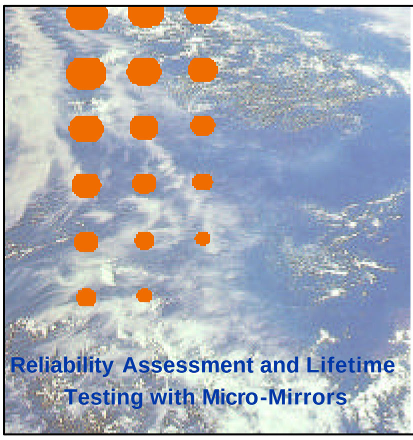


Reliability Assessment and Lifetime Testing with Micro-Mirrors

Fraunhofer Institut Photonische Mikrosysteme

NEULAND

ESA´s 4th Round Table on Micro/Nano-Technologies for Space

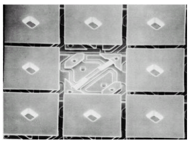
20-22 May 2003 ESTEC

CONTENTS

1. Introduction

Why micro-mirrors?

Micro Mirrors are already used commercially in TV projection systems and in beamers (e.g. Texas Instrument´s DLPTM technology). MMAs are attractive for active and integrated optics because they provide high spatial resolution, fill factors beyond 85%, pixel sizes ranging from 13 to ~ 300 µm and switching times in the order of microseconds. Besides MMAs 1-D and 2-D micro-scan mirrors are available off-the-shelf and may find applications in special areas of active optics.



Micro-mirrors are very well suited for reliability and lifetime modelling and testing because they include all essential MOEMS features: µ-optics, µ-electronics, and µ mechanics.

2. Reliability Aspects

2.1 Definitions: "Reliability" & "Failure Probability"

Reliability is understood as the probability that an item will perform its task for a certain amount of time, where T is the time to failure.

F(t) P{T ≤ t}
R(T) P{T > t}
R(T) = 1 – F(t)

F(t) = the probability that an item fails in [0,t] i.e. F( ) = 1, F(0) = 0
R(t) = the probability that an item survives until t

Probability of Failure

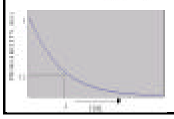
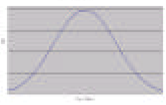
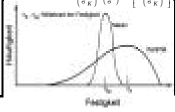
P{a} = the probability that the failure will occur
P{T (t < T < t+Δt) | T > t}
= the probability that a system fails in the interval (t, t+Δt)

Failure Rate

$$f(t) = \lim \frac{P\{t < T \le t + \Delta t | T > t\}}{\Delta t}$$

2. Reliability Aspects

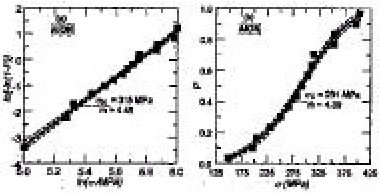
2.2 Probability of Failure – Failure Rate

a) Uniform Distribution	b) Lognormal Distribution	c) Weibull Distribution
For a system with multiple components with distinct MTTF and λ_i, it is often only possible to model the entire system as having a combined failure rate $\lambda_c = \sum_{i=1}^{n} \lambda_i$ This leads to the well know exponential probability function of $P(t) = \exp(-\lambda_c t)$ $f(t) = \lambda_c e^{-\lambda_c t}$	The logarithm of many failure times are found to be normally distributed. This has been termed a „lognormal distribution“. The physical justification for the lognormal model is that thermally activated systems will have a failure rate that is determined by the Arrhenius relation: $f(t) = \frac{1}{t\sigma\sqrt{2\pi}} e^{-\left(\frac{\ln(t-t_0)}{\sqrt{2}\sigma}\right)^2}$	Brittle solids have unpredictable behaviour under stress. Many components will fail at stresses much below and much above the average strength. Weibull Statistics is based on the probability of failure of a chain at its weakest point (*weakest link model).* $P(\sigma) = 1 - \exp[-(\sigma/\sigma_K)^m]$
		$f(\sigma) = dP(\sigma)/d\sigma = \left(\frac{\sigma}{\sigma_K}\right)^m \left(\frac{m}{\sigma}\right) \exp\left[-\left(\frac{\sigma}{\sigma_K}\right)^m\right]$ 

