第 9 卷第 4 期 2011 年 12 月
1672-6553/2011/09(4)/342-6
动力学与控制学报
JOURNAL OF DYNAMICS AND CONTROL
Vol. 9 No. 4
Dec. 2011

风力机叶片动力学建模研究*

程危危　曹登庆　初世明
（哈尔滨工业大学航天学院，哈尔滨　150001）

摘要　研究水平轴风力机叶片在回转平面内的横向振动. 将风力机叶片简化为以恒角速度绕定轴旋转的不可伸长的等截面欧拉伯努利梁. 采用一维动量叶素理论建立风力机叶片的空气动力学模型，并计及风力机叶片尖端损失的影响. 对无量纲化的动力学方程采用 Galerkin 方法得到由常微分方程描述的非线性动力系统. 采用由 NACA63 – B 系列风力机叶片气动数据拟合得到的气动升力与阻力系数进行分析，结果表明：将风力机叶片简化为恒角速度旋转的等截面不可伸长的欧拉贝努利悬臂梁，攻角在[– 10 ~ 30]度范围内变化时，如果计及叶尖损失的影响，则气动力法向系数和切向系数会出现为零的情况，从而导致气动力曲线出现尖点. 这一结论对于大型风力机叶片的非线性振动研究具有重要的参考价值.

关键词　风力机叶片，　气动力，　叶尖损失，　动力学建模，　非线性

引 言

风能是空气流动所产生的动能，是一种取之不尽、无任何污染的可再生能源. 风力发电是一种与传统燃料发电相竞争的无污染发电方式，是富有生命力的清洁能源. 风轮是风力机捕获风能的关键部件，组成风轮的叶片是最重要、最昂贵的核心部件，叶片不仅决定了风力机的效率而且还决定其输出功率.

叶片的受力复杂，在旋转过程中受气动力、弹性力和惯性力的作用. 随着大型风力机功率不断提高，风力机叶片的长度和柔性不断增加，叶片容易发生非线性振动. 而大幅值的振动会引起很大的动应力，加速叶片材料的疲劳，甚至引起叶片断裂. 因此，风力机叶片振动特性的研究，成为关系到风力机经济性和可靠性的重大问题，成为风力机研制十分关心的焦点.

国内外很多学者从不同方面进行了研究. Ormiston[1] 对大型低维修成本风力机叶片的气弹特性问题作了评述，并指出使用无铰链的悬臂梁构型降低了风轮转子的复杂性. 虞心田和崔尔杰[2] 给出了预示水平轴风力机的单个叶片挥舞 – 扭转耦合振动稳定边界的一种简单方法，采用了简化的弹性模型和简单的气动力表达式. Oh 等[3] 以各向异性的复合薄壁悬臂梁模型研究了具有恒定角速度的旋转预扭转叶片在横向剪切作用下的振动问题，但没有考虑气动力的影响. Larsen 和 Nielsen[4] 利用非线性 Euler – Bernoulli 梁理论建立了在动坐标系中风机旋转叶片的动力学方程，采用简单气动力表达式研究了单个叶片的稳定性. 张伟等[5] 研究了水平轴风力发电机旋转叶片的非线性动力学问题，将水平轴风力发电机的旋转叶片简化为定轴转动的柔性旋转悬臂梁，分析了风速的变化对旋转叶片振动的影响，其气动力采用了易于理论分析的模型. Shen 等[6] 分析了基于 Prandtl 叶尖损失函数的多种叶尖损失修正，提出了新的叶尖损失修正模型，通过数值和试验数据的对比验证了其有效性和精确性. 从上述研究中可以看出，想要更准确的分析风力机叶片的性能，建立与实际情况更为接近的风力机叶片模型和气动力模型很重要也很必要.

本文研究单个叶片在风轮回转平面内的振动特性，采用考虑风力机叶片尖端损失的一维动量叶素理论建立风力机叶片空气动力学模型. 将展弦比很大的风力机叶片简化为以恒角速度绕定轴旋转的不可伸长的等截面欧拉伯努利梁. 建立大型风力机叶片在回转平面内的横向运动的非线性动力学方程，为进一步研究叶片的非线性振动奠定基础.

