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DURABILITY ESTIMATIONS FOR IN-SERVICE TITANIUM COMPRESSOR DISKS SUBJECTED TO MULTIAXIAL CYCLIC LOADS IN LOW- AND VERY-HIGH-CYCLE FATIGUE REGIMES

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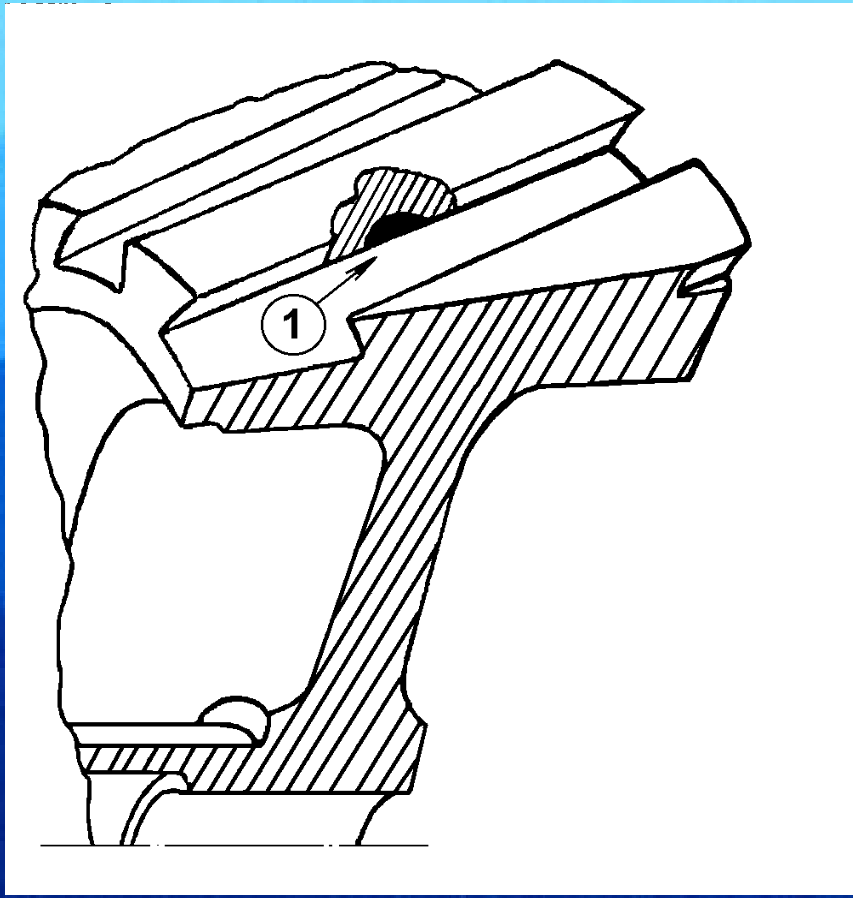
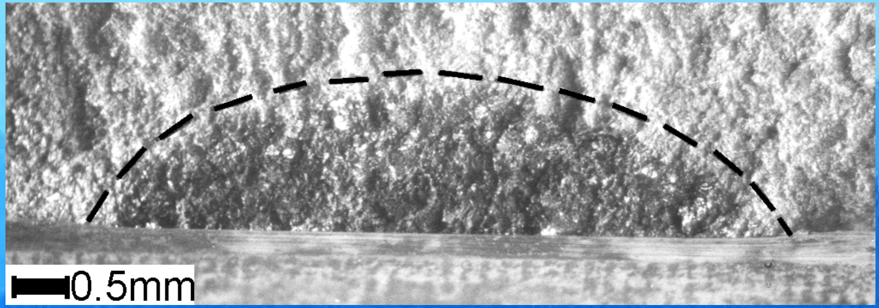
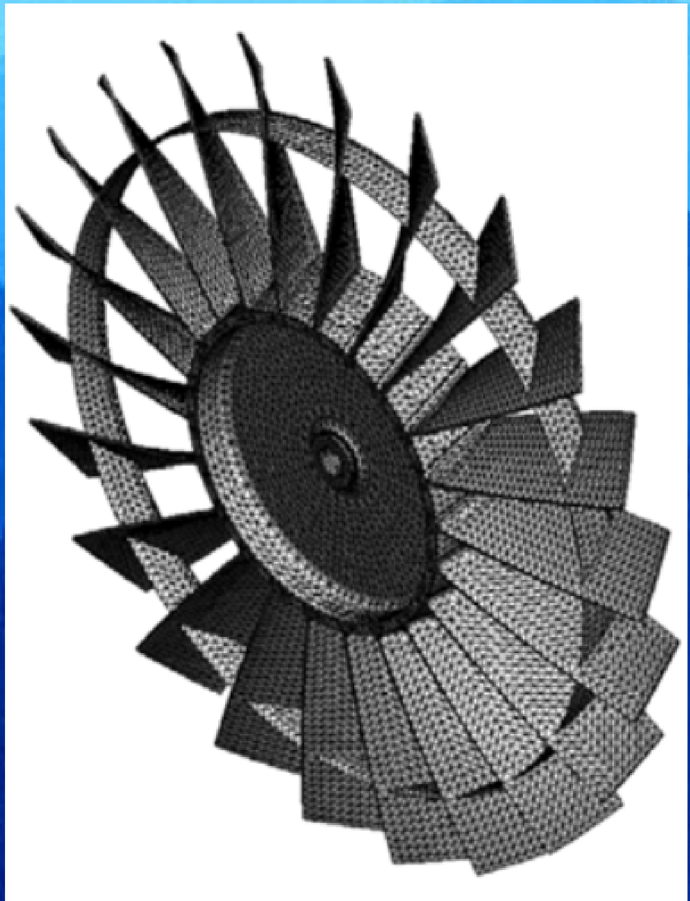
The Problem: to estimate durability
of in-service gas turbine engine (GTE) compressor disks

