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电子散斑干涉法在振动测量中的物光位相调制法

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【摘要】　介绍的物光正弦调制法是给振动物体的基座以低频振动，相当于物光位相受到正弦调制，仪器在不“冻结”参考状态（即 CCD 采样的信号不在帧存器中锁定）时，连续进行相邻两时刻散斑图的“相减”，并在监视器上得到与振型有关的实时图象。当物体达到自振频率时，将出现清楚的振型。因此，本方法可进行频率扫描，通过观察监视器的条纹场确定各阶自振频率及相应的振型，其条纹分辨率高于时间平均法，与相减法比较则可在很宽频率范围内进行频率扫描。

一、前　言

在实验力学领域中，电子散斑干涉系统（ESPI）主要用于变形分析、形状测量和振动分析等[1,2]。ESPI 方法与全息干涉法相比，可以获得实时或准实时的测量数据，无避光要求，有可能解决现代光测力学方法在现场测量的问题；同时它具有非接触性、全场性的优点，故 ESPI 法具有潜在的应用前景。目前，它在振动测量中的应用已经引起人们的兴趣。在振动物体振型测量方面已有一些成熟的方法，如时间平均法[3]、减法[4]。后者是在给定频率下首先选择参考状态“冻结”（即在帧存器内锁定的信息是包括物光、参考光位相信息的图象散斑场），然后以 40ms 速度与其后连续采样的散斑场光强信息相减，在相减的两幅图象之间给物光或参考光一定的相移时，可得到与振型相应的条纹场。此法的条纹分辨率高，但不能频率扫描。

本文的方法是给振动物体以总的低频振动，对物光波进行正弦调制。此法不进行参考状态的“冻结”，即不进行帧存器信号的锁定，由连续采样的散斑图中相邻时刻的两幅图相减，它实时地反映了振动物体的振型。它与时间平均法相似，能进行频率扫描测振，但又用了减法，光学上能更好地消除本底信息（直流分量），所以条纹清晰度比时间平均法高。本文将提供该方法的理论推导，同时还介绍了在发动机涡轮叶片及高压压气机盘—叶片振动测量的应用情况。在试验中采用压电晶体对被测对象激振，用本文提出的方法进行了频率扫描，测量各阶自振频率及相应的振型。涡轮叶片的振型十分清楚，在盘片耦合振动测量中，由于仪器光场的限制，只能按四分之一区域记录，高阶频率下的振型比低阶振型清楚。

二、物光位相调制法测振原理

典型的 ESPI 系统如图 1。系统使 He-Ne 激光器的光波分成两束（参考光波与物光波），参考光波由分光镜入射于 CCD 摄象机阵列（靶源）。断光波则由扩束镜射至物体后，在物体表

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面形成散斑场，并由变焦镜成象于CCD 摄象机阵列，此时参考光波 E_r 与物光波 E_o 在CCD 靶源上混合。此种基本光学结构可认为是一种图象全息系统（所以也称 ESPI 为 TV 全息）。其光波表达式为

$$E_o = A_o \exp[i\varphi_o(x,y,t)] \quad , \quad E_r = A_r \exp[i\varphi_r(x,y,t)] \tag{1}$$

当物体振动时，其物光波位相为

$$\varphi_o(x,y,t) = (2\pi/\lambda) K a(x,y,t) + \varphi_o(x,y) \tag{2}$$

a 为物体表面任一点与参考位置的离面位移，当物体振动时

$$a(x,y,t) = a_o(x,y)\sin(\omega t + \psi_o) \tag{3}$$

K 为几何因素，当物光垂直入射至表面时为 2。

CCD 摄象机阵列为平方律光强探测器，故其输出的视频信号光强为

$$I(x,y,t) = A_o^2 + A_r^2 + 2A_oA_r\exp[i(\varphi_o - \varphi_r)] \tag{4}$$

系统内设置电子滤波、整流线路，故视频信号经电子滤波整流输入 A/D 转换器后再输入帧存器中进行图象处理，此时输入 A/D 转换器的光强信息为

$$I(x,y,t) = 2A_oA_r\left|\cos(\varphi_o - \varphi_r)\right| \tag{5}$$

由于物体振动，使物光位相改变，(5) 式可表达为

$$I(x,y,t) = 2A_oA_r\left|\cos[(\varphi_o - \varphi_r) + (2\pi/\lambda)K a_o(x,y)\sin(\omega t + \psi_o)]\right| \tag{6}$$