1　考虑风力机叶片尖端损失的一维动量叶素理论

采用一维的动量叶素 (Blade element momen-

2010-12-06 收到第 1 稿，2011-07-03 收到修改稿.
* 哈尔滨市科技创新基金资助项目(2007RFLXG009)

tum, BEM)理论建立风力机空气动力学模型. 一维理论中假定的圆盘是由无限个叶片组成,而对于实际的风力机,其叶片数量总是有限的,因此在建立空气动力学模型过程中就需要考虑叶尖损失的影响[7].

根据动量理论,考虑叶尖损失,风轮的推力和转矩可表示为[8-9]:

$$\mathrm{d}q = 4\pi\rho_0^2 aF(1 - aF)r\mathrm{d}r \tag{1}$$

$$\mathrm{d}M = 4\pi\rho\omega v_0 bF(1 - aF)r^3\mathrm{d}r \tag{2}$$

式中:$F = \dfrac{2}{\pi}\arccos\left[\exp\left(-\dfrac{B(R-r)}{2r\sin\phi}\right)\right]$,且

ρ - 空气密度

v_0 - 来流风速

a - 轴向诱导因子

F - 普朗特叶尖损失修正因子

r - 叶片径向位置

ω - 风轮转动角速度

b - 周向诱导因子

ϕ - 入流角

B - 叶片个数

R - 风轮半径

根据叶素理论,考虑法向力和切向力的叶尖损失,风轮推力和转矩又可表示为[6]:

$$\mathrm{d}q = \frac{1}{2}B\rho c v_{rel}^2 F_1 C_n \mathrm{d}r \tag{3}$$

$$\mathrm{d}M = \frac{1}{2}B\rho c v_{rel}^2 F_1 C_t r\mathrm{d}r \tag{4}$$

式中:$F_1 = \dfrac{2}{\pi}\arccos\left[\exp\left(-g\dfrac{B(R-r)}{2r\sin\phi}\right)\right]$,且

$g = \exp[-0.125(B\lambda - 21)] + 0.1$

$C_n = C_1\cos\phi + C_d\sin\phi$

$C_t = C_1\sin\phi - C_d\cos\phi$

v_{rel} - 入流风速

c - 叶片弦长

λ - 叶尖速比

C_n - 法向力系数

C_t - 切向力系数

通过式(1)~(4)可以求出轴向诱导因子 a 和周向诱导因子 b,即:

$$a = \frac{2 + Y_1 - \sqrt{4Y_1(1-F) + Y_1^2}}{2(1 + FY_1)} \tag{5}$$

$$b = \frac{1}{(1 - aF)Y_2/(1 - a) - 1} \tag{6}$$

式中:

$Y_1 = 4F\sin^2\phi/(\sigma C_n F_1)$

$Y_2 = 4F\sin\phi\cos\phi/(\sigma C_t F_1)$

$\sigma = Bc/(2\pi r)$

当轴向因子 $a > 0.3$ 时,叶素理论将不再准确可靠,这时就需要对风力机的推力进行修正. 此时的轴向诱导因子 a 和周向诱导因子 b 可写成

$$a = \frac{2 + (1 - 2a_c F)Y_1}{2} - \frac{\sqrt{(1 - 2a_c F)^2 Y_1^2 + 4Y_1(1 - 2a_c F + a_c^2 F)}}{2} \tag{7}$$

$$b = \frac{1}{(1 - aF)Y_2/(1 - a) - 1} \tag{8}$$

式中:$a_c = 1/3$.

2　大型风力机叶片在回转平面内的横向运动微分方程

考虑叶片在回转平面内的横向运动,忽略横向振动对气动力的影响. 叶片在旋转过程中受气动力、弹性力和惯性力的作用,忽略叶片所受的重力,剪切力和扭矩,将风力机叶片简化为以恒角速度 ω 绕定轴旋转的不可伸长的等截面直欧拉伯努利梁. 简化后的几何模型如图 1 所示.