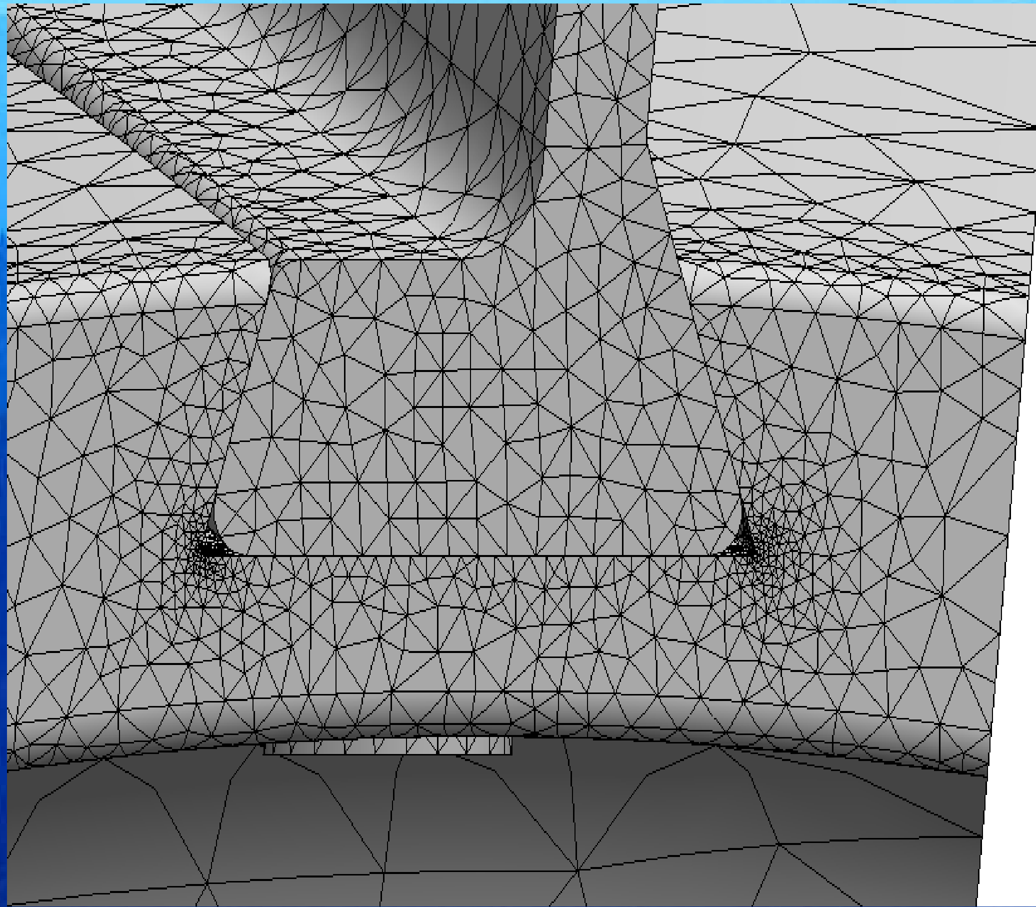
Zone of fatigue fracture nucleation





Finite element model (CosmosWorks)





Three-dimensional problem of solid mechanics

$$\rho d\mathbf{v} / dt = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g}$$

$$d\boldsymbol{\sigma} / dt = \lambda(\mathbf{e} : \mathbf{I})\mathbf{I} + 2\mu\mathbf{e} \qquad \mathbf{e} = (\nabla\mathbf{v} + \nabla\mathbf{v}^T)/2$$

Nonlinear contact conditions between the disk and blades

$$\sigma_n < 0 \qquad |\sigma_{n\alpha}| < q|\sigma_n| \qquad [\mathbf{v}_{\tau\alpha}] = 0 \qquad [u_n] = 0$$

$$\sigma_n < 0 \qquad \sigma_{n\alpha} = q|\sigma_n|[\mathbf{v}_{\tau\alpha}]/\|[\mathbf{v}_{\tau\alpha}]\| \qquad [\mathbf{v}_{\tau\alpha}] \neq 0 \qquad [u_n] = 0$$

$$[u_n] \geq 0 \qquad \sigma_{n\alpha} = \sigma_n = 0 \qquad (\alpha = 1, 2)$$

Aerodynamic loads on the blade

(Hypothesis of the isolated profile)

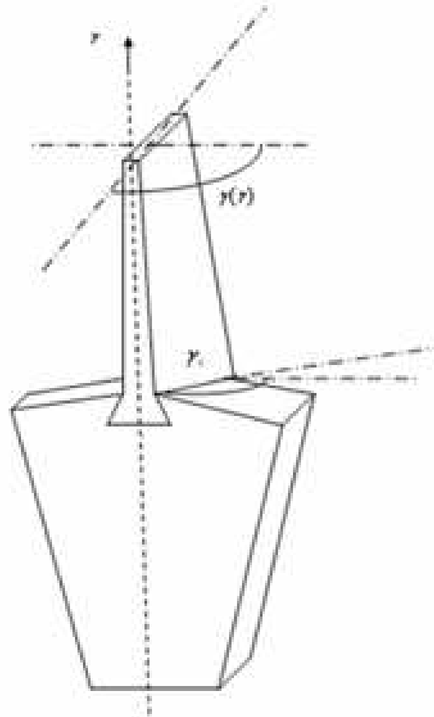
The pressure jump on the surface of a blade in a grid

$$\Delta p(r,x)=\rho\left(v_{\infty}^{2}+\omega^{2}r^{2}\right)\exp\left(-aN/_{2r}\right)\sin 2\alpha(r)\sqrt{sh\frac{N(a-x)}{2r}\Big/ sh\frac{N(a+x+\delta)}{2r}}$$

