

RTM 多孔注射工艺树脂流动过程数值模拟

李海晨, 王 彪, 周振功

(哈尔滨工业大学, 复合材料研究所 1247#, 哈尔滨 150001)

摘 要:介绍了 RTM 工艺过程及特点, 给出了树脂渗流控制方程。阐述了 RTM 工艺应用于大尺寸, 高纤维含量构件时存在的主要问题。采用贴体坐标/有限差分法模拟了双孔注射情形下树脂渗流过程, 给出了不同时刻树脂流动前沿曲线, 计算网格及终止时刻压力场分布, 确定了排气孔位置, 计算结果与其它研究结果吻合良好。

关键词: RTM; 数值模拟; 贴体坐标

中图分类号: TB12, TB33 **文献标识码:** A

1 引言

RTM (Resin Transfer Molding)即树脂传递模塑工艺, 已有近五十年的历史^[1]。七十年代, RTM 工艺主要用于航空领域, 如生产雷达罩, 航空飞行器螺旋桨叶片等等^{[2][3]}。八十年代中期以后, 随着增强纤维, 树脂基体, 树脂注射技术等工艺的不断发展和完善, RTM 技术开始大量应用于航空, 汽车, 电子, 体育设备等领域^[4]。由于 RTM 工艺成本低, 产品质量高, 易于实现过程自动化等优点而在复合材料成型领域获得广泛应用。

RTM 工艺是在一定的温度及压力下把低粘度的树脂注入置有增强纤维坯的模具中, 然后加热并固化成型的一种复合材料成型方法。其过程可分为以下几个阶段: (1) 增强纤维准备过程, (2) 树脂注射过程, (3) 固化过程, (4) 产品脱模过程, 如图 1 所示。

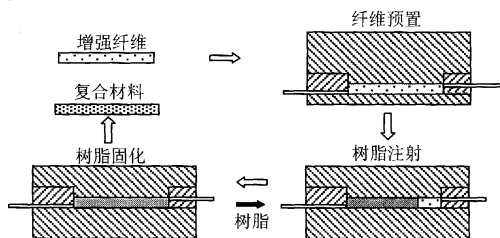


图 1 RTM 工艺过程示意图

Fig.1 The schematic process of RTM

九十年代以来, 人们对 RTM 技术做了大量研究工作, 其工艺不断完善, 应用领域不断扩大。有关 RTM 工艺树脂流动过程, 热传递过程, 固化过程, 工艺参数优化等问题国内外已经做了大量研究工作^[5~8]。

2 大尺寸构件带来的问题

对尺寸大, 纤维含量要求高的构件来说, RTM 工艺难度比较大, 其中一个关键因素是要使树脂在达到凝胶点以前使其充分润湿增强纤维, 以免产生气泡和空洞现象。目前对大尺寸构件主要采用多孔注射工艺, 如图 2 所示。