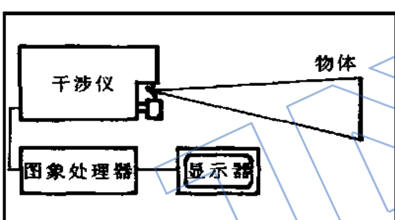

图 1 ESPI 系统图

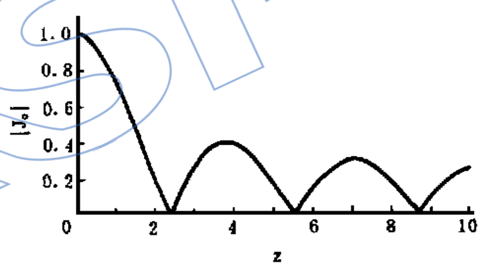

图 2 受贝塞尔函数调制的散斑图光强分布

利用贝塞尔函数及三角函数关系展开 (6) 式忽略贝塞尔函数高次项产生的影响，写成下式

$$I(x,y,t) = 2A_oA_r\left|J_o[(2\pi/\lambda)K a_o(x,y)]\cos(\varphi_o - \varphi_r)\right| + f(\omega t) \tag{7}$$

式中 $f(\omega t)$ 表示了 (7) 式的高阶项，其值比 J_o 项要小。而且由于物体振动频率比摄象机的帧频要大，光强度实际上是帧周期 τ 内的平均值，(7) 式中的 $f(\omega t)$ 项的积分值近似为 0。

当振动物体的基座产生低频振动时，其物体表面的散斑场位相为 $(\varphi_o - \varphi_r + \Delta\varphi)$，其中 $\Delta\varphi = \varphi\sin\Omega t$，$\Omega$ 为物光正弦调制频率，此时光强表达式为

$$I(x,y,t) = 2A_oA_r\left|J_o[(2\pi/\lambda)K a_o(x,y)]\cos[\varphi_o - \varphi_r + \Delta\varphi(t)]\right| \tag{8}$$

当相邻两时刻的散斑图相减时，则光强表达式为:

$$\begin{aligned} I(x,y) &= I_1(x,y,t) - I_2(x,y,t_2) \\ &= 4A_oA_r\left|J_o[(2\pi/\lambda)K a_o(x,y)]\right|\left|\sin\{(\varphi_o - \varphi_r) \right. \\ &\quad \left. + (1/2)[\Delta\varphi(t_1) + \Delta\varphi(t_2)]\}\sin(1/2)[\Delta\varphi(t_1) - \Delta\varphi(t_2)]\right| \end{aligned} \tag{9}$$

(9) 式实际上是高频变化的散斑场被缓慢变化的一类零阶贝塞尔函数所调制。式中 $\Delta\varphi(t_1) - \Delta\varphi(t_2)$ 显然与时间有关，但它们只影响条纹的反差，而不影响条纹的分布，而且在监视器上的条纹场亮度变化是缓慢的，不影响观察与记录。$\left|J_o[(2\pi/\lambda)K a_o(x,y)]\right|$ 的分布如

图 2, 它表示了散斑场光强的分布规律。J_o 的最大值为 1, 相应于 $(2\pi/\lambda) K a_o(x, y) = 0$ 时的值, 此时振幅 $a_o(x, y) = 0$, 即为振型的节线, 此处光强度最大, 条纹最亮。依次由 $J_o[(2\pi/\lambda) K a_o(x, y)]$ 的根值可求得各级暗条纹的级数, 即 N_i= 2.4048、5.5021、8.5631……, 由此可求出振动物体的振幅分布。

三、在航空发动机零件振动分析中的应用

ESPI 测振方法在航空发动机零件振动测量中得到应用, 采用物光调制法测量了某发动机一级涡轮工作叶片的一阶弯曲、一阶扭转振动时的振型; 对高压压气机的盘—片的耦合振动进行了较宽频率范围内的扫描测量, 在频率 482Hz 至 2421Hz 范围内测量到 7 个自振频率及相应的振型。测量线路见图 3, 振动物体基座存在低频振动, 实现了物光的正弦相位调制。

试验件的激振方法采用压电晶体片激振, 根据具体结构选择晶体片型式及晶体片的分布。激振频率由功率放大器控制, 在频率扫描过程中适当调节功率大小以控制振幅数值。由 SEPI 的监示器上的条纹场的清晰及稳定程度确定自振频率, 精确的频率由数字频率计读出。