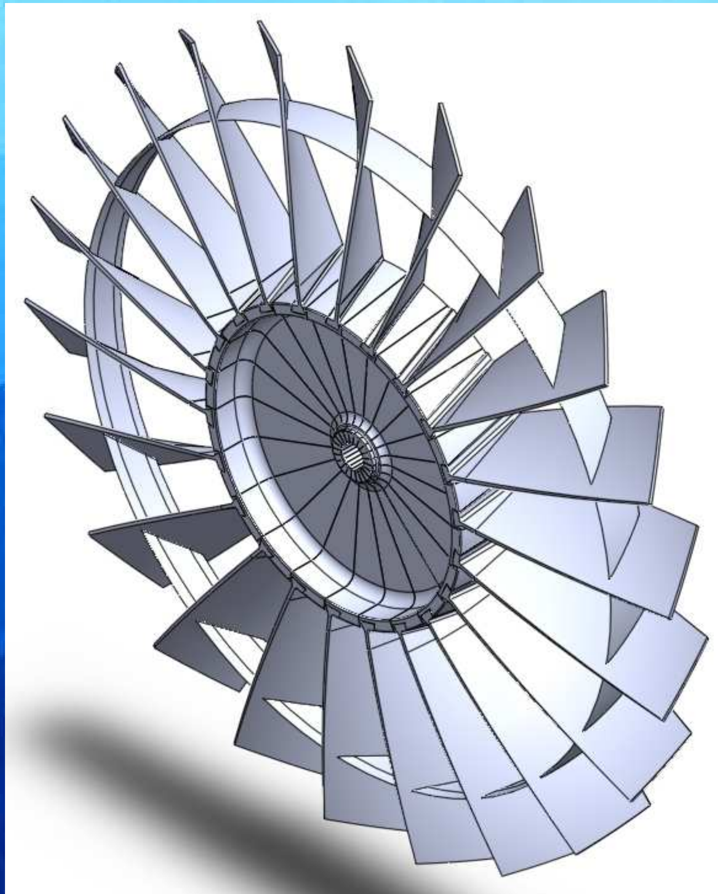
$$\Delta p^{c}(r,x)=\Delta p(r,x)/\sqrt{1-M^{2}}$$

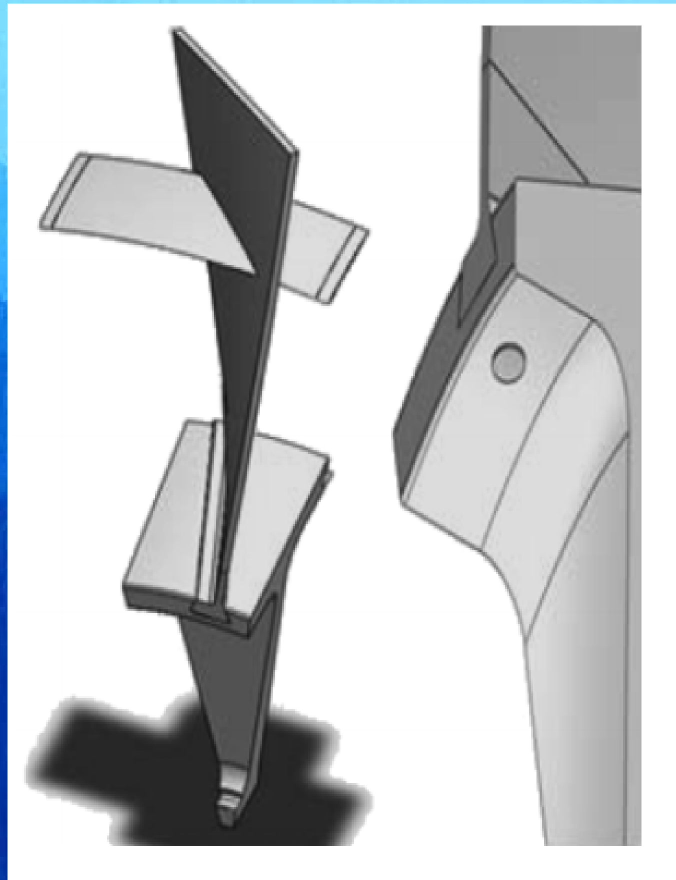
$$M=w/c=\sqrt{v_{\infty}^{2}+\omega^{2}r^{2}}/c$$