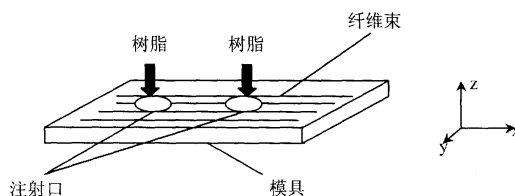


图 2 RTM 多孔注射工艺示意图

Fig.2 The multi-injection process of RTM

RTM 多孔注射工艺主要任务之一是要预先确定树脂注射口及排气孔位置, 以使增强纤维充分润湿, 树脂注射压力合适。因此, 预先了解 RTM 工

收稿日期: 2000-07-18; 修改日期: 2000-10-20

作者简介: 李海晨(1971), 男, 辽宁辽阳人, 博士研究生, 主要从事复合材料成型工艺研究

王 彪(1963), 男, 教授, 博士, 中国力学学会理事, 从事复合材料细观力学研究

周振功(1963), 男, 教授, 博士, 从事复合材料断裂力学研究

艺树脂流动过程,特别是树脂流动前沿曲线对模具设计非常重要。

RTM 工艺过程数值模拟为模具设计 树脂注射过程提供了理论依据。数值模拟的难点是求解区域随着树脂的注入不断发生变化,压力场、温度场及固化度场互相耦合。模拟方法主要有有限元法^[9~11]和贴体坐标/有限差分法^[12~14]。有限元法适合解决复杂模具边界情况,但程序不易编制,计算过程复杂。目前采用的贴体坐标/有限差分法都是单一网格划分方法,这种方法程序相对易于编制,但不适合解决复杂边界情况^[15]。本文采用分区网格划分方法模拟了双孔注射情形下树脂流动过程,给出了不同时刻树脂流动前沿曲线及终止时刻压力场分布情况,该方法可以解决复杂模具边界情形。由于 RTM 工艺主要应用于薄板构件,本文只考虑二维情形,由于旨在模拟树脂流动过程,本文未考虑温度变化及树脂化学反应产生的影响。

3 树脂流动控制方程

树脂在纤维中的流动过程可认为是流体(树脂)在多孔介质(纤维)中的渗流过程,选择渗透率主轴方向为坐标系方向,Darcy 定律可表示为:

$$k_i p_{i,i} + m u_i = 0 \quad (i = x, y) \quad (1)$$

式中 k 为纤维主轴方向渗透率, u 为树脂渗流速度, p 为树脂压力, m 是树脂粘度。本文假定树脂为不可压缩流体,根据不可压缩流体连续性方程得到:

$$u_{i,i} = 0 \quad (i = x, y) \quad (2)$$

将(1)式代入(2)式,得到:

$$\begin{aligned} k_x p_{,xx} + k_y p_{,yy} + (k_x - \frac{k_x}{m} m_{,x}) p_{,x} \\ + (k_y - \frac{k_y}{m} m_{,y}) p_{,y} = 0 \end{aligned} \quad (3)$$

(3)式即为树脂流动控制方程。不考虑树脂流动前沿表面张力,边界条件可写为:

$$\begin{cases} p = p_0 & (\text{注射口}) \\ p_{,n} = 0 & (\text{模具边界}) \\ p = 0 & (\text{流动前沿}) \end{cases} \quad (4)$$

4 网格生成

贴体坐标法可把不规则的物理域问题变换到规则的计算域中去求解,如图3所示。

用贴体坐标生成网格主要有三种方法:代数法、微分方程法及保角变换法^[16~18],本文采用微分方程法。设在物理域中形成的贴体坐标系为 \mathbf{x} 、 \mathbf{h} ,

应用 Poisson 方程求解 \mathbf{x} 、 \mathbf{h} 的方程为:

$$\begin{cases} \nabla^2 \mathbf{x}(x, y) = P(x, y) \\ \nabla^2 \mathbf{h}(x, y) = Q(x, y) \end{cases} \quad (5)$$

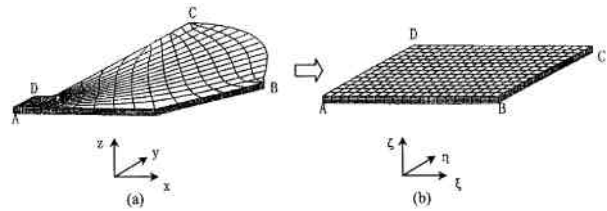


图3 物理域和计算域的坐标系变换(a 物理域 b 计算域)

Fig.3 The coordinate transformation between physical domain and computational domain

(a: physical domain b: computational domain)

式中 $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$, 由于在物理域中求解 \mathbf{x} 、 \mathbf{h} 很

不方便,实际求解时采用式(5)的逆变换形式:

$$\begin{cases} a x_{i,jj} - 2b x_{i,jk} + g x_{i,kk} + J^2 (P x_{i,j} + Q x_{i,k}) = 0 \\ (i=1,2) (x_1 = x, x_2 = y) (j=x, k=h) \end{cases} \quad (6)$$

