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碳纤维缆索悬索桥竖向非线性自由振动研究*

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摘要　在把碳纤维缆索悬索桥与钢缆索悬索桥比较的基础上,研究了悬索桥的竖向非线性自振问题,利用Galerkin原理及L-P法求出了悬索桥竖向非线性自振的近似解,讨论分析了温度、振幅等因素对悬索桥竖向非线性自振的影响.得到了温度升高使悬索桥非线性自振频率降低,且对钢缆索悬索桥振动时程曲线影响较大,而温度变化对碳纤维缆索悬索桥振动时程曲线几乎无影响,振幅增大将使悬索桥非线性自振频率增大的结论.

关键词　碳纤维,　缆索,　悬索桥,　非线性,　振动

引言

随着科学技术的发展,工程材料的更新,结构计算理论、设计方法及施工技术的进步,抗风抗震研究的深入,悬索桥跨径不断增大,悬索桥正朝着更大跨径、更大承载力、更高动力稳定性和更好耐久性等方面发展.钢缆索悬索桥的一个致命弱点是耐腐蚀性差,因此在悬索桥主缆架设时需要经过繁锁的防腐涂装工序,成桥营运后还需要进行贯穿始终的日常维护,如日本明石峡大桥主缆采用除湿机对主缆进行维护,保持较低的湿度来防止主缆锈蚀[1];同时主缆因腐蚀严重而进行更换极其困难,必须拆除加劲梁等上部结构,施工难度较大[2].新兴的碳纤维复合材料因具有轻质高强、耐腐蚀等诸多优于钢材的性能,斜拉桥的拉索现已开始采用碳纤维复合材料拉索替代钢缆拉索[3,4].由于碳纤维复合材料可望从根本解决传统钢缆索悬索桥发展中遇到的一些问题,因此可以预见碳纤维复合材料缆索将会取代悬索桥的钢缆索[5].文献[6-12]研究了钢缆索悬索桥的振动问题,但是文献[6-7]在研究悬索桥竖向自振时忽略了非线性项对自振的影响;文献[13-15]研究了碳纤维缆索悬索桥的抗风性能.由于悬索桥固有振动特性的研究是悬索桥抗风、抗震及车辆活载所致振动效应的研究基础[16-17],因此本文在把碳纤维缆索悬索桥与钢缆索悬索桥比较的基础上,研究了悬索桥的竖向非线性自振问题.

1　悬索桥非线性自振近似解

文献[6-7]研究了钢缆悬索桥的竖向自振.但文献[6-7]都把钢缆索悬索桥的竖向非线性自振问题按竖向线性振动来研究.本文以图1所示悬索桥为例研究其竖向非线性自由振动,现作如下基本假定[6]:(1)在恒载作用下加劲梁呈水平;(4)在恒载作用下主索呈抛物线型曲线;(3)吊杆为刚性;(4)吊杆的间隔与桥梁跨度相比是微小的,因此吊杆力可视为连续分布的.

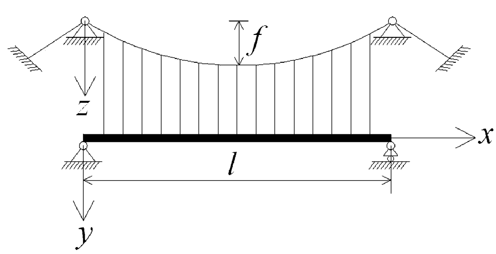

图1　悬索桥坐标图

Fig.1　The suspension bridge coordinates

参阅文献[1]可知图1所示悬索桥在均匀温度场中的振动控制方程为

$$EI\frac{\partial^4 y}{\partial x^4}-(H_p+H_q)\frac{\partial^4 y}{\partial x^4}+\frac{qH_p}{H_q}+m\frac{\partial^2 y}{\partial t^2}=0 \quad (1)$$

$$H_p=\frac{qE_1A}{H_0l}\int_0^l y\mathrm{d}x-\frac{E_1A}{2l}\int_0^l\frac{\partial^2 y}{\partial x^2}y\mathrm{d}x-E_1A\alpha_s\Delta t \quad (2)$$

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式中，$H_q=\frac{ql}{8f}$，q 为恒载，f 为缆索垂度，E、E_1 为加劲梁、缆索的弹性模量，I 为加劲梁的惯性矩，A 为缆索的横截面积，m 为加劲梁单位长度的质量，H_p、H_q 分别为由活载、恒载引起的缆索张力水平分量，$y(x,t)$ 为加劲梁的横振位移，α_s 为悬索的热膨胀系数，Δt 为温度增量.