$$\alpha(r)=\gamma(r)-arctg(v_{\infty}/\omega r)$$



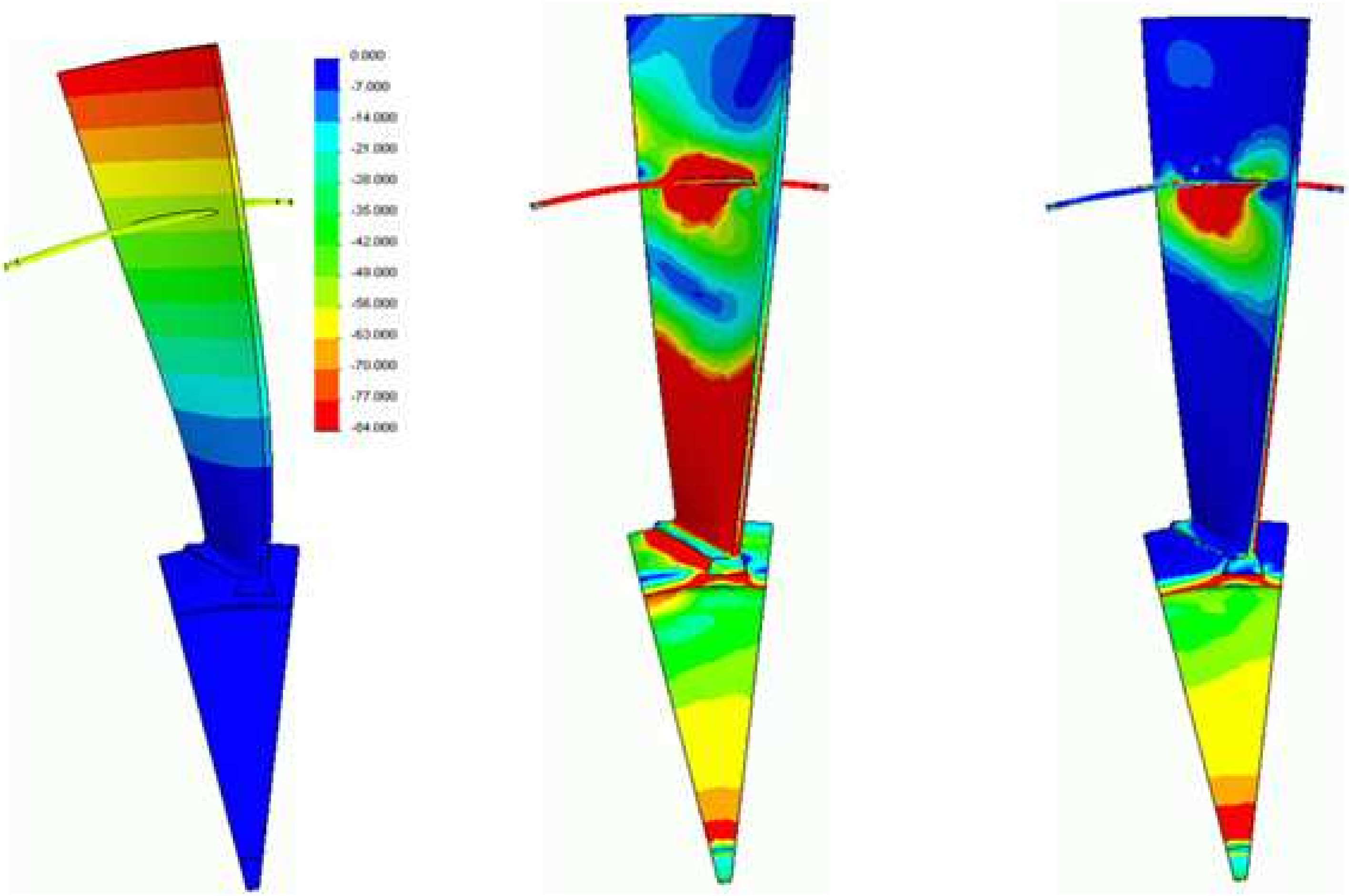
Two stages: 1) computation of the entire compressor disk (a coarse mesh)
2) computation of the disk sector with the blade (a refined mesh)





Flight loading cycle: V=200 m/s   n=3000 r/min   T~2-3 hours

Results of the stress-strain state computation

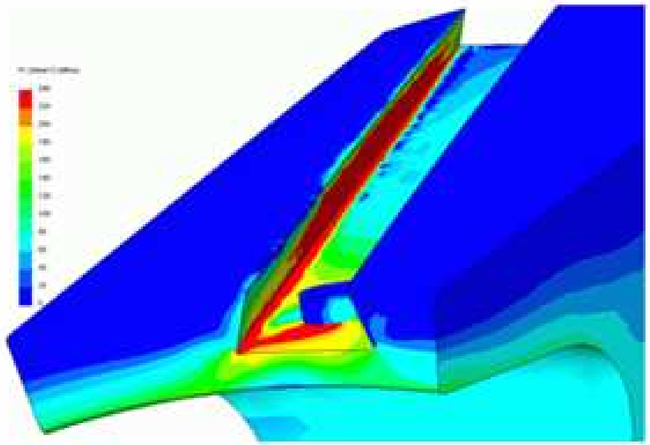


Displacements

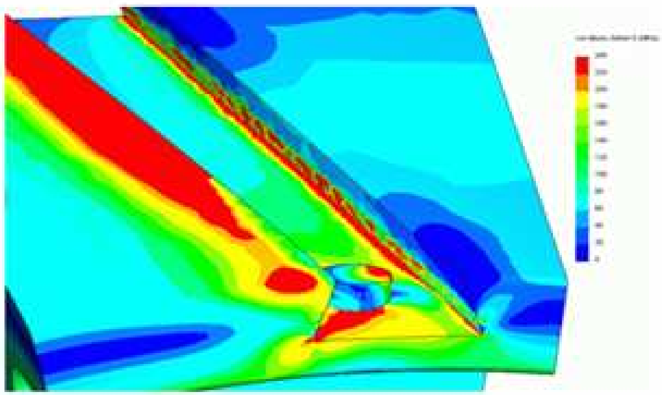
Mises invariant

Maximal main stress

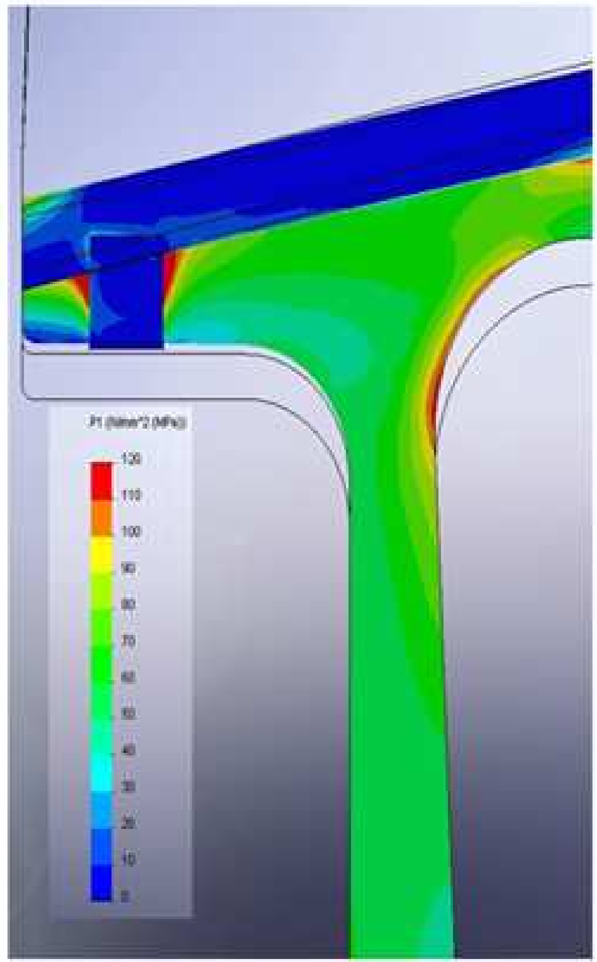
Results of the stress-strain state computation