式中:

$$\begin{cases} a = x_{,h}^2 + y_{,h}^2, & b = x_{,x} x_{,h} + y_{,x} y_{,h} \\ g = x_{,x}^2 + y_{,x}^2, & J = x_{,x} y_{,h} - x_{,h} y_{,x} \end{cases} \quad (7)$$

源项 P 、 Q 用于调节网格疏密程度,本文取为零。

本文模拟了双孔注射工艺过程,网格区域划分如图4所示,模具边界为 ABCD,模具内左、右各有一注射口。当流动前沿曲线未相交时,可对两注射口分别采用单一网格划分方法。流动前沿曲线相交后,沿交线 MN 剖分,将物理域划分为 ABFNM(域 a)和 CDGMNH (域 b)两部分分别求解。

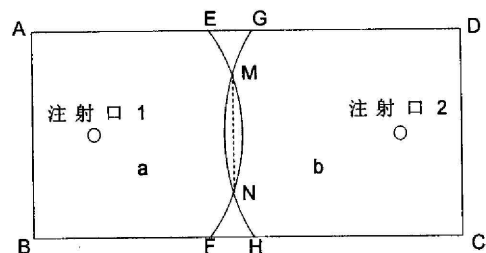


图4 网格剖分示意图

Fig.4 The schematic diagram of mesh subdivision

5 方程变换及求解过程

网格生成后,控制方程及边界条件也应变换到计算域去求解。树脂渗流控制方程变换到计算域为:

$$c_{11} p_{,xx} - 2c_{12} p_{,xh} + c_{22} p_{,hh} + c_1 p_{,x} - c_2 p_{,h} = 0 \quad (8)$$

式(8)中各系数如表1所示。

表 1 公式(8)系数

Table 1 The coefficients of equation (8)

$c_{11} = k_x y_h^2 + k_y x_h^2$	$c_{12} = k_x y_x y_h + k_y x_x x_h$
$c_{22} = k_x y_x^2 + k_y x_x^2$	$d_1 = c_{11} y_{xx} - 2c_{12} y_{xh} + c_{22} y_{hh}$
$d_2 = c_{11} x_{xx} - 2c_{12} x_{xh} + c_{22} x_{hh}$	$d_3 = k_x x_x - \frac{k_x}{m} m_x$
$d_4 = k_x x_h - \frac{k_x}{m} m_h$	$d_5 = k_y y_x - \frac{k_y}{m} m_x$
$d_6 = k_y y_h - \frac{k_y}{m} m_h$	
$c_1 = \frac{1}{J} (d_1 x_h - d_2 y_h) + d_3 y_x^2 - d_4 y_x y_h + d_5 x_h^2 - d_6 x_x x_h$	
$c_2 = \frac{1}{J} (d_1 x_x - d_2 y_x) + d_3 y_x y_h - d_4 y_x^2 + d_5 x_x x_h - d_6 x_x^2$	

边界条件变换到计算域为(见图 4):

$$\begin{cases} p = p_0 & (\text{注射口}) \\ (k_x y_x^2 + k_y x_x^2) p_h & (\text{模具边界}) \\ -(k_x y_x y_h + k_y x_x x_h) p_x = 0 & (\text{流动前沿}) \\ p = 0 & (\text{流动前沿}) \\ p_a = p_b, v_a = v_b & (\text{切线MN}) \end{cases} \quad (9)$$

式中下标 a 和 b 表示计算域 a 和 b 。本文采用中心差分法求解坐标变换方程, 控制方程, 速度方程过程为(以计算域 a 为例):

- 在每一个时间步内求解坐标变换方程, 得出计算域各点对应的 x, y 坐标;
- 求解控制方程, 得出流场内各点压力值;
- 求解速度方程, 得出流场内各点速度;
- 选择合适的时间步长, 得到新的计算域及物理域;
- 重复第一步计算, 直到流体充满整个物理域为止。

