Fatigue and aircraft diagnostic systems

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Fatigue and aircraft diagnostic systems

https://www.meil.pw.edu.pl/add/ADD/Teaching/Subjects/Fatigue-and-Aircraft-Diagnostic-Systems

http://itlims-zsis.meil.pw.edu.pl/pomoce/MAT_LOT/ANS652_MR1.pdf

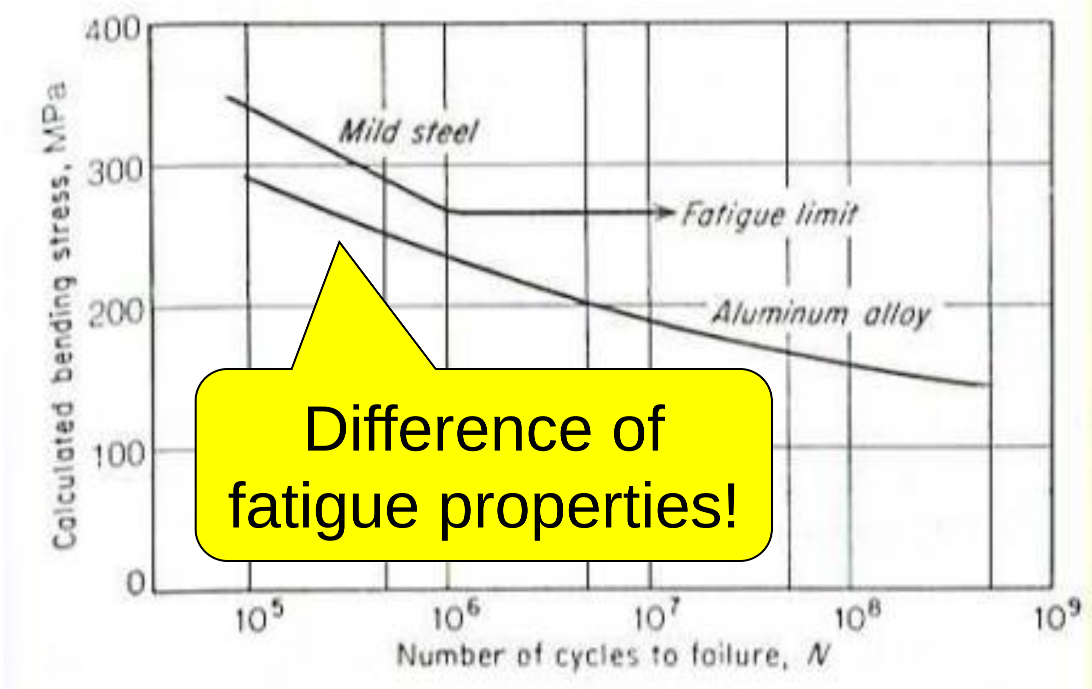
password: "fatig"

Factors causing fatigue failure

1) A maximum tensile stress of sufficiently high value.
2) A large ammount of variation or fluctuation in the apllied stresses
3) A sufficiently large number of cycles of the applied loads

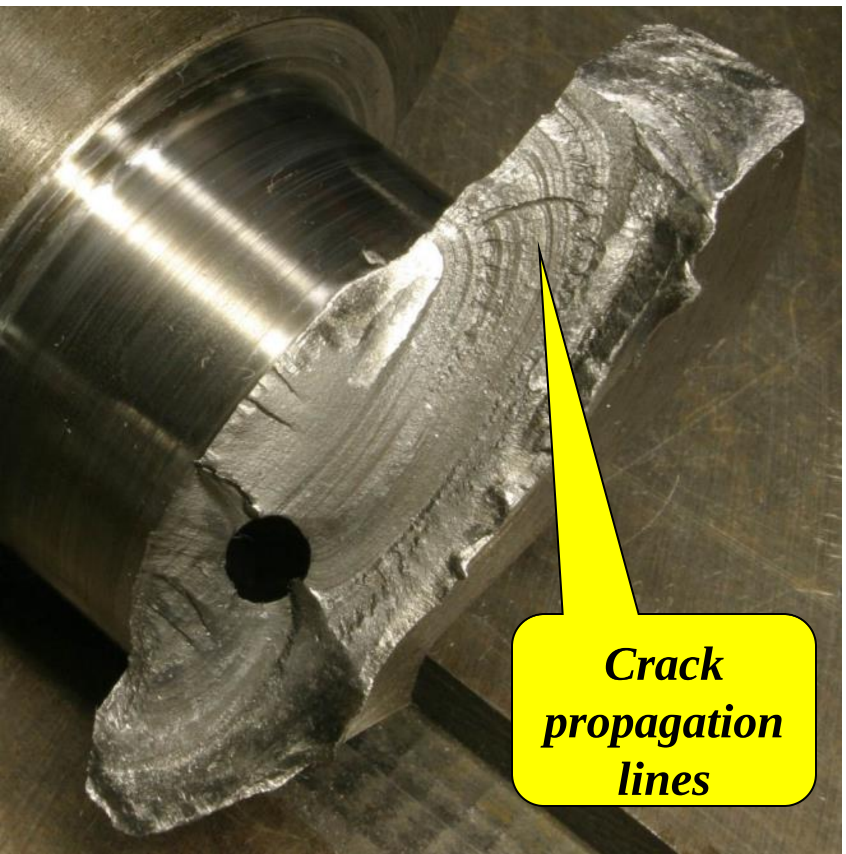
Other factors:

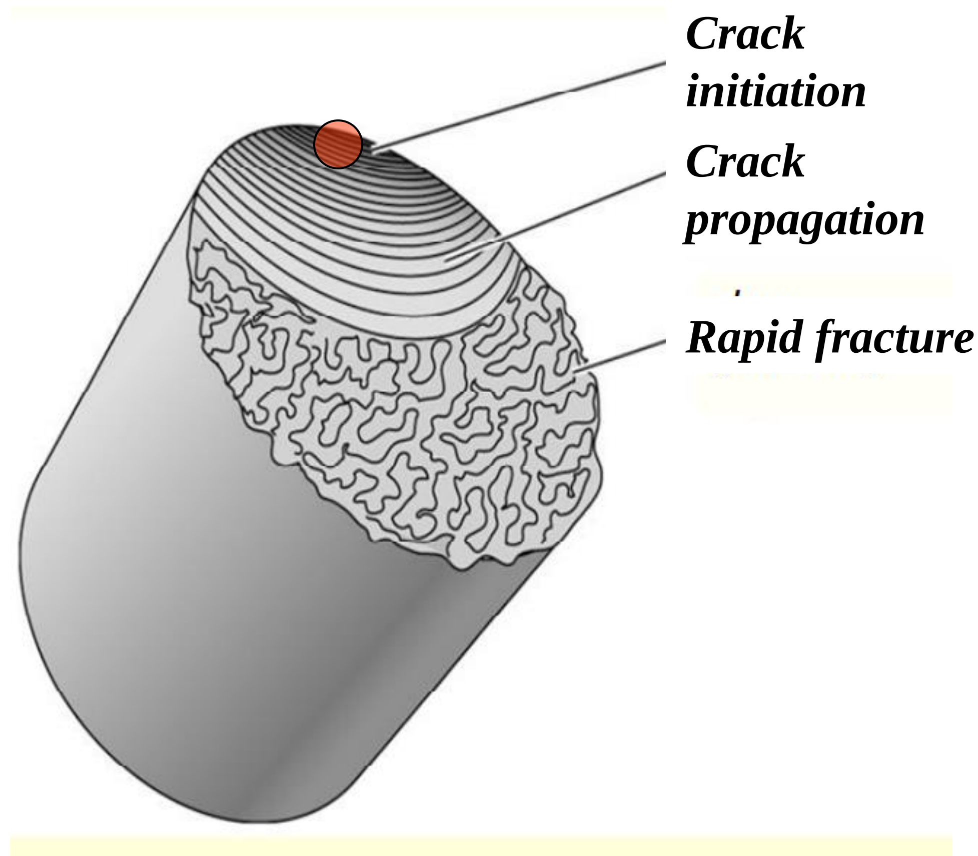
- •Stress concentration
- •Corrosion
- •Temperature
- •Overload
- •Metallurgical structure
- •Residual stress
- •Combined stress



