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损伤法则在时间相关疲劳寿命预测中的应用

北京航空材料研究所　董照钦　段作祥　何晋瑞

动力机械如燃气涡轮、蒸汽轮机、锅炉和核压力容器都在高温、高压、高应力和各种腐蚀环境下工作。为保证这类机械能长时间安全运转，人们日趋重视对零部件采用抗蠕变-疲劳-环境（统称为时间相关疲劳）开裂设计。尤其是对先进的航空发动机热端部件更重要。于是迫切需要准确的寿命预测方法。近些年来已提出不少时间相关疲劳寿命预测方法[1]，其中，国内外广泛流行的是应变范围区分法（SRP）[2]与应变能区分法（SEP）[3]。本文重点放在线性损伤法则（LDR）和交互作用损伤法则（IDR）及其对SRP与SEP的应用上。

一、损伤法则的分析与讨论

1. **线性损伤法则（LDR）** Taira[4]把Miner[5]用于疲劳和Robinson[6]用于蠕变的线性累积损伤法则结合起来，提出了用于蠕变——疲劳交互作用的损伤法则。将这种损伤法则用于应变范围区分法（SRP）和应变能区分法（SEP），即为

$$(N_f/N)_{pp}+(N_f/N)_{pc}+(N_f/N)_{cp}+(N_f/N)_{cc}=1 \qquad (1)$$

式中$(N_f/N)_{pp}$和$(N_f/N)_{cc}$为疲劳和蠕变的损伤分数；$(N_f/N)_{pc}$，$(N_f/N)_{cp}$为蠕变-疲劳交互作用的损伤分数。一般情况下，（1）式可写为

$$N_f^{-1}=D^{-1}\left(N_{pp}^{-1}+N_{pc}^{-1}+N_{cp}^{-1}+N_{cc}^{-1}\right) \qquad (2)$$

式中D为损伤参数。记D＝1时，$N_f=N_{f1}$，则当$D>1$时，$N_f>N_{f1}$；当$D<1$时，$N_f<N_{f1}$。D值越接近1，就说明越符合线性损伤法则；否则，越偏离1，就说明越不符合线性损伤法则。

SRP、SEP按（1）式的计算程序为

（1）按$(N_f)_{pp}=C_{pp}(\Delta\ _{pp})^{\alpha_{pp}}$或$(N_f)_{pp}=C'_{pp}(\Delta\ _{pp}\sigma_T)^{\alpha'_{pp}}$利用最小二乘法拟合常数$C_{pp}$、$\alpha_{pp}$、$C'_{pp}$、$\alpha'_{pp}$，式中$\Delta\ _{pp}$为塑性应变范围；$\sigma_T$为峰值拉伸应力。

（2）由于得不到纯PC、CP、CC试验，一般说来，PC、CP型试验中含有PP分量，CC型试验中含有PP、PC（或CP）分量。应按（1）式求出相应于PC、CP、CC试验中的疲劳寿命N_{pc}、N_{cp}、N_{cc}，即

$$\left.\begin{aligned}N_{pc}&=\left[(N_f^{-1})_{pc}-(N_{pp}^{-1})_{pc}\right]^{-1}\\N_{cp}&=\left[(N_f^{-1})_{cp}-(N_{pp}^{-1})_{cp}\right]^{-1}\\N_{cc}&=\left[(N_f^{-1})_{cc}-(N_{pp}^{-1})_{cc}-(N_{pc}^{-1})_{cc}-(N_{cp}^{-1})_{cc}\right]^{-1}\end{aligned}\right\} \qquad (3)$$

式中　$(N_f)_{ij}(i,\ j=P,\ C)$—ij试验中的N_f；

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（3）利用最小二乘法拟合下式中的常数：

$$\text{SRP}\quad\left\{\begin{array}{l}N_{pc}=C_{pc}(\Delta\varepsilon_{pc})^{\alpha_{pc}}\\N_{cp}=C_{cp}(\Delta\varepsilon_{cp})^{\alpha_{cp}}\\N_{cc}=C_{cc}(\Delta\varepsilon_{cc})^{\alpha_{cc}}\end{array}\right\}\tag{4}$$

$$\text{SEP}\quad\left\{\begin{array}{l}N_{pc}=C'_{pc}(\Delta\varepsilon_{pc}\sigma_T)^{\alpha'_{pc}}\\N_{cp}=C'_{cp}(\Delta\varepsilon_{cp}\sigma_T)^{\alpha'_{cp}}\\N_{cc}=C'_{cc}(\Delta\varepsilon_{cc}\sigma_T)^{\alpha'_{cc}}\end{array}\right\}\tag{5}$$