6 算例

6.1 Martin 等人^[19]采用有限元法对二维问题进行了研究, 物性参数为: 纤维渗透率 $k_x = k_y = 1.0 \times 10^{-9} \text{ m}^2$, 树脂粘度 $m = 1.44 \text{ Pa} \cdot \text{s}$, 注射压力 $p = 152 \text{ kPa}$ 。本文先采用单一网格划分方法, 计算结果如图 5 所示, 可以看出, 树脂开始时刻流动前沿曲线为半圆形, 然后逐渐过渡成直线, 与 Martin 等人的研究结果(图 6)相吻合。

6.2 本文模拟了图 4 所示树脂注射过程。物性参数

为: 模具长 0.7 m , 宽 0.3 m 。纤维渗透率 $k_x = k_y = 6.2 \times 10^{-9} \text{ m}^2$, 树脂粘度 $m = 1.44 \text{ Pa} \cdot \text{s}$, 左右注射口注射压力分别为 152 kPa 和 252 kPa , 采用分区网格划分方法, 得到不同时刻树脂流动前沿曲线及计算网格, 如图 7 所示。

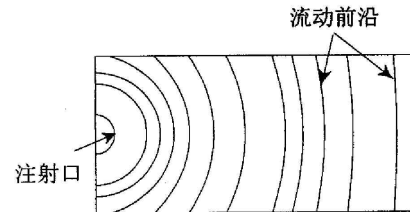


图 5 不同时刻树脂流动前沿曲线

Fig.5 The successive resin flow front position

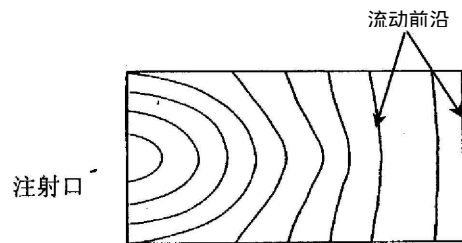
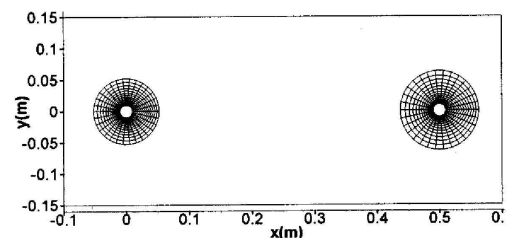
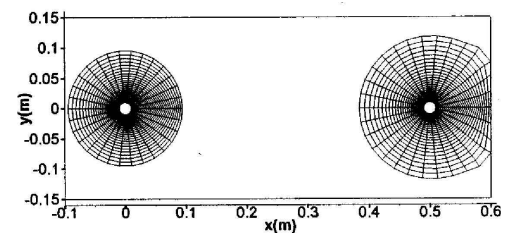


图 6 Martin 等人得到的树脂流动前沿曲线

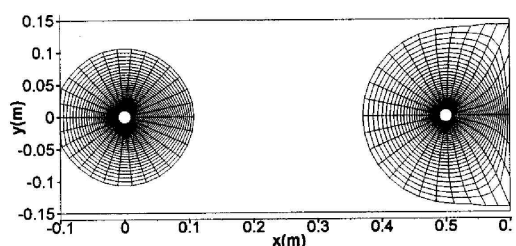
Fig.6 The resin flow front position by Martin et al.



(a)



(b)



(c)