设加劲梁的横振位移为

$$y(x,t)=Y(x)T(t) \tag{3}$$

把式(2)、式(3)代入式(1)中，利用伽辽金原理可以得到

$$\frac{d^2T}{dt^2}+\omega_0^2T+\varepsilon\alpha T^2+\varepsilon^2\beta T^3=F \tag{4}$$

式中，

$$\omega_0^2=[EI\int_0^l\frac{d^4Y}{dx^4}Y\mathrm{d}x+\frac{q^2E_1A}{H_q^2l}(\int_0^lY\mathrm{d}x)^2-H_q\int_0^l\frac{d^2Y}{dx^2}Y\mathrm{d}x+\alpha_sE_1A\Delta t\int_0^l\frac{d^2Y}{dx^2}Y\mathrm{d}x]/m\int_0^lY^2\mathrm{d}x$$

$$\varepsilon\alpha=-\frac{3qE_1A}{2H_ql}\int_0^lY\frac{d^2Y}{dx^2}\mathrm{d}x\int_0^lY\mathrm{d}x/m\int_0^lY^2\mathrm{d}x$$

$$\varepsilon^2\beta=\frac{E_1A}{2l}(\int_0^l\frac{d^2Y}{dx^2}Y\mathrm{d}x)^2\int_0^l/m\int_0^lY^2\mathrm{d}x$$

$$F=\frac{q\alpha_sE_1A\Delta t}{H_q}\int_0^lY\mathrm{d}x/m\int_0^lY^2\mathrm{d}x$$

设式(4)的初始条件为

$$t=o,T(0)=a=a'+A,\frac{dT(0)}{dt}=0 \tag{5}$$

令 $\tau=\omega t$，可把式(4)化为

$$\omega\frac{d^2T}{d\tau}+\omega_0^2T+\varepsilon\alpha T^2+\varepsilon^2\beta T^3=F \tag{6}$$

令

$$\begin{cases}\omega=\omega_0+\varepsilon\omega_1+\varepsilon^2\omega_2+\cdots\\T=T_0+\varepsilon T_1+\varepsilon^2T_2+\cdots\end{cases} \tag{7}$$

把式(7)代入式(6)中可得

$$\frac{d^2T_0}{d\tau^2}+T_0=\frac{F}{\omega_0^2} \tag{8a}$$

$$\frac{d^2T_1}{d\tau^2}+T_1=-\frac{2\omega_1}{\omega_0}\frac{d^2T_0}{d\tau^2}-\frac{\alpha}{\omega_0^2}T_0^2 \tag{8b}$$

$$\frac{d^2T_2}{d\tau^2}+T_2=-\frac{2\omega_1}{\omega_0}\frac{d^2T_1}{d\tau^2}-\frac{1}{\omega_0^2}(2\omega_0\omega_2+\omega_1^2)\frac{d^2T_0}{d\tau^2}-\frac{2\alpha}{\omega_0^2}T_0T_1-\frac{\beta}{\omega_0^2}T_0^3 \tag{8c}$$

由式(8a)可以求得

$$T_0(\tau)=a'\cos\tau+\frac{F}{\omega_0^2} \tag{9}$$

由式(5)、式(9)可以求得

$$A=\frac{F}{\omega_0^2},a'=a-\frac{F}{\omega_0^2} \tag{10}$$

把式(6)的各阶摄动项表示为待定的傅立叶级数

$$T(\tau)=T_0(\tau)+\varepsilon T_1(\tau)+\varepsilon^2T_2(\tau)+\cdots=(a'\cos\tau+A)+\sum_{j=1}^{\infty}\varepsilon^j(c_j+b_j\cos\tau+\sum_{j=2}^{\infty}a_{ij}\cos i\tau) \tag{11}$$