Maximal main stress



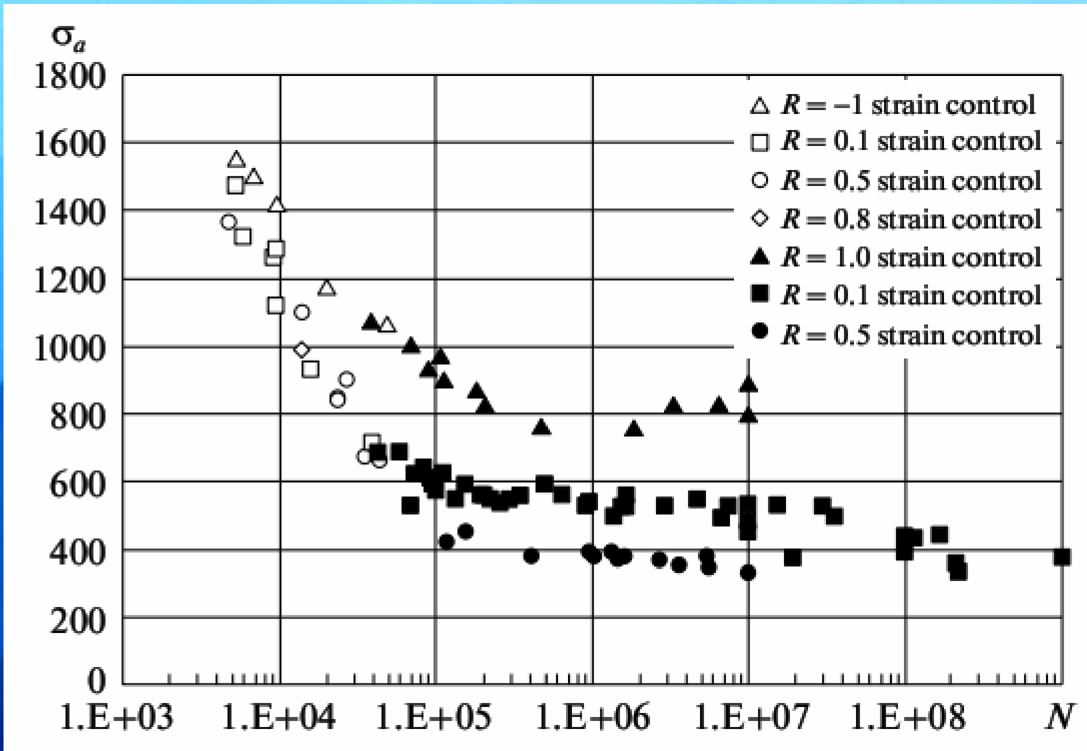
Mises invariant



Maximal main stress

Low-cycle fatigue fracture

(flight loading cycle)



$$\sigma_a = (\sigma_{max} - \sigma_{min})/2$$

$$R = \sigma_{min}/\sigma_{max}$$

$$\sigma = \sigma_u + \sigma_c N^{\beta}$$

Uniaxial fatigue curve

Models of Multiaxial Fatigue Fracture Based on the Stress State

$$\Delta\tau/2+\alpha_s\sigma_{mean}=S_0+AN^b$$

Sines

$$\Delta\tau/2+\alpha_c(\bar{\sigma}_{\max}-\Delta\tau/2)=S_0+AN^b$$

Crossland

$$(\Delta\tau_s/2+\alpha_F\sigma_n)_{\max}=S_0+AN^\beta$$

Findley

$$\Delta\tau=\sqrt{(\Delta\sigma_1-\Delta\sigma_2)^2+(\Delta\sigma_1-\Delta\sigma_3)^2+(\Delta\sigma_2-\Delta\sigma_3)^2}/3$$

$$\sigma_{mean}=(\sigma_1+\sigma_2+\sigma_3)_{mean}$$

$$\bar{\sigma}_{\max}=(\sigma_1+\sigma_2+\sigma_3)_{\max}$$

Models of Multiaxial Fatigue Fracture Based on the Strain State

$$\frac{\Delta\gamma_{\max}}{2} + \alpha_{bm}\Delta\varepsilon_{\perp} = \beta_1 \frac{\sigma_c - 2\sigma_{\perp mean}}{E}(2N)^b + \beta_2\varepsilon_c(2N)^c$$

Brown-Miller

$$\frac{\Delta\gamma_{\max}}{2}\left(1 + k\frac{\sigma_{\perp\max}}{\sigma_y}\right) = \frac{\tau_c}{G}(2N)^{b0} + \gamma_c(2N)^{c0}$$

Fatemi-Socie

$$\frac{\Delta\varepsilon_1}{2}\sigma_{\perp 1\max} = \frac{\sigma_c{}^2}{E}(2N)^{2b} + \sigma_c\varepsilon_c(2N)^{b+c}$$

Smith-Watson-Topper

Models of Fatigue Fracture with Damage

$$\frac{dD}{dN} = \left[1-(1-D)^{\beta+1}\right]^{\alpha}\left[\frac{A_{IIa}}{M_0(1-3b_2\overline{\sigma})(1-D)}\right]^{\beta}$$

Lemaitre-Chaboche

$$N = \frac{\gamma+1}{C}\left\langle\frac{\sigma_u - \theta\cdot\sigma_{VM}}{A_{IIa} - A^*}\right\rangle f_{cr}^{-(\gamma+1)}$$

ULG

$$\alpha = 1 - a\left\langle\frac{(A_{IIa} - A^*)}{(\sigma_u - \sigma_{VM})}\right\rangle$$