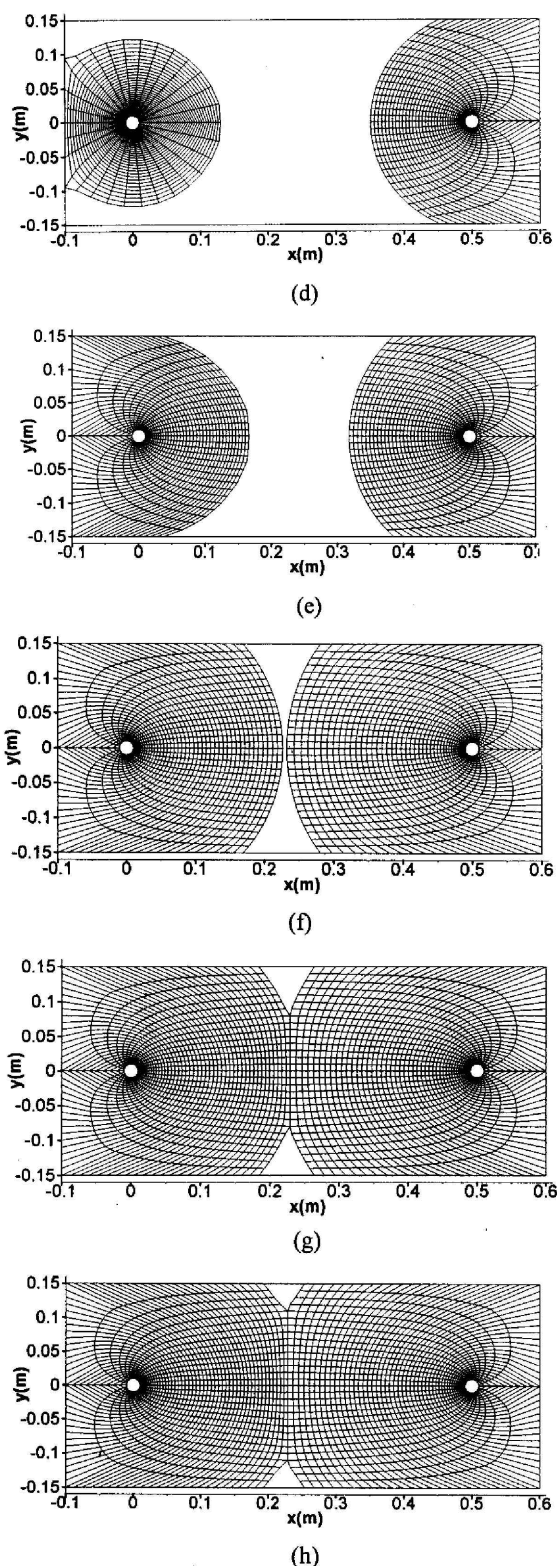


图 7 不同时刻流动前沿及计算网格

Fig.7 The successive resin flow front and computational mesh

终止时刻等压线如图 8 所示,各等压线间压力差为 15.75kPa,压力场分布如图 9 所示,各时刻树脂流动前沿曲线如图 10 所示。从图 10 可见,树脂最后充满的区域 A 和 B 应留有气孔。不同时刻两注

射口间压力如图 11 所示,从图 11 可见,树脂在初始时刻压降最大,随着时间的增加,压降逐渐变小。当树脂流动前沿曲线相交后,交线位置压力值突然增大,这是由于树脂流动前沿相互作用,受迫流向气孔位置而引起的。