2. Reliability Aspects

2.3 Application of Weibull Statistics to Fracture Toughness of Optical Materials

$\ln[-\ln(1-P)] = -m\ln(\sigma_N) + \ln(\sigma)$ $\qquad P(\sigma) = 1 - \exp[-(\sigma/\sigma_N)^m]$



Opt. Eng., Vol. **41**, (Dec. 2002), pp. 3151-60

s_N = nominal strength, m = Weibull parameter

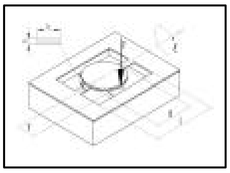
3. MOEMS Failure Mechanisms

The potential failure mechanisms for micro-mirror elements:

1. hinge fracture by overstress
2. hinge fracture by fatigue (as a result of routine operation)
3. hinge wear out – hinge memory
4. mirrors or hinge fracture as a result of vibration or shock
5. mirror sticking
6. delamination of layers
7. lifetime limitations due to high or low temperature
8. lifetime limitation due to ionising radiation (primarily CMOS)
9. packaging

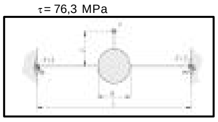
4. Failure Modelling

4.1 Neuland-ID´s Stress Calculation for 1-D Scan Mirror

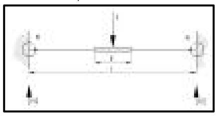


Deflection angle Äî
Äî = 7°
Dimensions of the torsion bars
b = 6,4 µm
h = 30,0 µm
(l-d)/2 = 518,8 µm
Material data for Si
E = 130 GPa
µ = 0,28

a) Shearing stress by torsion
τ = 76,3 MPa



b) Axial stress by bending
σ = 89,1 MPa



4. Failure Modelling

4.2 FhG-IPMS Finite Element Stress Calculation

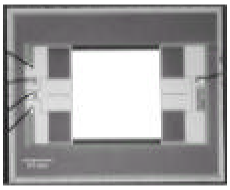


Foto of 1-D Scan Mirror by FhG -IPMS

- Torsion beams: L x B x H: 518.8 µm x 6.4 µm x 30 µm
- SOI material (handle & device layer): 100% Silicon
- Angular deflection: +/- 7 deg with 23 supply voltage
- Torsion stress: 117 MPa (calculated by FhG -IPMS using FEA)

5. Previous Reliability and Lifetime Tests

5.1 FhG-IPMS

Mirror with specially designed torsion bands were manufactured to allow testing at enhanced torsion stress:

- torsion band length: 150 µm
- calculated maximal stress: 756 MPa (at mechanical deflection of 16.9°)
- number of cycles: 1.6 x 10^9

Result:

No damage or fatigue was observed.

Conclusion:

Larger deflection angles will be necessary to determine the maximum allowable load.

5. Previous Reliability and Lifetime Tests

5.2 Texas Instruments DMD Test Results

Four mirror arrays (640 x 480 elements) were tested at 10 times the nominal frequency for 19.000 hours.

Result:

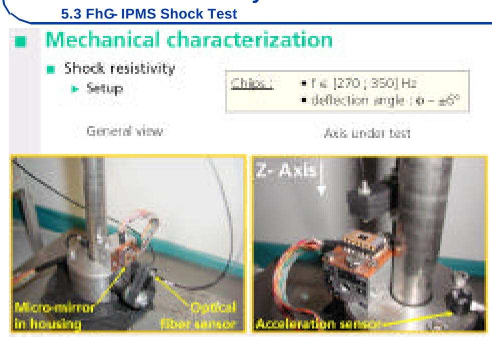
Each mirror has exceeded 1.7 x 10^{12} cycles with no evidence of hinge fatigue. One device had one added defect.

Conclusion:

Each DMD has 307.200 functional mirrors and each mirror switched more than 1.7 x 10^{12} times, the test has demonstrated more than 2 x 10^{18} total micro-mirror movements with only one added micro-mirror defect.