为了使式(11)满足式(5)，需补充约束条件

$$c_j+b_j+\sum_{j=1}^{\infty}a_{ij}=0 \tag{12}$$

把 $T_0(\tau)$，$T_1(\tau)$ 的级数表达式代入式(8)有关分式中，利用式(12)且参阅文献[16]即可求得悬索桥竖向非线性自振的系统频率和时间响应函数分别为

$$\omega=\omega_0+\frac{\varepsilon\alpha F}{\omega_0^3}+\frac{3\varepsilon^2\beta(a\omega_0^2-F)^2}{8\omega_0^5}+\frac{3\varepsilon^2\beta F^2}{2\omega_0^5}-\frac{3\varepsilon^2\alpha F^2}{2\omega_0^7}-\frac{5\varepsilon^2\alpha^2(a\omega_0^2-F)^2}{12\omega_0^7} \tag{13}$$

$$\begin{aligned}y(x,t)=\{&(a-\frac{F}{\omega_0^2})\cos\omega t+\frac{F}{\omega_0^2}-\frac{\varepsilon\alpha}{\omega_0^2}[\frac{1}{2}(a-\frac{F}{\omega_0^2})^2+\frac{F^2}{\omega_0^4}]+\frac{\varepsilon\alpha}{\omega_0^2}[\frac{1}{3}(a-\frac{F}{\omega_0^2})^2+\frac{F^2}{\omega_0^4}]\cos\omega t+\\&\frac{\varepsilon\alpha}{\omega_0^2}(a-\frac{F}{\omega_0^2})^2\cos2\omega t+\frac{\varepsilon^2\alpha^2F}{\omega_0^6}(a-\frac{F}{\omega_0^2})^2+\\&\frac{2\varepsilon^2\alpha^2F^3}{\omega_0^{10}}-\frac{3\varepsilon^2\beta F}{2\omega_0^4}(a-\frac{F}{\omega_0^2})-\frac{\varepsilon^2\beta F^3}{\omega_0^8}-\\&\frac{\varepsilon^2\alpha^2}{3\omega_0^4}(a-\frac{F}{\omega_0^2})^3-\frac{\varepsilon^2\alpha^2F^2}{\omega_0^8}(a-\frac{F}{\omega_0^2})+\\&[\frac{\varepsilon^2\beta F}{\omega_0^4}(a-\frac{F}{\omega_0^2})^2+\frac{\varepsilon^2\beta F^3}{\omega_0^8}+\frac{2\varepsilon^2\alpha^2F^2}{3\omega_0^8}(a-\frac{F}{\omega_0^2})+\frac{29\varepsilon^2\alpha^2}{144\omega_0^4}(a-\frac{F}{\omega_0^2})^3-\frac{2\varepsilon^2\alpha^2F^2}{3\omega_0^6}(a-\frac{F}{\omega_0^2})^2-\frac{2\varepsilon^2\alpha^2F^3}{3\omega_0^{10}}-\frac{\varepsilon^2\beta}{32\omega_0^2}(a-\frac{F}{\omega_0^2})^3]\cos\omega t+\\&[\frac{\varepsilon^2\beta F}{2\omega_0^4}(a-\frac{F}{\omega_0^2})^2+\frac{\varepsilon^2\alpha^2}{9\omega_0^4}(a-\frac{F}{\omega_0^2})^3+\frac{\varepsilon^2\alpha^2F^2}{3\omega_0^8}(a-\frac{F}{\omega_0^2})-\frac{\varepsilon^2\alpha^2F}{3\omega_0^6}(a-\frac{F}{\omega_0^2})^2]\cos2\omega t+\\&[\frac{\varepsilon^2\beta}{32\omega_0^2}(a-\frac{F}{\omega_0^2})^3+\frac{\varepsilon^2\alpha^2}{48\omega_0^4}(a-\end{aligned}$$

$$\frac{F}{\omega_0^2})^3]\cos3\omega t\}\sin\frac{\pi x}{l} \tag{14}$$

当悬索桥竖向非线性自振的振型函数确定后,把式(13)、式(14)代入式(3)中即可得到悬索桥竖向非线性自振的横振位移表达式.

2　算例分析

为了讨论分析碳纤维缆索悬索桥竖向非线性自振的特性,以便把碳纤维缆索悬索桥与钢缆索悬索桥进行比较研究,本文在某国外钢缆索悬索桥基础上,按照等轴向刚度、等强度等准则构造了三座碳纤维缆索悬索桥. 悬索桥的构造参数见表 1,悬索桥跨度 $l=452m$,缆索垂度 $f=46m$,仅以碳纤维缆索替换钢缆索,悬索桥其他结构皆不变. 表 1 中 1#缆索为钢缆索,2#缆索为与 1#缆索等截面的碳纤维缆索,3#缆索为按照等轴向刚度准则构造的碳纤维缆索,4#缆索为按照等强度准则构造的碳纤维缆索.