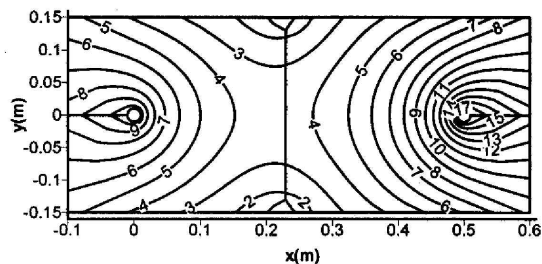


图 8 终止时刻等压线分布

Fig.8 The iso-pressure line at final stage

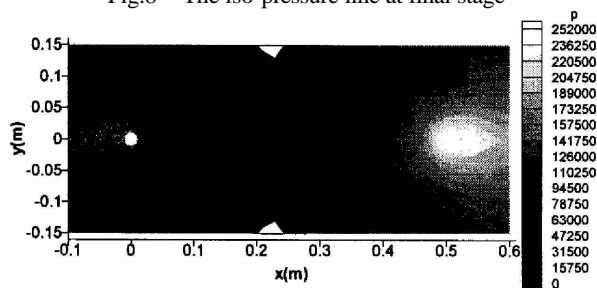


图 9 终止时刻压力场分布

Fig.9 The pressure distribution at final stage

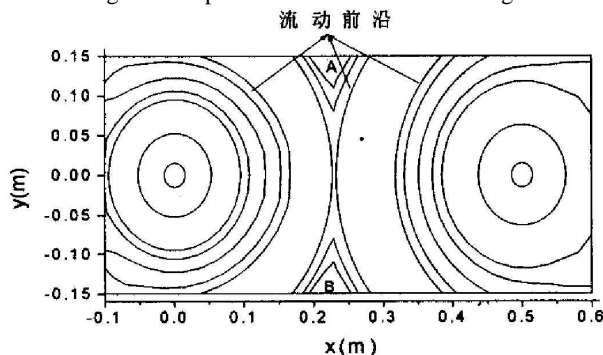


图 10 不同时刻树脂流动前沿曲线

Fig.10 The successive resin flow front position

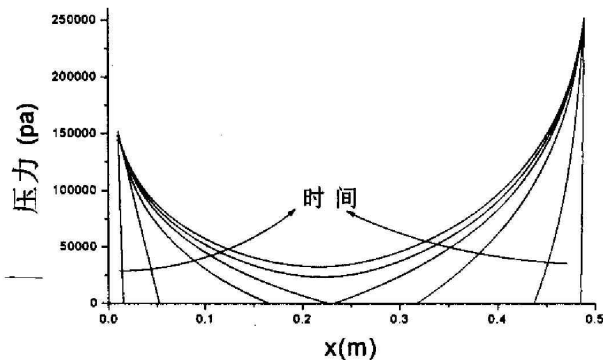


图 11 不同时刻注射口间压力分布

Fig.11 The pressure distribution at different stage

7 结论

- 1、给出了不同时刻树脂流动前沿曲线及计算网格；
- 2、给出了终止时刻压力场分布，确定了排气孔位置；
- 3、初始时刻树脂压降最大，随着时间增加，压降逐渐变小；
- 4、本文提供的方法可用于更多注射口情形。