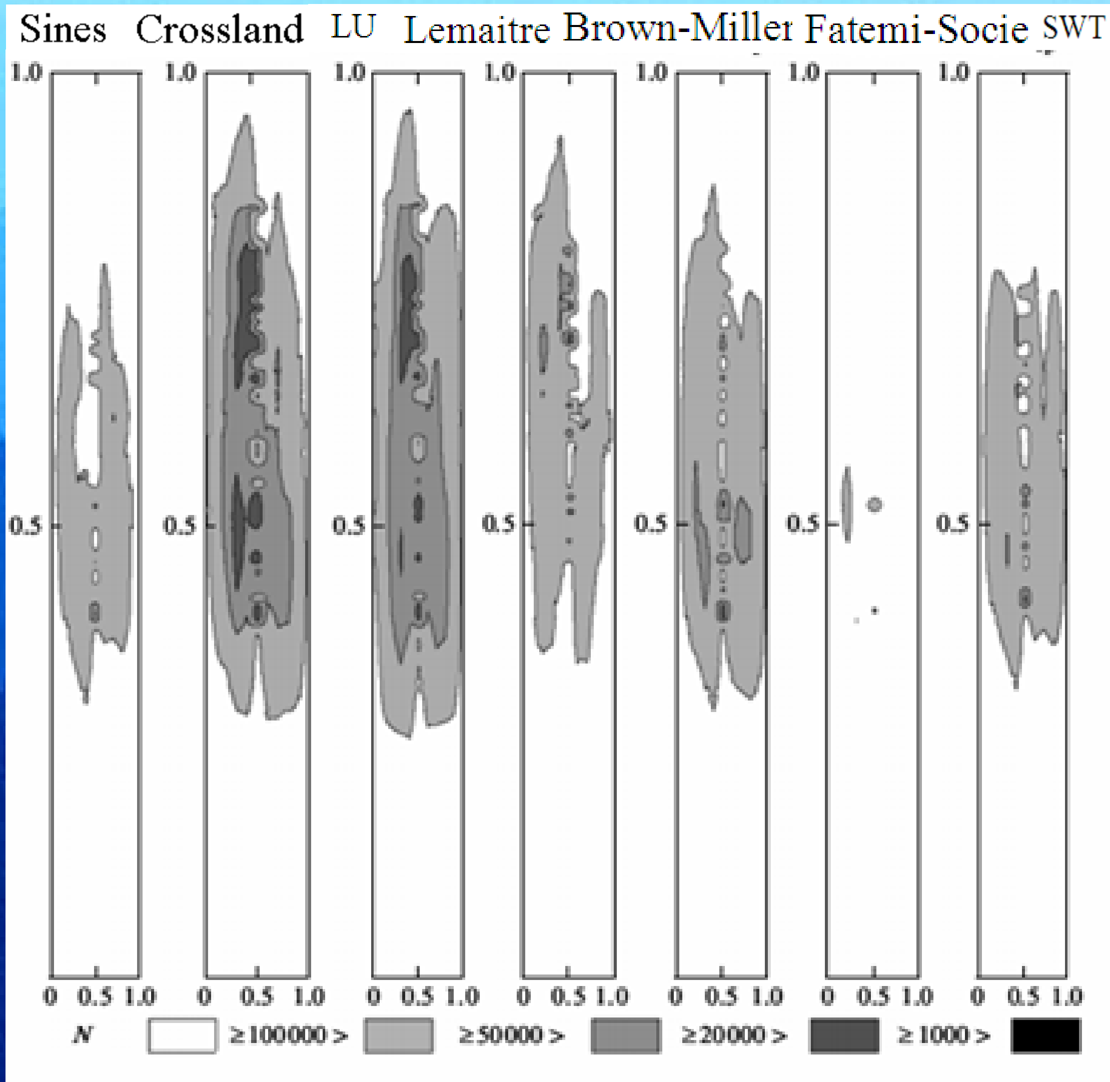
$$\sigma_{VM} = \frac{1}{\sqrt{2}}\sqrt{S_{ij,\max}S_{ij,\max}}$$

$$\sigma_H = (\sigma_1 + \sigma_2 + \sigma_3)_{\max}/3$$

$$A_{IIa} = \frac{1}{2}\sqrt{\frac{3}{2}\left(S_{ij,\max} - S_{ij,\min}\right)\left(S_{ij,\max} - S_{ij,\min}\right)}$$

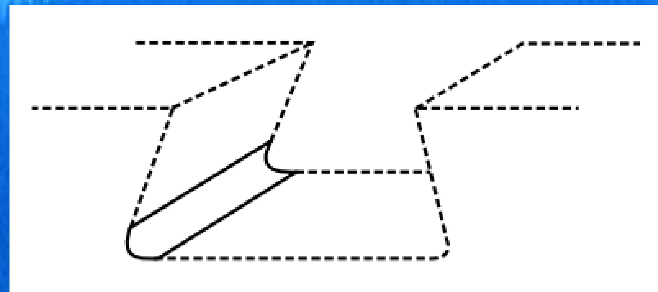
$$f_{cr} = \frac{1}{b}\left(A_{IIa} + a\cdot\sigma_H - b\right)$$