（4）对于PP、PC、CP、CC型试验，再按（1）式求预测寿命。

在（2）中，由（3）式求得的N_{pc}、N_{cp}、N_{cc}应满足

$$N_{pc}>(N_f)_{pc},\quad N_{cp}>(N_f)_{cp},\quad N_{cc}>(N_f)_{cc}\tag{6}$$

这即为LDR应满足的物理条件。以PC试验为例，从损伤的观点证明，总损伤D为

$$D=D_{pp}+D_{pc}\tag{7}$$

显然，损伤参量D_{pp}为非负值，于是有

$$D>D_{pc}\tag{8}$$

由于损伤和疲劳寿命成反比，因此，（6）式中第一式成立；同理，可证明其余两式也成立。

2. 交互作用损伤法则（IDR） Manson[7]等利用损伤分数，提出了交互作用损伤法则，

$$1/N_f=F_{pp}/N_{pp}+F_{pc}/N_{pc}+F_{cp}/N_{cp}+F_{cc}/N_{cc}\tag{9}$$

式中 N_{ij}取决于寿命预测模型，对SRP，则$N_{ij}=C_{ij}(\Delta\varepsilon_{in})^{\alpha_{ij}}$，$F_{ij}=\Delta\varepsilon_{ij}/\Delta\varepsilon_{in}$，其中$\Delta\varepsilon_{ij}$——非弹性应变分量，$\Delta\varepsilon_{in}$——总的非弹性应变范围。对SEP，式中各量为$F_{ij}=\Delta\varepsilon_{ij}\sigma_T/\Delta\varepsilon_{in}\sigma_T=\Delta\varepsilon_{ij}/\Delta\varepsilon_{in}$，$N_{ij}=C'_{ij}(\Delta\varepsilon_{in}\sigma_T)^{\alpha'_{ij}}$。Manson等虽然提出这个损伤法则，但并没有给出明确的物理解释。对IDR进行和LDR同样分析，应有

$$N_{pc}>(N_f)_{pc},\quad N_{cp}>(N_f)_{cp},\quad N_{cc}>(N_f)_{cc}\tag{10}$$

这即为IDR应满足的物理条件。

二、国外材料的验证与讨论

我们用SRP、SEP按LDR、IDR对国产GH33A原材料（700℃）、盘材（电弧炉、双真空两种冶炼工艺，700℃）、1Cr18Ni9Ti（600℃）进行了寿命预测研究[1,3]，表明LDQ比IDR的计算结果较好。为了在更大范围内估算LDR、IDR在SRP、SEP中的预测能力，选用了现有的某些国外数据，这些原始数据全部引自文献[8]中的附录，总计试样345根。在计算过程中，发现按LDR计算，所选全部数据满足(6)式；而按IDR计算，不但不满足(10)式，而且对有些材料还会出现N_{pc}、N_{cp}、N_{cc}为负值。事实上，还有其他一些作者也说明按IDR计算求得负寿命[9]，他们认为，这是由于PP型试验的分散性引起的，但他们并没有发现要满足（10）式。PP型试验中的分散性固然会影响到其它三种类型的寿命预测，但是按LDR计算，就不会出现负寿命，且满足（6）式。关键在于LDR有明确的物理意义。此外，LDR比IDR计算简洁。

SRP、SEP按LDR、IDR求得的观察寿命与预测寿命的比值发现，SRP、SEP按IDR计算时，观察寿命和预测寿命差别最大的是在长寿命区。SRP、SEP按LDR、IDR求得各种材料

的预测能力如表 1 所示，由此可见，对SRP、SEP都有LDR比IDR预测能力大有改进，且对同一损伤法则，SEP比SRP的预测能力有所改进。

表 1 SRP, SEP (LDR. IDR) 预测能力

	SRP						SEP					
	LDR			IDR			LDR			IDR		
	分散带	标准差	φ%	分散带	标准差	φ%	分散带	标准差	φ%	分散带	标准差	φ%
Rene'80 Uncoated 871℃ (TRW)	3.47	.187	95	3.47	.255	85	2.24	.146	95	2.24	.190	90
Rene'80 Coated 871℃ (TRW)	2.73	.156	90	3.40	.199	95	2.10	.137	95	2.58	.175	95
Rene'80 Coated 1000℃ (TRW)	1.96	.120	100	2.39	.216	75	1.74	.121	100	2.11	.182	95
Rene'80 Uncoated 1000℃ (NASA)	1.67	.141	100	3.17	.269	69	1.93	.138	100	2.72	.244	75
Rene'80 Coated 1000℃ (NASA)	2.10	.152	95	3.03	.208	85	1.94	.131	100	2.63	.202	90
IN-100 Cast 925℃ (NASA)	1.91	.142	100	2.03	.202	94	2.01	.148	94	2.62	.215	88
IN-100 Gaterized 760℃ (NASA)	3.59	.216	88	4.65	.267	81	3.34	.182	88	4.46	.272	81
IN-100 Gaterized 650℃ (P&WA)	2.04	.137	94	8.43	.504	53	2.33	.159	94	7.62	.467	53
IN-100 Coated 900℃ (ONERA)	1.66	.134	100	2.71	.230	78	1.55	.105	100	2.86	.222	83
IN-100 Coated 1000℃ (ONERA)	1.69	.132	100	2.57	.242	69	1.73	.107	100	5.64	.319	69
Mar Moo2 850℃ (CIT)	1.77	.125	100	2.12	.181	92	1.85	.111	100	1.89	.168	100
Mar MOO2 1040℃ (CIT)	1.28	.053	100	4.29	.276	86	1.17	.035	100	1.85	.153	100
Nimonic 90 810℃ (NGTE)	3.32	.195	85	6.66	.328	78	3.30	.176	93	5.80	.304	81
Waspaloy 750℃ (CEAT)	1.53	.077	100	—	—	—	1.48	.066	100	—	—	—
Ti A16V4 450℃ (DFVLR)	1.95	.137	100	3.81	.306	62	3.02	.162	96	5.67	.361	62
Rene'95 650℃ (AFML)	5.04	.192	88	13.43	.399	56	3.19	.161	92	9.81	.370	60