参考文献：

- [1] G Cooper. Forming processes for metal matrix composites[J]. Composites, 1970, (1):153-159.
- [2] M Cray. Development of a polymeric resin injection process for advanced composite structures, Proc. Symposium: Fabrication Techniques for Advanced Reinforced Plastics, April, Salford: IPC Science and Technology, 1984. 35-39.
- [3] R M Carthy, G Haines, R Newley. Polymer composite applications to aerospace equipment[J]. Composites Manufacturing, 1994, 5(2):83-93.
- [4] Kevin Potter. Resin Transfer Molding(Book)[M]. Chapman & Hall Press, London, 1997.
- [5] Wen-Bin Young. Thermal behaviors of resin and mold in the process of resin transfer molding[J]. J. Reinforced Plast. Comp, 1995, 14(4):310-331.
- [6] Moon-Kwang UM, Woo IL LEE. A study on the mold filling process in resin transfer molding[J]. Polym Compos, 1991, 31(11):765-771.
- [7] B Richard. Dessenberger, L Charles. Tucker. Mold filling and curing analysis in liquid composite molding[J]. Polym Compos, 1995, 16(6):495-506.
- [8] C Alfred, Loos, S George. Springer. Curing of epoxy matrix composites[J]. J of Comp Mater, 1983, (17): 135-169.
- [9] W Albert, Chan, Sun-Tak Hwang. Molding of the impregnation process during resin transfer molding[J]. Polymer Engineering and Science, 1991, 31(15):1149-1156.
- [10] Wen-Bin Young. A simplified flow model for resin transfer molding of polymer composites[J]. Journal of Advanced Materials, 1994, (4):60-64.
- [11] R J Lin, L James Lee, J Ming. Liou. Mold filling and curing analysis in liquid composite molding[J]. Polymer Composites, 1993, 14(1):71-81.
- [12] S Li, R Gauvin. Numerical analysis of the resin flow in resin transfer molding[J]. J. of Reinf. Plast. and Comp, 1990, 10(5):314-327.
- [13] B Friedrichs, S I Gucer. A hybrid numerical technique to model 3-D flow fields in resin transfer molding[J]. Polym. Eng. Sci, 1995, 35(23): 1834-1851.
- [14] P John, Coulter, I Selcuk, Gucer. Resin impregnation during the manufacturing of composite materials subject to prescribed injection rate[J]. J. of Reinforced Plastics and Composites, 1988, 7(5):200-219.
- [15] Francois Trochu, Raymond Gauvin. Limitation of a boundary-fitted finite difference method for the simulation of the resin transfer molding process[J]. J. of Reinforced Plastics and Composites, 1992, 11(7): 772-786.
- [16] J F Thompson, Z V A Warsi, C W Mastin. Boundary-fitted coordinate systems for numerical solutions of partial differential equations-a review[J]. J. Computational Phys, 1982, (47): 1-108.
- [17] 焦德勇, 冯国泰. 叶轮机内流场数值计算[M]. 哈尔滨工业大学出版社, 1990. 60-67.
De-yong Jiao, Guo-tai Feng. Numerical analysis of flow field in turbine[M]. Harbin Institute of Technology Press, 1990. 60-67.
- [18] 苏铭德, 黄素逸. 计算流体力学基础[M]. 清华大学出版社, 1997. 140-161.
Ming-de Su, Su-yi Huang. Fundamentals of computational fluid mechanics[M]. Tsinghua University Press, 1997. 140-161.
- [19] G Q Martin, J S Son. Proc of the ASM/ESD 2nd Conf. on Adv[C]. Composites, Dearborn, Michigan, 1986. 149-157.

(下转 146 页)

structures. : implementation[J]. Journal of Engineering Mechanics, 1994, 120(8): 1761-1772.

models using internal balancing theory[J]. Journal of Guidance, Control and dynamics, 1984, 7(6): 725-732.

[4] Jr. C Z Gregory. Reduction of large flexible spacecraft

ON ACTIVE CONTROL OF INTELLIGENT FRAME STRUCTURES

ZHOU Xing-de , WANG Feng-quan , HAN Xiao-Lin

(Department of Mechanics, Southeast University Nanjing Jiangsu 210096)

Abstract: Frame systems are characterized by complexity, indeterminacy and high flexibility. In recognition of the equality between controllable Grammian matrix and observable Grammian matrix, a condensing method for active control of intelligent frame structures is proposed in this paper. An internal balancing theory is adopted to ensure controllability of system. The modes of high controllability are taken as controlling objects of a system. A discrete system model is first constructed before procurement of system control. A generalized predictive control scheme is introduced, which has better control effect on imprecise models with unknown external forces. A numerical example is presented to show the effectiveness of the method.

Key words: generalized predictive control; active control; frame; internal balancing theory

(上接 123 页)

NUMERICAL SIMULATION OF RESIN FLOW DURING MULTIPLE PORT INJECTION PROCESS IN RESIN TRANSFER MOLDING

LI Hai-chen, WANG Biao, ZHOU Zhen-gong

(Center for Composite Materials, Harbin Institute of Technology, Box 1247, Harbin 150001)

Abstract: This paper addresses the Resin Transfer Molding (RTM) process. The governing equations of resin flow are presented. The major problems involved in fabricating large, high fiber volume fraction components by RTM, are discussed. A boundary-fitted coordinate system and the finite difference method are employed for simulating the resin flow process in the case of two injection ports. The successive resin flow fronts, and the pressure distribution at the final stage are obtained, which is helpful for locating the air vent. Good agreement is reached between the present results and those of other investigations.

Key words: RTM; numerical simulation; boundary-fitted coordinate system