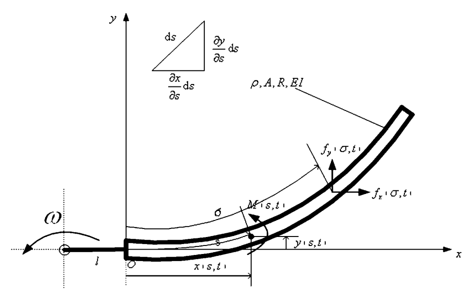

图 1　风力机叶片简化模型

Fig. 1　The Simplified model of wind turbine blade

在 t 时刻,s 点处,其弯矩方程可写为:

$$M(s,t) = EIk(s,t) \tag{9}$$

式中:

E - 杨氏模量,N/m^2

I - 对中性轴的惯性矩,m^4

k - 曲率,m^{-1}

曲率方程为:

$$k(s,t) = \sqrt{\left(\frac{\partial^2 x}{\partial s^2}\right)^2 + \left(\frac{\partial^2 y}{\partial s^2}\right)^2} \tag{10}$$

考虑到 $\left(\dfrac{\partial x}{\partial s}\right)^2 + \left(\dfrac{\partial y}{\partial s}\right)^2 = 1$ 有

$$\frac{\partial x}{\partial s}=\sqrt{1-\left(\frac{\partial y}{\partial s}\right)^2}\approx 1-\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2 \tag{11}$$

因此

$$k(s,t)=\frac{\frac{\partial^2 y}{\partial s^2}}{\sqrt{1-\left(\frac{\partial y}{\partial s}\right)^2}}\approx\frac{\partial^2 y}{\partial s^2}\left[1+\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right] \tag{12}$$

$$M(s,t)\approx\frac{\partial^2 y}{\partial s^2}\left[1+\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right]EI \tag{13}$$

在点 s 处分布力 $f_x(s,t)$,$f_y(s,t)$ 表示为气动力 f_u,牵连惯性力和科氏惯性力之和:

$$f_x(s,t)=-f_u\frac{\partial y}{\partial s}+\rho A\omega^2 l+2\rho A\omega\frac{\partial y}{\partial t}+\rho A\omega^2\int_0^s\left(1-\frac{1}{2}\left(\frac{\partial y}{\partial \sigma}\right)^2\right)\mathrm{d}\sigma \tag{14}$$

$$f_y(s,t)=f_u\left[1-\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right]+\rho A\omega^2 y+2\rho A\omega\int_0^s\frac{\partial y}{\partial \sigma}\frac{\partial^2 y}{\partial\sigma\partial t}\mathrm{d}\sigma \tag{15}$$

$$r^2=(l+x(s))^2+y^2(s),$$
$$x=\int_0^s\left(1-\frac{1}{2}\left(\frac{\partial y}{\partial \sigma}\right)^2\right)\mathrm{d}\sigma \tag{16}$$

式中:

ρ – 梁的密度,kg/m^3

A – 梁的横截面积,m^2

l – 轮毂的长度,m

r – 叶素的位置,m

如图 1 所示,弯矩 $M(s,t)$ 可表示为:

$$M(s,t)=\int_s^R\left[\left(f_y(\sigma,t)-\rho A\frac{\partial^2 y}{\partial t^2}\right)\int_s^\sigma\left(1-\frac{1}{2}\left(\frac{\partial y}{\partial \eta}\right)^2\right)\mathrm{d}\eta\right]\mathrm{d}\sigma-\int_s^R\left[\left(f_x(\sigma,t)+\rho A\int_0^\sigma\left(\frac{\partial^2 y}{\partial\xi\partial t}\right)^2\mathrm{d}\xi\right)\int_s^\sigma\frac{\partial y}{\partial\eta}\mathrm{d}\eta\right]\mathrm{d}\sigma-\int_s^R\left[\rho A\int_0^\sigma\frac{\partial y}{\partial \xi}\frac{\partial^3 y}{\partial\xi\partial t^2}\mathrm{d}\xi\int_s^\sigma\frac{\partial y}{\partial\eta}\mathrm{d}\eta\right]\mathrm{d}\sigma \tag{17}$$

式中:η,ξ,σ 是 s 的哑元,R 是梁的长度.