注[10]：表中分散带 $\overset{定义}{=\!=}$ $Max\left\{\frac{N_{obi}}{N_{pri}}, \frac{N_{pri}}{N_{obi}}\right\}$，标准差 $\overset{定义}{=\!=}$ $\sqrt{\frac{1}{n-1}\sum_{i=1}^{1}\left(\lg\frac{N_{obi}}{N_{pri}}\right)^2}$；$\varphi \overset{定义}{=\!=} \frac{n_0}{n}\times 100\%$

其中N_{obi}、Npri——分别为第i个试样的观察寿命与预测寿命；(1≤i≤n)

n——试验的总个数；n_0——满足不等式1≤Max{(Nobi/Npri)，(Npri/Nobi)}≤2的个数

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parison of numerical results with experimental data indicates that the numerical method presented is generally feasible.

A NEW APPROACH TO IMPROVEMENT OF FANS

Su Hanshou

(Beijing Institute of Aeronautics and Astronautics)

Abstract

This paper presents experimental results of 3-D flowfields in the fan tip region for two actual fans. It is shown that the fan performance can be significantly improved as proplets are attached to the blade tips. The improving mechanism have been studied and can be stated as follows: The proplets retain the tip vortex and thus the tip induced loss is reduced remarkably, and the additional propulsion moment is gained because the proplets partly balance the drag moment due to profile loss in the tip section. The conclusions presented in this paper may be applied to the tip section of propeller or helicopter rotor for performance improvement.

APPLICATION OF UNSTEADY FLOW REFRIGERATION TO RECORVERY OF PETROLEUM GAS

Shen Zhenhua

(Shenyang Institute of Aeronautical Engineering)

Abstract

The refrigeration principle of "thermal separator" is analyzed in light of unsteady flow dynamics and a simplified physical model is presented to improve the refrigeration efficiency. The analytical study shows that it is necessary to control the pressure ratio P_4/P_1 properly and to match the length of working pipes with the size and revolution speed of the unit in order to increase its efficiency. The unit may be used for recovery of petroleum gas, cold storage and central airconditioning.

APPLICATION OF DAMAGE RULES TO TIME-DEPENDENT FATIGUE LIFE PREDICTION

Dong Zhaoqin, Duan Zuoxiang, He Jinrui

(Beijing Institute of Aeronautical Materials)

Abstract

Linear Damage Rule (LDR) and Interaction Damage Rule (IDR) are compared and applied to Strain Range Partitioning(SRP) and Strain Energy Partitioning(AEP) methods. From the viewpoint of damage, the physical unequalities which LDR and IDR should fit are derived. With the data of materials available abroad it is verified that the scatter band and standard deviation by LDR are smaller than those by IDR. For the same damage, the predictability of SEP appears a little better than that of SRP.

STEADY-STATE UNBALANCE RESPONSES FOR A MULTISPAN ROTOR

Ren Pingzhen

(*Northwestern Polytechnical University*)

Abstract

A node transfer matrix is deduced which considers the angular stiffness and damping in spline coupling. The steady-state unbalance responses for a rotor with several spans are obtained by using Lund method and the simplified transfer matrix method. An model rotor has also been experimented so that the damping ratio, eccentricity and deflection are measured with amplitude-frequency characteristic method. The steady-state unbalance responses have been obtained from these data. Both analytical and experimental results are in good agreement.

CORRESPODENCES

EFFECT OF POLUTION ON HOT-WIRE ANEMOMETER MEASUREMENT

Li Yapin

(*Wuxi Aeroengine Research Institute*)

A NEW FLAME PROPAGATION TECHNIQUE FOR BARCHAN FLAME-HOLDER

Zhao Guanwu

(*Shenyang Aeroengine Company*)