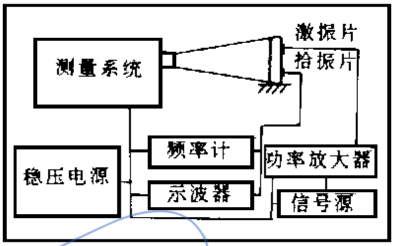

图 3　ESPI 振动分析框图

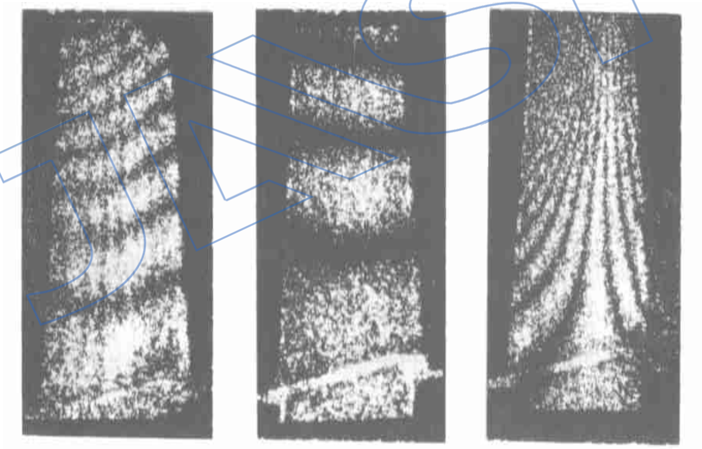

图 4　涡轮工作叶片振型

1. 涡轮工程叶片的测量　测量了涡轮工作叶片的一阶弯曲振型及一阶扭转振型, 振型见图 4。本方法测得的自振频率值与振动台激振测出的频率是一致的, 如一阶弯曲振动频率本方法测量结果 f_p= 1679Hz。由于叶片曲率不太大, 物光可以近似认为垂直入射于叶片表面, 此时可由振型图的条纹场根据 (9) 式确定条纹级数 N_i (N_i 应是 J_o 的根值, 而非整数) 计算各点最大振幅 $a_o(x, y)$。同时因物光近似垂直物体表面, 则 (9) 式中的 $K \doteq 2$。

$$a_o(x, y) \doteq N_i\lambda/4\pi \tag{10}$$

2. 压气机盘—叶片耦合振动测量　测量系统见图 3。试件安装于活动平台上, 当试件被激振时, 平台存在低频振动, 对物光相位进行正弦调制。由于仪器光场限制, 不能测整个结构的条纹场, 按 1/4 面积测量, 全场振型图为拼接而成。首先开启 ESPI 系统后, 调节变焦镜

得到清晰图象，同时调节参考光强，在监视器上见到活动的散斑点。当物体激振后，即可

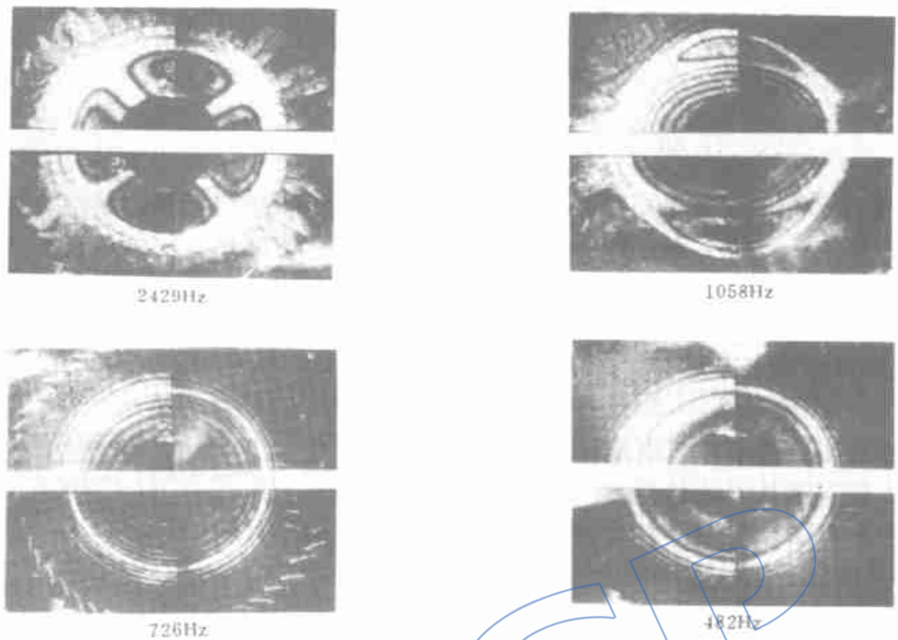

图 5 盘片藕合振动的振型图

用频率扫描法从低频至高频连续改变物体激振频率，测得的盘、叶片、盘—片耦合振动的振动频率及相应的振型见图 5。

四、结 论

用 ESPI 系统进行物体的振动分析具有非接触性、全场性、实时性的特点。利用时间平均法或相位调制法可以扫描测量，进行各阶频率振型的实时测量，并且条纹场受零阶贝塞尔函数的调制，零阶条纹亮度最高，迹线清楚，能清楚地得到振型。ESPI 测振技术中，除了本文所用的物光调制法外，时间平均法、相移相减法等都能应用。今后在 ESPI 的应用中，还需着重开发数据处理的自动化技术。

参 考 文 献

[1] Jones R., and Wykes, "Holographic and Speckle Interferometry", Cambridge Univ. Press, Cambridge, 1983.
[2] Lokberg O. J. Proc. SPIE. p. 746, 1987.
[3] VIDISPEC Instruction Manual, Ealing Electro-optics, plc. 1986.
[4] Lu Boxiang, et al., "Time-Average Subtraction Method in Electronic Speckle Pattern Interferometry", Opties Communications Volume 71, number3, 1989.