联立方程(13)和(17),并使用 Leibniz 法则对求二阶偏导,得到恒角速度旋转的不可伸长的欧拉–贝努利悬臂梁动力学方程为:

$$\rho A\left\{\left[1-\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right]\frac{\partial^2 y}{\partial t^2}+\frac{\partial y}{\partial s}\frac{\partial^2 y}{\partial s^2}\int_s^R\frac{\partial^2 y}{\partial t^2}\mathrm{d}\sigma+\frac{\partial y}{\partial s}\int_0^s\left[\left(\frac{\partial^2 y}{\partial\sigma\partial t}\right)^2+\frac{\partial y}{\partial\sigma}\frac{\partial^3 y}{\partial\sigma\partial t^2}\right]\mathrm{d}\sigma-\frac{\partial^2 y}{\partial s^2}\int_s^R\int_0^\sigma\left[\left(\frac{\partial^2 y}{\partial\eta\partial t}\right)^2+\frac{\partial y}{\partial\eta}\frac{\partial^3 y}{\partial\eta\partial t^2}\right]\mathrm{d}\eta\mathrm{d}\sigma\right\}+EI\left\{\left[1+\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right]\frac{\partial^4 y}{\partial s^4}+3\frac{\partial y}{\partial s}\frac{\partial^2 y}{\partial s^2}\frac{\partial^3 y}{\partial s^3}+\left(\frac{\partial^2 y}{\partial s^2}\right)^3\right\}-\frac{\partial^2 y}{\partial s^2}\int_s^R f_x(\sigma,t)\mathrm{d}\sigma-\frac{\partial y}{\partial s}\frac{\partial^2 y}{\partial s^2}\int_s^R f_y(\sigma,t)\mathrm{d}\sigma+f_x(s,t)\frac{\partial y}{\partial s}-f_y(s,t)\left[1-\frac{1}{2}\left(\frac{\partial y}{\partial s}\right)^2\right]=0 \tag{18}$$

将式(14),(15)和(16)代入方程(18)即可得到简化的风力机叶片非线性动力学方程. 对风力机叶片非线性动力学方程(18)进行无量纲化,令

$$\tilde{y}=\frac{y}{R},\ \tilde{\sigma}=\frac{\sigma}{R},\ \tilde{\eta}=\frac{\eta}{R},\ \tilde{s}=\frac{s}{R},\ \tau=\omega_* t,$$
$$\omega_*=\sqrt{\frac{EI}{\rho AR^4}},\ \tilde{\Omega}=\frac{\omega}{\omega_*},\ \tilde{v}=\frac{v_0}{R\omega_*\tilde{\Omega}},\ \tilde{l}=\frac{l}{R}$$

代入方程(18)得到:

$$\rho A\omega_*^2 R\left\{\left[1-\frac{1}{2}\left(\frac{\partial\tilde{y}}{\partial\tilde{s}}\right)^2\right]\frac{\partial^2\tilde{y}}{\partial\tau^2}+\frac{\partial\tilde{y}}{\partial\tilde{s}}\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\int_{\tilde{s}}^1\frac{\partial^2\tilde{y}}{\partial\tau^2}\mathrm{d}\tilde{\sigma}+\frac{\partial\tilde{y}}{\partial\tilde{s}}\int_0^{\tilde{s}}\left[\left(\frac{\partial^2\tilde{y}}{\partial\tilde{\sigma}\partial\tau}\right)^2+\frac{\partial\tilde{y}}{\partial\tilde{\sigma}}\frac{\partial^3\tilde{y}}{\partial\tilde{\sigma}\partial\tau^2}\right]\mathrm{d}\tilde{\sigma}+\left[1+\frac{1}{2}\left(\frac{\partial\tilde{y}}{\partial\tilde{s}}\right)^2\right]\frac{\partial^4\tilde{y}}{\partial\tilde{s}^4}+3\frac{\partial\tilde{y}}{\partial\tilde{s}}\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\frac{\partial^3\tilde{y}}{\partial\tilde{s}^3}+\left(\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\right)^3-\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\int_{\tilde{s}}^1\int_0^{\tilde{\sigma}}\left[\left(\frac{\partial^2\tilde{y}}{\partial\tilde{\eta}\partial\tau}\right)^2+\frac{\partial\tilde{y}}{\partial\tilde{\eta}}\frac{\partial^3\tilde{y}}{\partial\tilde{\eta}\partial\tau^2}\right]\mathrm{d}\tilde{\eta}\mathrm{d}\tilde{\sigma}\right\}-\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\left(\int_{\tilde{s}}^1 f_x(\tilde{\sigma},\tau)\mathrm{d}\tilde{\sigma}\right)-\frac{\partial\tilde{y}}{\partial\tilde{s}}\frac{\partial^2\tilde{y}}{\partial\tilde{s}^2}\left(\int_{\tilde{s}}^1 f_y(\tilde{\sigma},\tau)\mathrm{d}\tilde{\sigma}\right)+f_x(\tilde{s},\tau)\frac{\partial\tilde{y}}{\partial\tilde{s}}-f_y(\tilde{s},\tau)\left[1-\frac{1}{2}\left(\frac{\partial\tilde{y}}{\partial\tilde{s}}\right)^2\right]=0 \tag{19}$$

