}{6EJ_{yi}}$$

非均匀转子中盘的传递矩阵为

$$[c]_i = \begin{bmatrix} 1 & 0 & 0 & m_i\Omega^2 & 0 & 0 & 0 & 0 \\ 0 & 1 & -I_i\Omega^2 & 0 & 0 & 0 & -iI_{0i}\omega\Omega & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & m_i\Omega^2 \\ 0 & 0 & iI_{0i}\omega\Omega & 0 & 0 & 1 & -I_i\Omega^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

3 强迫振动时非均匀支承转子中盘的传递矩阵

强迫振动时均匀支承转子中盘的传递矩阵为 10 阶矩阵,如下

$$[c]_i^0 = \begin{bmatrix} 1 & 0 & 0 & p_i & 0 & 0 & 0 & 0 & t_{xi} & 0 \\ 0 & 1 & -I_i\omega^2 & 0 & 0 & 0 & -q_i & 0 & 0 & u_{xi} \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & p_i & t_{yi} & 0 \\ 0 & 0 & q_i & 0 & 0 & 1 & -I_i\omega^2 & 0 & 0 & -u_{yi} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

4 计算及分析

如图 1 所示的实验转子为单盘双支承转子, 其中两个支承用弹簧钢制成鼠笼式弹性支承。为了使支承弹性沿圆周方向明显地不均匀, 各选择不对称位置切断两根筋。经加载试验测得各主平面中的刚性。

取 0~56 个截面(截面 0~5)把转子分成 5 段, 用上述传递矩阵写出参数方程, 为

$$[Q_{x5} \ M_{y5} \ \phi_{x5} \ A_{x5} \ Q_{y5} \ M_{x5} \ \phi_{y5} \ A_{y5}]^{-1} = [b]_5[a]_4[c]_3[a]_2[b]_1[Q_{x0} \ M_{y0} \ \phi_{x0} \ A_{x0} \ Q_{y0} \ M_{x0} \ \phi_{y0} \ A_{y0}]^{-1}$$

边界条件为 $Q_{x0} = Q_{y0} = M_{x0} = M_{y0} = Q_{x5} = Q_{y5} = M_{x5} = M_{y5} = 0$

将各传递矩阵和边界条件代入方程, 展开, 取实部, 可得频率方程。计算结果如图 2~图 4 所示。

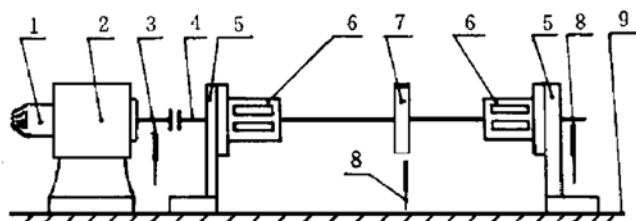


Fig. 1 Rotor scheme being used in test and calculation

- 1) Electric generator of measuring rotation speed
- 2) DC electric motor
- 3) Rotation speed sensor
- 4) Axis
- 5) Support frame
- 6) Elasticity unit
- 7) Plate
- 8) Amplitude sensor
- 9) Steel track

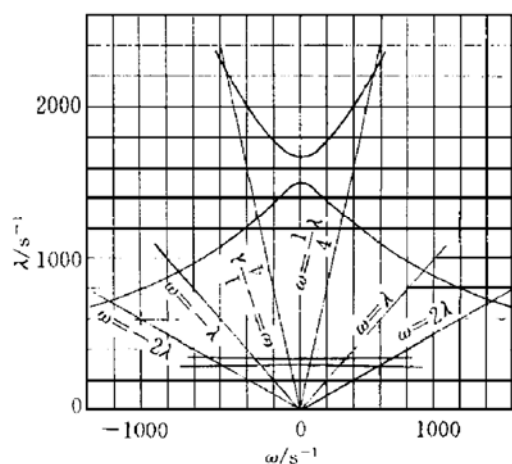


Fig. 2 The frequency spectrum of non-homogeneous rotor

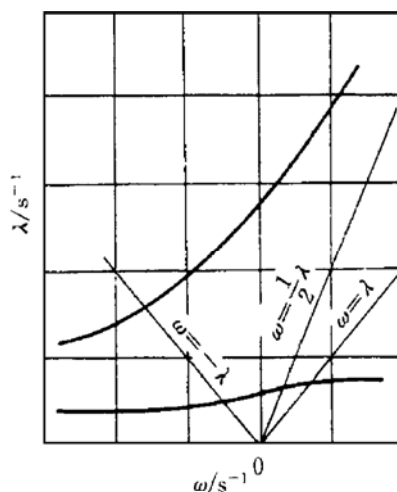


Fig. 3 The frequency spectrum of homogeneous rotor

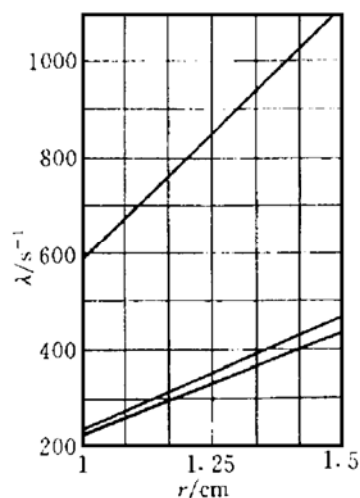


Fig. 4 Free vibration frequency shaft radius and versus stiffness ratio

(下转第 45 页)

1 何洪庆, 沈达宽, 张哲文. 涡轮泵转子的临界转速研究(I)均匀支承转子临界转速的传递矩阵法. 推进技术, 1998, 19(6)