表 1　构件的材料和截面特性

Table 1　Materials and sectional characteristics of components

components	E/Nm^{-2}	A/m^2	I/m^4	m/kgm^{-1}	q/kgm^{-1}	α/℃$^{-1}$
stiffening girder	3.65×10^{10}		5.3557	33670		
cable(NO.1)	2×10^{11}	0.1946			37760	2.32×10^{-5}
cable(NO.2)	1.47×10^{11}	0.1946			37760	0.68×10^{-6}
cable(NO.3)	1.47×10^{11}	0.2648			37760	0.68×10^{-6}
cable(NO.4)	1.47×10^{11}	0.098			37760	0.68×10^{-6}

分别设悬索桥竖向非线性自振的振型函数为(对称振动)和(反对称振动),利用以上有关各式和有关参数可以得到悬索桥竖向非线性自振的系统频率和时程曲线,如表 2—表 4 和图 2—图 7 所示.

表 2　悬索桥竖向对称振动线性系统频率(单位:Hz)

Table 2　The linear natural frequency of suspension bridge with vertical symmetric vibration(unit: Hz)

vibrationmode	materials	ΔT/℃								
		0	5	10	15	20	25	30	35	40
symmetric	cable(NO.1)	0.5828	0.5772	0.5716	0.5659	0.5601	0.5543	0.5485	0.5425	0.5365
	cable(NO.2)	0.5755	0.5754	0.5753	0.5752	0.5750	0.5749	0.5748	0.5747	0.5746
	cable(NO.3)	0.5828	0.5826	0.5825	0.5823	0.5821	0.5820	0.5818	0.5816	0.5815
	cable(NO.4)	0.5654	0.5653	0.5653	0.5652	0.5651	0.5651	0.5650	0.5650	0.5649
antisymmetric	cable(NO.1)	0.7147	0.6963	0.6775	0.6581	0.6381	0.6175	0.5962	0.5741	0.5511
	cable(NO.2)	0.7147	0.7143	0.7139	0.7135	0.7131	0.7127	0.7123	0.7119	0.7115
	cable(NO.3)	0.7147	0.7141	0.7136	0.7131	0.7126	0.7120	0.7115	0.7110	0.7104
	cable(NO.4)	0.7147	0.7145	0.7143	0.7141	0.7139	0.7137	0.7135	0.7133	0.7131

表 3　悬索桥竖向对称振动非线性系统频率(单位:Hz)

Table 3　The nonlinear natural frequency of suspension bridge with vertical symmetric vibration(unit: Hz)

materials	a/m	ΔT/℃								
		0	5	10	15	20	25	30	35	40
cable(NO.1)	0.01	0.582779	0.578811	0.574907	0.571076	0.567326	0.563666	0.560108	0.556664	0.553345
	0.02	0.582779	0.578811	0.574906	0.571074	0.567324	0.563664	0.560106	0.556660	0.553341
	0.03	0.582779	0.578810	0.574906	0.571073	0.567322	0.563662	0.560103	0.556657	0.553337
	0.04	0.582780	0.578810	0.574905	0.571072	0.567321	0.563660	0.560100	0.556654	0.553334
cable(NO.2)	0.01	0.575528	0.575433	0.575337	0.575242	0.575146	0.575051	0.574955	0.574860	0.574764
	0.02	0.575528	0.575433	0.575337	0.575242	0.575146	0.575051	0.574955	0.574860	0.574764
	0.03	0.575528	0.575433	0.575337	0.575242	0.575146	0.575051	0.574955	0.574860	0.574764
	0.04	0.575528	0.575433	0.575337	0.575242	0.575146	0.575051	0.574955	0.574860	0.574764
cable(NO.3)	0.01	0.582783	0.582666	0.582549	0.582432	0.582315	0.582198	0.582081	0.581964	0.581847
	0.02	0.582783	0.582666	0.582549	0.582432	0.582315	0.582198	0.582081	0.581964	0.581847
	0.03	0.582783	0.582666	0.582549	0.582432	0.582315	0.582198	0.582081	0.581964	0.581847
	0.04	0.582784	0.582666	0.582549	0.582432	0.582315	0.582198	0.582081	0.581964	0.581847
cable(NO.4)	0.01	0.565393	0.565337	0.565282	0.565227	0.565172	0.565116	0.565061	0.565006	0.564951
	0.02	0.565393	0.565337	0.565282	0.565227	0.565172	0.565116	0.565061	0.565006	0.564951
	0.03	0.565393	0.565337	0.565282	0.565227	0.565172	0.565116	0.565061	0.565006	0.564951
	0.04	0.565393	0.565338	0.565282	0.565227	0.565172	0.565117	0.565061	0.565006	0.564951