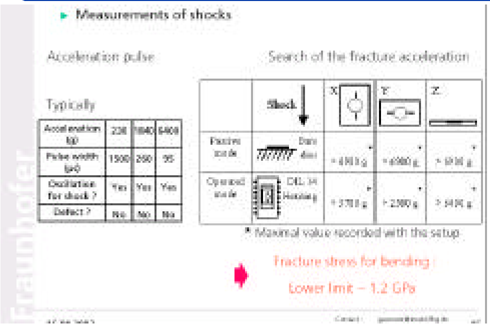
5. Previous Reliability and Lifetime Tests

5.3 FhG- IPMS Shock Test



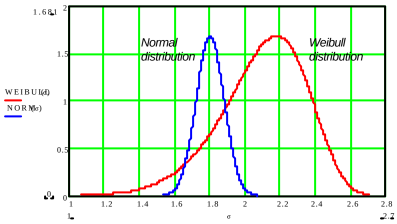
5. Previous Reliability and Lifetime Tests

5.3 FhG- IPMS Shock Test



6. Weibull Statistics and Reliability Testing

a)	Tensile strength of single crystal Si:	$\sigma = 3.79$ GPa
b)	Expected tensile strength for MEMS Si:	$\sigma = 2.2$ GPa
	Weibull modulus:	m = 10



Accumulated failure probability:

$P(0.1) = 3.764 \times 10^{-14}$

$P(0.2) = 3.855 \times 10^{-11}$

$P(0.5) = 3.677 \times 10^{-7}$

$P(1.0) = 3.764 \times 10^{-4}$

$P(1.5) = 0.021$

$P(2.2) = 0.632$

7. Weibull Statistics and Reliability Testing

Conclusion:

Meaningful reliability testing of micro-mirrors either

a) with ***large numbers***,
i.e. < 10^{12} at nominal operation conditions

or

b) with ***enhanced stress***
close to fracture limit

Large numbers are not practicable, therefore enhanced stress must be applied.

Operational margins in general are not sufficient to produce sufficient enhanced stress. Special configurations must be manufactured.

A tight co-operation with MEMS manufacturer is mandatory.

8. Lifetime Testing, Test Acceleration

8.1 Necessity of Test Acceleration

Practical long-term reliability tests cannot be performed at operational conditions due to the excessively long tests that would be required. In order to achieve practical failure times during the reliability tests, the failure mechanisms of interest must be accelerated by some means. However, it is important that the conditions under which the test is performed are not excessive enough to excite additional failure mechanisms.

8.2 Acceleration by Increase of Frequency or Duty Cycle

The simplest way to accelerate lifetime tests is to operate the test item at higher rates or duty cycles than are encountered under normal operation.

In this way the TI DMD was verified to survive 1.7 x 10^{12} cycles at a 10 times higher switching rate.

8. Lifetime Testing, Test Acceleration

8.3 Acceleration by Change of Environmental Conditions

Accelerated testing of electronics is done at elevated temperature, because the failure statistics follows the lognornal distribution and obeys Arrhenius law.

Accelerating lifetime tests by changing the environmental conditions is significantly more difficult for MEMS. Since failure mechanisms are not well understood, there is no simple way of acceleration testing. Furthermore, the vast difference in types of MEMS devices means that each set of devices may require unique acceleration conditi ons.

9. Envisaged Micro-Mirror Test Campaign

1. Reliability Test - Enhanced Stress Test

Test on especially designed samples which allow enhanced stress, close to the expected fracture limit.

2. Fatigue Test – Life Test

Tests will be performed over a certain period with the samples working at their operational limits and at high duty cycles.

3. Environmental Tests

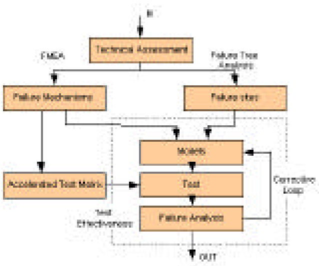
a) high and low temperature

b) vibration and shock

c) radiation

9. Envisaged Micro-Mirror Test Campaign

Strategy for „Test Effectiveness“



Closing the loop from ***test results***, and subsequent ***failure analysis*** to ***model update*** is very important to ensure benefit for future reliability and lifetime activities.