DURABILITY ESTIMATIONS FOR COMPRESSOR DISK



Low-cycle fatigue fracture

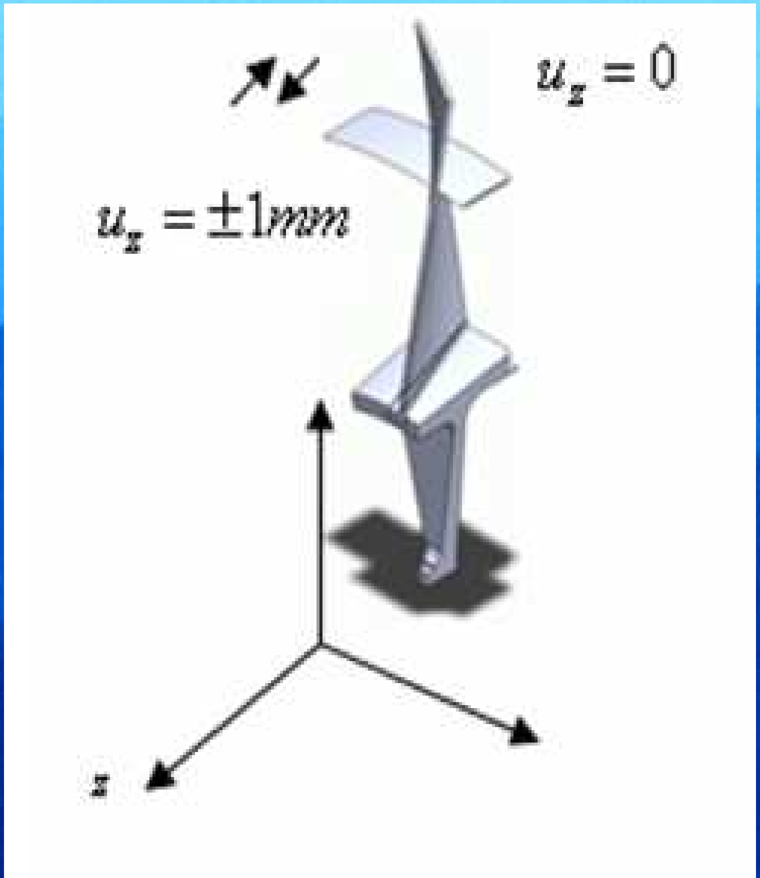
(flight loading cycle)



Number of cycles for fracture:
20000-50000 flight cycles ~
40000-100000 hours

Very-high-cycle fatigue fracture

(influence of vibration loads)

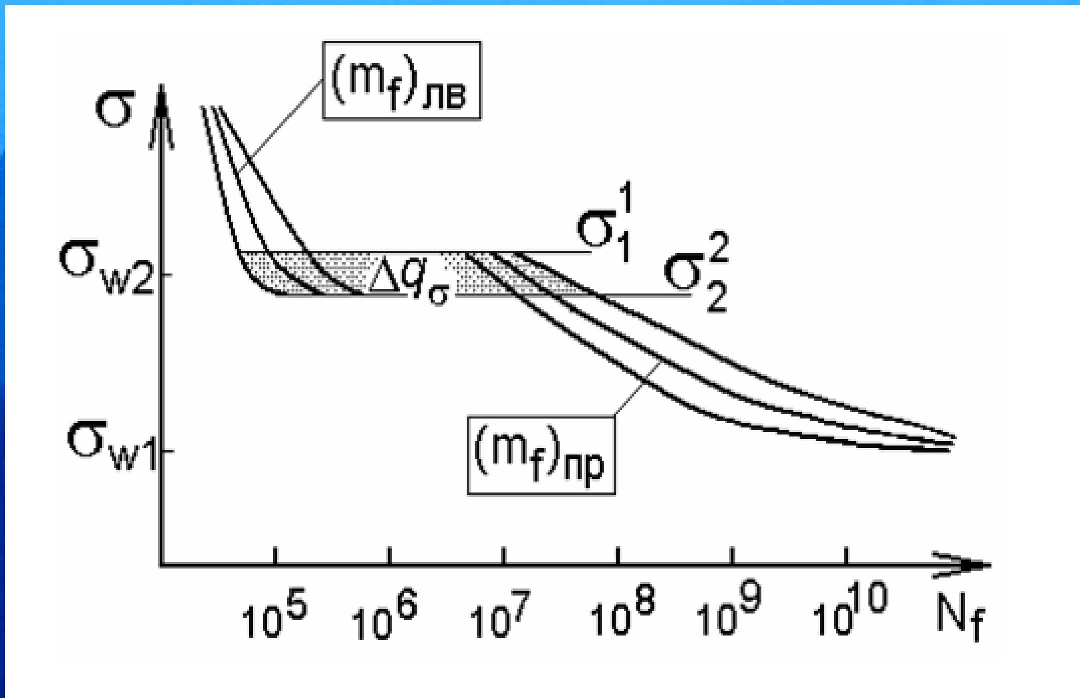


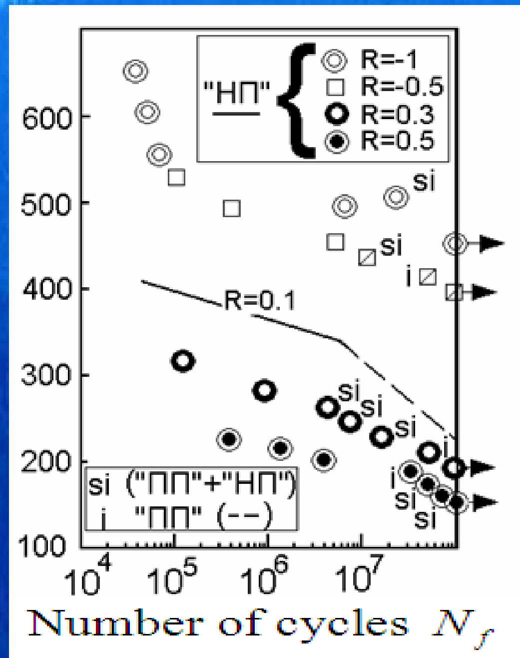
High frequency axial vibrations:

A ~ 1 mm T ~ 0.2 sec

Very-high-cycle fatigue fracture

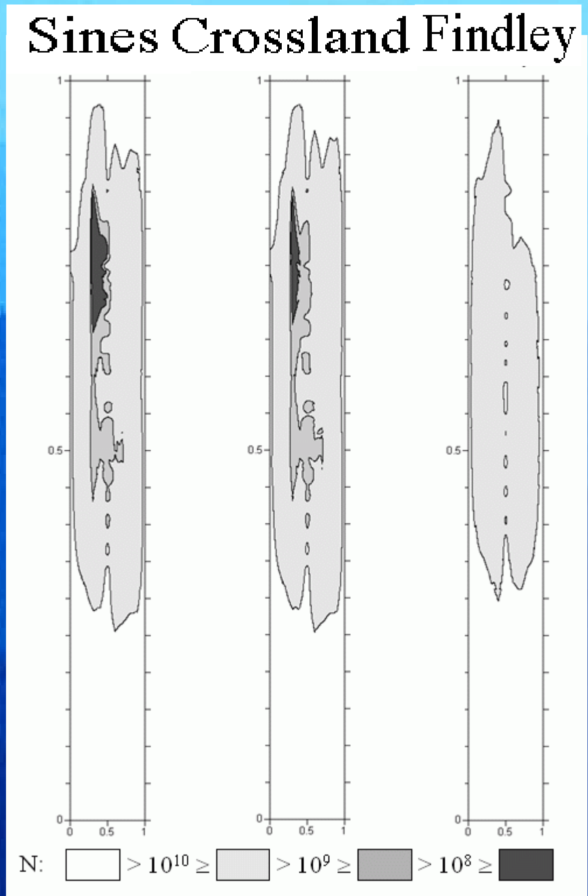
(bimodal distribution of fatigue durability)