式中:

$$f_x(\tilde{s},\tau)=-\tilde{f}_u\frac{\partial\tilde{y}}{\partial\tilde{s}}+2\rho AR\omega_*^2\tilde{\Omega}\frac{\partial\tilde{y}}{\partial\tau}+\rho AR\omega_*^2\tilde{\Omega}^2\left[\tilde{l}+\int_0^{\tilde{s}}\left(1-\frac{1}{2}\left(\frac{\partial\tilde{y}}{\partial\tilde{\sigma}}\right)^2\right)\mathrm{d}\tilde{\sigma}\right] \tag{20}$$

$$f_y(\tilde{s},\tau)=\tilde{f}_u\left[1-\frac{1}{2}\left(\frac{\partial\tilde{y}}{\partial\tilde{s}}\right)^2\right]+\rho AR\omega_*^2\left\{\tilde{\Omega}^2\tilde{y}+2\tilde{\Omega}\int_0^{\tilde{s}}\frac{\partial\tilde{y}}{\partial\tilde{\sigma}}\frac{\partial^2\tilde{y}}{\partial\tilde{\sigma}\partial\tau}\mathrm{d}\tilde{\sigma}\right\} \tag{21}$$

$$\tilde{f}_u=G\left(\tilde{y},\frac{\partial\tilde{y}}{\partial\tilde{s}},\tilde{s}\right) \tag{22}$$

与方程(19)相关的边界条件为:

$$\tilde{y}(0,\tau)=\frac{\partial\tilde{y}(0,\tau)}{\partial\tilde{s}}=\frac{\partial^2\tilde{y}(1,\tau)}{\partial\tilde{s}^2}=\frac{\partial^3\tilde{y}(1,\tau)}{\partial\tilde{s}^3}=0 \tag{23}$$

对考虑叶尖损失的周向气动力解析表达式进行无量钢化,则周向气动力的解析表达式:

$$\tilde{f}_u = 4\pi\rho_{air}R^3\tilde{\Omega}^2\omega_*^2\tilde{v}bF(1-aF)\tilde{r}^2 \tag{24}$$

式中:

$$a = \frac{2+Y_1-\sqrt{4Y_1(1-F)+Y_1^2}}{2(1+FY_1)}$$

$$b = \frac{1}{(1-aF)Y_2/(1-a)-1}$$

$$F = \frac{2}{\pi}\arccos\left[\exp\left(-\frac{3(1-\tilde{r})}{2\tilde{r}\sin(\mathrm{arccot}(\tilde{r}/\tilde{v}))}\right)\right]$$

$$F_1 = \frac{2}{\pi}\arccos\{\exp(-\frac{3(1-\tilde{r})}{2\tilde{r}\sin(\mathrm{arccot}(\tilde{r}/\tilde{v}))}\times[\exp(-0.125(3\tilde{r}/\tilde{v}-21))+0.1])\}$$