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EXPERIMENTAL INVESTIGATION ON BLADE LOSS TRANSIENT RESPONSE OF ROTOR WITH FLEXIBLE DAMPED SUPPORT

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ABSTRACT A rotor system with flexible damped support has been investigated experimentally under the conditions of simulated blade loss. Some results of the transient response dynamics are presented. Experiments under different sudden unbalances applied to the rotor system with various Squeeze Film Damper (SFD) film clearances were performed at different rotational speeds. The instability conditions characterized by limiting circle orbits for large amplitude at damper location can be determined, and some particular phenomena caused by nonlinearity of the rotor system such as lock up, bistable jump and subharmonic etc. have been observed. The effectiveness and the capability of SFD for suppressing instability of the rotor system are analyzed.

LIFE PREDICTION OF A MEMBER UNDER LOW-CYCLE FATIGUE-CREEP INTERACTION

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ABSTRACT A structural member model under low-cycle fatigue-creep interaction has been investigated experimentally and its life predicted with the help of several available methods. On the basis of the comparison between the expermental data and the prediction results, an approach is provided to analyze the cycle creep and influence of average stress according to difference between the properties of the material and the member. The rule of the low-cycle fatigue-creep interaction has been researched thoroughly. Finally, a better approach of life prediction is proposed.

PHASE MODULATING IN ESPI FOR VIBRATION PATTERN MEASUREMENT

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ABSTRACT The conventional method of electronic speckle pattern interferometry (ESPI) for vibration pattern measurement is to freeze reference beam. This method enables to sweep over a wide frequence range and to identify resonant modes. However, the obtained fringe contrast is not too fine. In order to enhance the visibility of

fringe pattern, it is possible to subtract two time average pattern at any given frequancy. In result, the fringe pattern is obtained with high visibility but only valid at the given frequency. A phase shifting technique is adopted to overcome this shortcoming. A time average image is put into processor and frame store (renewed and put into processor per 40ms), then a subsequent image with a phase shift of $\Delta\Phi$ resulted from sinusoidal modulation in object beam is recorded and subtracted from the first image. This method is similar to modulation of light intensity function of speckle pattern. The advantage of this method is the capabilities of obtaining real time fringe pattern of vibration with high resolution and of performing frequency scanning at a wide range. Its application to the vibration pattern measurement of disk-blade coupling in an aeroengine is a great success.

ANALYSIS OF TENON AND MORTISE CONTACT PROBLEMS BY BOUNDARY ELEMENT METHODS

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ABSTRACT The boundary element equations of 2-D elastic contact problems are established by the incremental principle and some concrete approaches to solution of the contact procedure are considered. The contact stresses of the dove tail and the pine tree joints of the disk/blade assembly are numerically analyzed. From the comparsion of the numerical results of boundary element methods (BEM) with those of FEM and photoelasticity experiments it is concluded that the results of BEM are satisfactory in contrast with FEM, the BEM not only simplifies data preparation but also gives the results of the same accuracy level with fewer discrete elements and saves the computer time tremendously.

A COMPOUND FATIGUE INVESTIGATION OF PLATE SPECIMEN UNDER LOW-CYCLE LOAD SUPERPOSED ON HIGH CYCLE LOAD

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ABSTRACT According to real operating conditions of turbine-engine blades in service, a series of combination tests of various load matching and frequency matching for plate specimens was carried out on the compound fatigue testing rig which can simulate operating loads on the blades. From the test results and theoretical analyses, some characteristics and the regularities of this compound fatigue are obtained. A new method of life prediction for this compound fatigue is presented in this paper. The calculated results of this method are in good agreement with the experiments.

RESEARCH ON DAMAGE TOLERANCE OF COMPRESSOR BLADE

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ABSTRACT This paper discribes the damage tolerance analysis of compressor blade by fracture mechanics. Finite element method with 20-nodes solid elements is used for the stress calculation. A displacement method is provided to determine the stress intensity factors K_{I}, K_{II} and K_{III} versus crack length a of the blade. Based on the material toughness