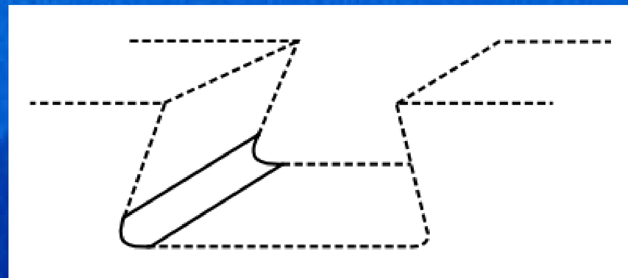
Titanium alloy Ti-6Al-4V

DURABILITY ESTIMATIONS FOR COMPRESSOR DISK



Very-high-cycle fatigue fracture

(influence of vibration loads)



Number of cycles for fracture $10^9 - 10^{10}$ ~ 50000 hours

Conclusions

The procedure of structure elements durability estimation for two alternative LCF (flight cycles) and VHCF (vibrations) fatigue mechanisms is developed.

The comparative study of durability estimation of the GTE compressor disk-blade contact structure is performed on the basis of multiaxial fatigue models.

Obtained results indicate very close durability estimations for LCF and VHCF with in-service time for titanium compressor disk one of the GTE.

Details

A.A. Shanyavskiy

Modeling of Metal Fatigue fracture. (Monograph, Ufa, Russia 2007)

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Models of Multiaxial Fatigue Fracture and Service Life Estimation of Structural Elements.

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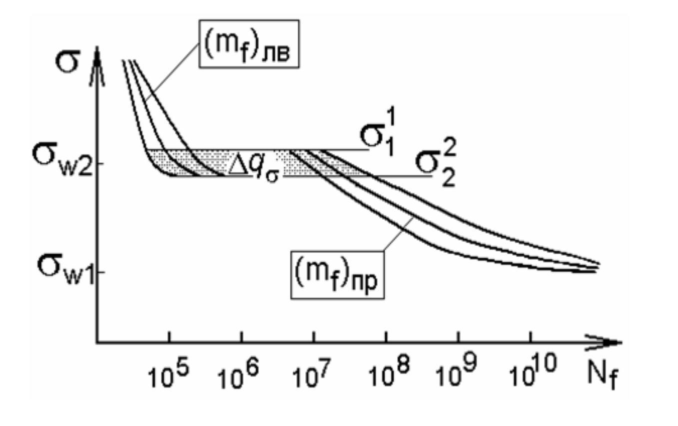
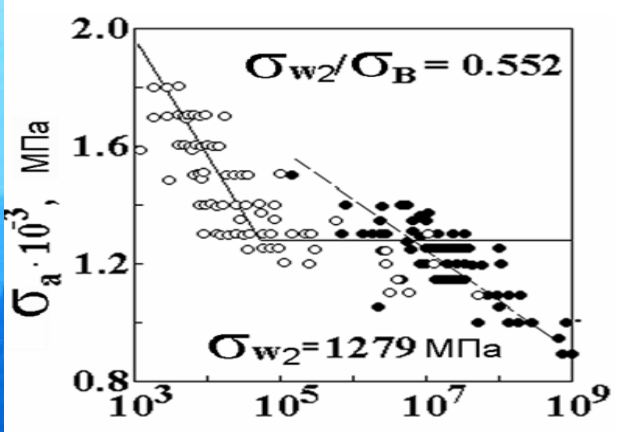
Thank you !

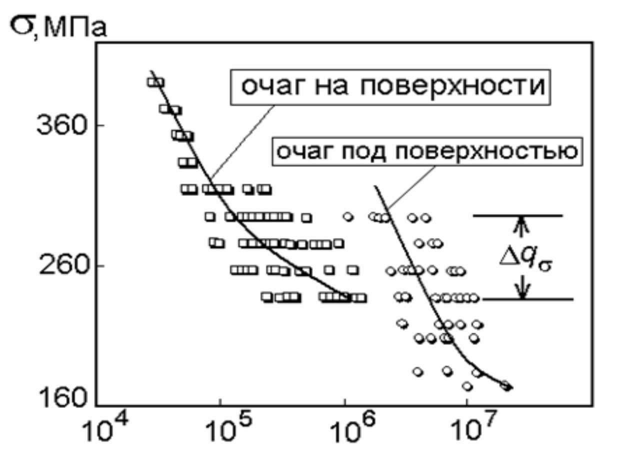
Very-high-cycle fatigue fracture

(bimodal distribution of fatigue durability)

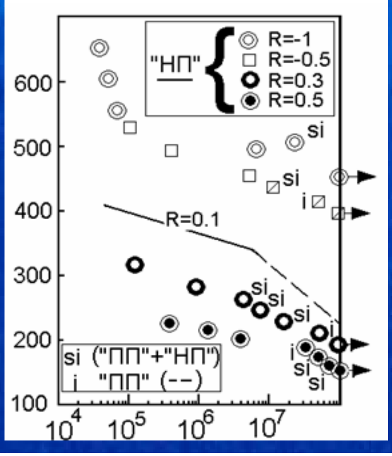




Aluminium alloy 2024-T3



Steel SUJ2



Titanium alloy Ti-6Al-4V