$$Y_1 = \frac{16\tilde{r}\sin^2(\mathrm{arccot}(\tilde{r}/\tilde{v}))}{3\tilde{c}F_1(C_l\cos(\mathrm{arccot}(\tilde{r}/\tilde{v}))+C_d\sin(\mathrm{arccot}(\tilde{r}/\tilde{v})))}\arccos\left[\exp\left(-\frac{3(1-\tilde{r})}{2\tilde{r}\sin(\mathrm{arccot}(\tilde{r}/\tilde{v}))}\right)\right]$$

$$Y_2 = \frac{16\tilde{r}\sin^2(\mathrm{arccot}(\tilde{r}/\tilde{v}))\cos^2(\mathrm{arccot}(\tilde{r}/\tilde{v}))}{3\tilde{c}F_1(C_l\sin(\mathrm{arccot}(\tilde{r}/\tilde{v}))-C_d\cos(\mathrm{arccot}(\tilde{r}/\tilde{v})))}\arccos\left[\exp\left(-\frac{3(1-\tilde{r})}{2\tilde{r}\sin(\mathrm{arccot}(\tilde{r}/\tilde{v}))}\right)\right]$$

$$\tilde{r} = \sqrt{(\tilde{l}+\tilde{s})^2-(\tilde{l}+\tilde{s})\int_0^{\tilde{s}}\left(\frac{\partial\tilde{y}}{\partial\tilde{\sigma}}\right)^2\mathrm{d}\tilde{\sigma}+\frac{1}{4}\left(\int_0^{\tilde{s}}\left(\frac{\partial\tilde{y}}{\partial\tilde{\sigma}}\right)^2\mathrm{d}\tilde{\sigma}\right)^2+\tilde{y}^2}$$

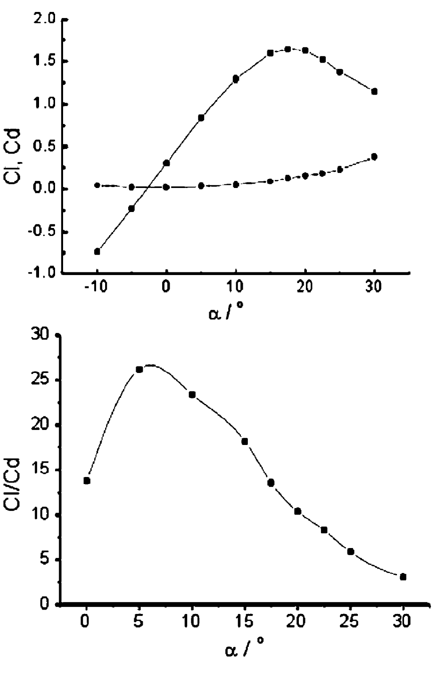

图 2　NACA63-B 系列翼型升力阻力系数和升阻比随攻角变化曲线

Fig. 2　Lift and drag coefficients and lift/drag ratio of NACA63 – B series airfoil with the angle of attack

选取 NACA63 – B 系列翼型为风力机叶片翼型,其相应的升力系数、阻力系数和升阻比可由实验数据[10]拟合得到. 如图 2 所示,将升、阻力系数拟合为攻角的多项式函数(式中攻角为无量纲量):

$$C_l(i) = -11.0007i^3 - 3.4233i^2 + 6.1993i + 0.3492 \tag{25}$$

$$C_d(i) = 1.5348i^3 + 0.4613i^2 - 0.0166i + 0.0317 \tag{26}$$

3　分析气动力尖点

根据工程数据统计[11]:攻角的变化范围为 –10 ~ 30 度,风轮转速的范围为 20 ~ 50 转/分钟,风速的范围为 4 ~ 25 米/秒,安装角的范围为 0 ~ 20 度. 在参数变化范围内,选取合适的参数进行计算.

气动力在某些位置处有尖点,如图 3 所示. 进一步研究发现,攻角在 –10 ~ 30 度范围内变化时,若将风力机叶片简化为考虑叶尖损失的恒角速度旋转的等截面不可伸长欧拉贝努利悬臂梁,则气动力法向系数和切向系数会出现为零的情况,从而导致尖点的产生.