表 4 悬索桥竖向反对称振动非线性系统频率(单位:Hz)

Table 4 The nonlinear natural frequency of suspension bridge with vertical antisymmetric vibration(unit: Hz)

materials	a/m	ΔT/℃								
		0	5	10	15	20	25	30	35	40
cable(NO.1)	0.01	0.714677	0.696333	0.677492	0.658112	0.638144	0.617530	0.596205	0.574087	0.551083
	0.02	0.714679	0.696335	0.677494	0.658114	0.638146	0.617532	0.596207	0.574089	0.551085
	0.03	0.714682	0.696338	0.677497	0.658117	0.638149	0.617536	0.596210	0.574093	0.551088
	0.04	0.714686	0.696342	0.677501	0.658121	0.638153	0.617540	0.596215	0.574098	0.551094
cable(NO.2)	0.01	0.714677	0.714287	0.713896	0.713506	0.713115	0.712724	0.712332	0.711941	0.711549
	0.02	0.714678	0.714288	0.713898	0.713507	0.713116	0.712725	0.712334	0.711942	0.711550
	0.03	0.714680	0.714290	0.713900	0.713509	0.713118	0.712727	0.712336	0.711944	0.711553
	0.04	0.714683	0.714293	0.713903	0.713512	0.713121	0.712730	0.712339	0.711947	0.711555
cable(NO.3)	0.01	0.714677	0.714146	0.713615	0.713083	0.712551	0.712018	0.711485	0.710951	0.710418
	0.02	0.714679	0.714148	0.713616	0.713085	0.712552	0.712020	0.711487	0.710953	0.710419
	0.03	0.714682	0.714151	0.713619	0.713087	0.712555	0.712022	0.711489	0.710956	0.710422
	0.04	0.714686	0.714155	0.713623	0.713091	0.712559	0.712026	0.711493	0.710960	0.710426
cable(NO.4)	0.01	0.714677	0.714480	0.714284	0.714087	0.713891	0.713694	0.713497	0.713300	0.713103
	0.02	0.714677	0.714481	0.714284	0.714088	0.713891	0.713694	0.713498	0.713301	0.713104
	0.03	0.714678	0.714482	0.714285	0.714089	0.713892	0.713695	0.713499	0.713302	0.713105
	0.04	0.714680	0.714483	0.714287	0.714090	0.713894	0.713697	0.713500	0.713303	0.713107

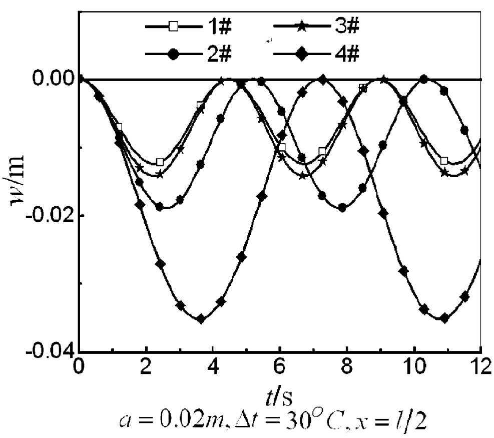

图 2 悬索桥竖向对称振动时程曲线

Fig. 2 The time – history curve of suspension bridge with vertical symmetric vibration