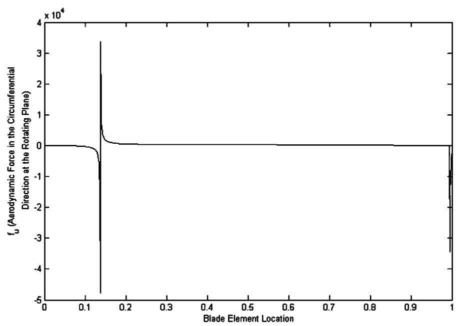

图 3　无量纲气动力随叶素位置关系

Fig. 3　Relationship between blade element location and dimensionless aerodynamic force

由等截面的不可伸长的欧拉贝努利悬臂梁假设,叶片截面弦长为常数,沿叶片径向安装角为常数,根据叶素理论,忽略周向和轴向诱导速度有

$$i = \mathrm{arccot}((r+l)*\omega/v) - \beta \tag{27}$$

其中 i, r, l, w, v, β 分别为攻角,叶素位置,轮毂长度,风轮转速,风速和安装角.

攻角的变化范围(–10 ~ 30 度),由式(27)可得图 4 和图 5,由图 4 知安装角越大,叶片长度越短,由图 5 知满足攻角变化范围的组成叶片的叶素距离轮毂不足 6 米. 因此,将大型风力机叶片简化

为等截面的不可伸长的欧拉贝努利悬臂梁是不适当的.

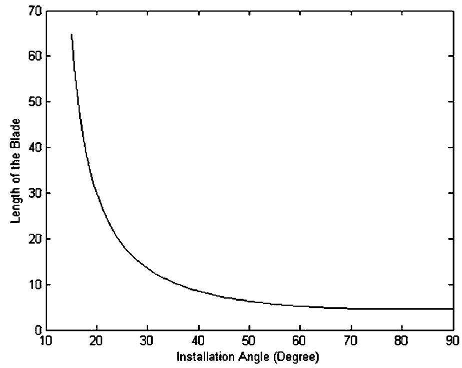

图 4 叶片长度与安装角的关系

Fig. 4 The relationship between length of the blade and installation angle

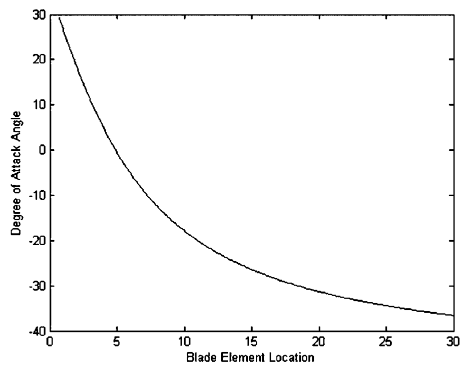

图 5 攻角区间内叶素位置区间

Fig. 5 Range of blade element location with the angle of attack

4 结论

以考虑风力机叶片尖端损失的一维动量叶素理论建立风力机叶片空气动力学模型,将展弦比很大的风力机叶片简化为以恒角速度绕定轴旋转的不可伸长的等截面的直欧拉伯努利梁,建立了风力机叶片在风轮回转平面内的非线性动力学方程. 在叶片长度不超过 5 米的条件下,这个方法是可行的,但是与现有叶片超过 60 米长叶片的风力机超大型化的发展趋势不符合. 在叶片长度超过 6 米的条件下,会出现气动力曲线的尖点,此时将风力机叶片简化为以恒角速度绕定轴旋转的不可伸长的等截面的直欧拉伯努利梁是不合适的,应该考虑将大型风力机叶片简化为截面弦长为常值的预扭转悬臂梁. 基于此,我们建议在研究大型风力发电机叶片的振动特性时,可采取以下方式:

(1) 针对预扭叶片建立用偏微分方程描述的非线性动力学方程,采用叶素理论建立气动力模型,选取适当的模态进行动力学分析;

(2) 利用有限元建模软件建立结构动力学模型,仍采用叶素理论建立气动力模型,采用模态分析方法得到仅有少数几个自由度的非线性动力学方程,再用定性的分析方法求解.

参 考 文 献

1 Ormiston R A. Rotor dynamic considerations for large wind power generator systems. Wind Energy Conversion Systems, Workshop Proceedings, Washington, D. C. , 1973 (11-13):80 ~ 88

2 虞心田,崔尔杰. 分析水平轴风力机叶片气弹稳定性的简单方法. 太阳能学报, 1990, 11 (1): 52 ~ 59 (Yu X T, Cui R J. Simplified method for predicting the stability boundaries of a horizontal-axis wind turbine blade. *Acta Energiae Solaris Sinica*, 1990, 11 (1): 52 ~ 59 (in Chinese))

3 Oh S Y, Lihrescu L. Effects of pretwist and presetting on coupled bending vibrations of rotating thin-walled composite beams. *International Journal of Solids and Structures*, 2003,40: 1203 ~ 1224

4 Larsen J W, Nielsen S R K. Nonlinear dynamics of wind turbine wings. *International Journal of Non-Linear Mechanics*, 2006, 41:629 ~ 634

5 张伟,冯景,姚明辉等. 水平轴风机旋转叶片非线性动力学模型的建立及分析. 科技导报, 2010, 28 (5): 40 ~ 44 (Zhang W, Feng J, Yao M H, et al. Model establishment and nonlinear dynamic analysis of the rotating horizontal axis wind turbine blade. *Science and Technology Review*, 2010, 28 (5): 40 ~ 44 (in Chinese))

6 Shen W Z, Mikkelsen R, Sφrensen J N, et al. Tip loss correction for wind turbines computations. *Wind Energy*, 2005, 8: 457 ~ 475

7 陈进,王旭东,沈文忠等. 风力机叶片的形状优化设计. 机械工程学报, 2010, 46(3):131 ~ 134 (Chen J, Wang X D, Shen W Z, et al. Optimization design of blade shapes for wind turbines. *Journal of Mechanical Engineering*, 2010, 46(3):131 ~ 134 (in Chinese))

8 贺德馨. 风工程与工业空气动力学. 北京: 国防工业出版社, 2006 (He D X. Wind engineering and industrial aerodynamics. Beijing: National Defence Industrial Press, 2006 (in Chinese))

9 Glauert H. Airplane propellers. Berlin: Springer Verlag, 1935

10 唐进. 提高风力机叶型气动性能的研究, 工学硕士论文. 清华大学, 2004: 5 ~ 59 (Tang J. Research of improving aerodynamic performance of wind turbines blade profile. Thesis for MEng, Tsinghua University, 2004: 5 ~ 59 (in Chinese))

11 肖劲松(译). 风力机空气动力学(第二版). 北京:中国电力出版社, 2009 (Xiao J S (Translation). Aerodynamics of wind turbines (Second Edition). Beijing: China Electric Power Press, 2009 (in Chinese))

DYNAMICS MODELING FOR THE BLADE OF A WIND TURBINE *

Cheng Weiwei Cao Dengqing Chu Shiming

(*School of Astronautics*, *Harbin Institute of Technology*, *PO Box*137, *Harbin* 150001, *China*)

Abstract The vibration of a blade of the large horizontal axis wind turbine in the rotating plane was investigated. The blade was simplified as an Euler – Bernoulli beam, which rotates constantly around fixed axis and has constant section, while the length of the blade is much larger than the chordal length of the section. The aerodynamics force model was established by the blade element momentum theory with a tip loss correction. The experimental aerodynamics data reported for the aerofoil of NACA63 – B series were fitted first to express the coefficients as the function of the attack angle. A further analysis indicates that if the blade is simplified as an Euler – Bernoulli beam, which rotates constantly around fixed axis and the attack angle is restricted in the region from – 10 to 30 degree, the aerodynamics force coefficient may be approximate to zero in the vertical or tangential direction for the blade with tip loss correction. This leads to peaked points on the aerodynamics force curve, which is reasonless in the sense of physics. Such a conclusion may be useful in the design and nonlinear vibration analysis of blades of a large wind turbine.

Key words wind turbine blade, aerodynamics, tip loss correction, dynamics modeling, nonlinear vibration

Received 6 December 2010, revised 3 July 2011.

* The project was supported by Harbin Science and Technology Innovation Fund (2007RFLXG009)