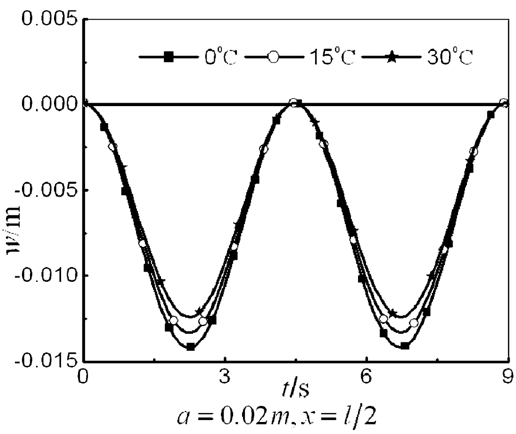

图 4 悬索桥(1#缆索)竖向对称振动时程曲线

Fig. 4 The time – history curve of suspension bridge with vertical symmetric vibration(1#)

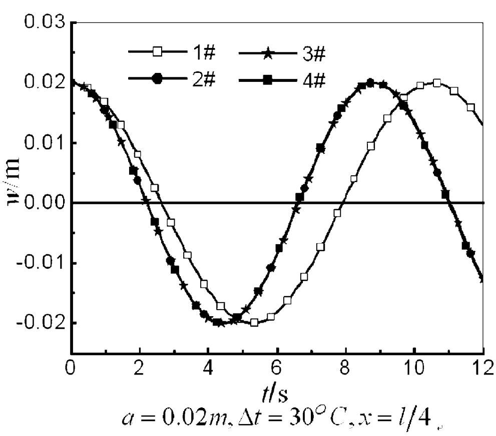

图 3 悬索桥竖向反对称振动时程曲线

Fig. 3 The time – history curve of suspension bridge with vertical antisymmetric vibration

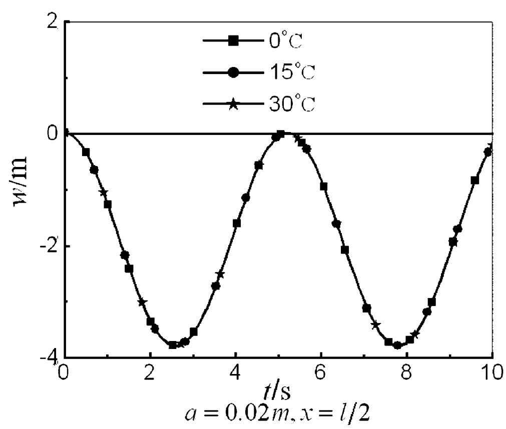

图 5 悬索桥(2#缆索)竖向对称振动时程曲线

Fig. 5 The time – history curve of suspension bridge with vertical symmetric vibration(2#)

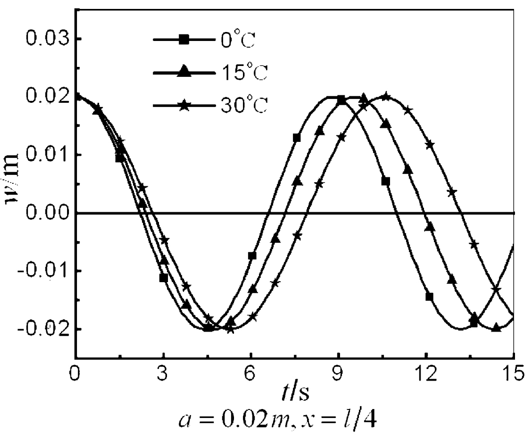

图 6　悬索桥(1#缆索)竖向反对称振动时程曲线

Fig. 6　The time – history curve of suspension bridge with vertical antisymmetric vibration(1#)

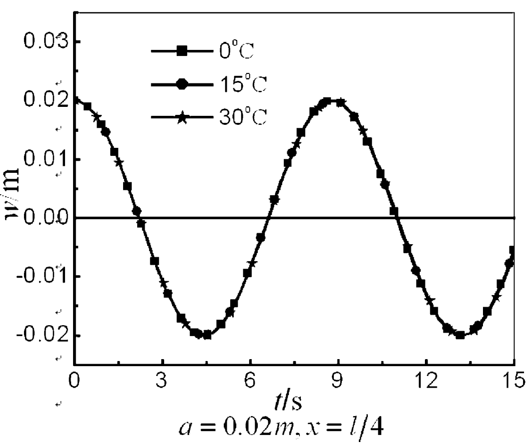

图 7　悬索桥(2#缆索)竖向反对称振动时程曲线

Fig. 7　The time – history curve of suspension bridge with vertical antisymmetric vibration(2#)

对表 2—表 4、图 2—图 7 进行分析可知:

1)、按线性振动理论计算的悬索桥系统频率大于按非线性振动理论计算的悬索桥系统频率,悬索桥对称振动系统频率小于悬索桥反对称振动系统频率. 按照等轴向刚度准则构造的碳纤维缆索悬索桥的系统频率大于按照等强度准则构造的碳纤维缆索悬索桥的系统频率、大于碳纤维缆索与钢缆索等截面的悬索桥的系统频率. 当振幅一定时,随着温度的增加,碳纤维材料悬索桥或钢缆索悬索桥的非线性自振频率将变小;当温度一定时,随着振幅的增大,碳纤维缆索悬索桥或钢缆索悬索桥的非线性自振频率将增大. 这说明悬索桥非线性振动呈“硬弹簧”特性. 与一般结构不同,由于悬索桥在振动过程中索力不断变化导致其刚度变化,实际上它属于非线性硬化刚度体系.

2)、在温度变化增量为零的情况下,钢缆悬索索桥的系统频率大于按照等强度准则构造的碳纤维缆索悬索桥的系统频率、大于碳纤维缆索与钢缆索等截面的悬索桥的系统频率,小于按照等轴向刚度准则构造的碳纤维缆索悬索桥的系统频率;当温度变化增量达到 25 度时,钢缆悬索索桥的系统频率均小于按照等强度准则构造的碳纤维缆索悬索桥、碳纤维缆索与钢缆索等截面的悬索桥、按照等轴向刚度准则构造的碳纤维缆索悬索桥的系统频率.

3)、在温度一定的情况下:钢缆索悬索桥竖向对称振动时程曲线的振幅小于按照等强度准则构造的碳纤维缆索悬索桥竖向对称振动时程曲线的振幅、小于碳纤维缆索与钢缆索等截面的悬索桥竖向对称振动时程曲线的振幅,小于按照等轴向刚度准则构造的碳纤维缆索悬索桥竖向对称振动时程曲线的振幅;钢缆索悬索桥竖向反对称振动时程曲线的振幅则与按照等强度准则构造的碳纤维缆索悬索桥竖向反对称振动时程曲线的振幅、碳纤维缆索与钢缆索等截面的悬索桥竖向反对称振动时程曲线的振幅、按照等轴向刚度准则构造的碳纤维缆索悬索桥竖向反对称振动时程曲线的振幅相同.

4)、温度变化对钢缆索悬索桥振动时程曲线影响较大,且随着温度升高对称振动时程曲线的振幅将变小,钢缆索悬索桥反对称振动时程曲线的虽振幅无变化,但温度升高却使反对称振动时程曲线运动滞后;而温度变化对碳纤维缆索悬索桥振动时程曲线几乎无影响,碳纤维缆索悬索桥振动时程曲线基本上重合;这些都说明钢缆索悬索桥的非线性振动对温度的变化较为敏感.

3　结论

悬索桥非线性振动呈“硬弹簧”特性. 与一般结构不同,由于悬索桥在振动过程中索力不断变化导致其刚度变化,故实际上它属于非线性硬化刚度体系.

温度变化对钢缆索悬索桥振动时程曲线影响较大,而温度变化对碳纤维缆索悬索桥振动时程曲线几乎无影响,碳纤维缆索悬索桥振动时程曲线基本上重合;这些都说明钢缆索悬索桥的非线性振动对温度的变化较为敏感.

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VERTICAL NONLINEAR FREE VIBRATION OF SUSPENSION BRIDGES USING CARBON FIBER CABLES *

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Abstract On the basis of comparing the suspension bridges using carbon fiber cables with those bridges using steel cables, the vertical nonlinear vibration feature of suspension bridges was studied, the approximate solutions of suspension bridges' vertical nonlinear vibration were obtained with Galerkin principle and L-P method, and the impact of temperature, amplitude and other factors on the vertical nonlinear vibration of suspension bridges was analyzed. The temperature increment will make the nonlinear vibration frequency of suspension bridges fall, and have larger impact on the time-histories curve of suspension bridges using steel cables. On the contrary, temperature change nearly hasn't any impact on the time-histories curve of suspension bridges using carbon fiber cables, and amplitude increment will make the nonlinear vibration frequency of suspension bridges increase.

Key words carbon fiber, cable, suspension bridge, nonlinear, vibration

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