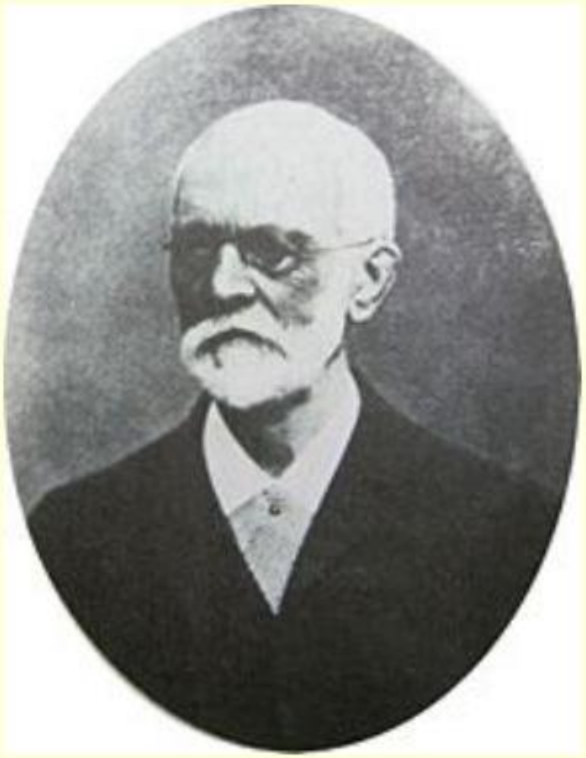
Introduction

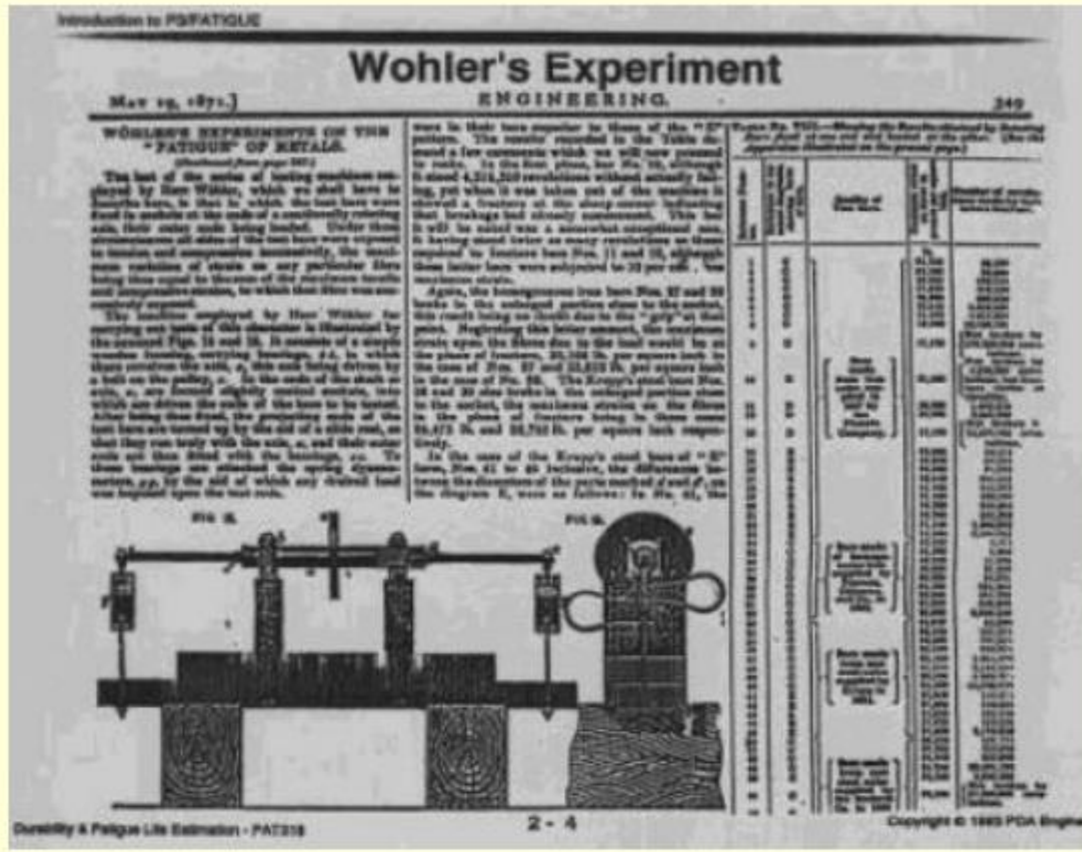
Fatigue phenomenon





Introduction

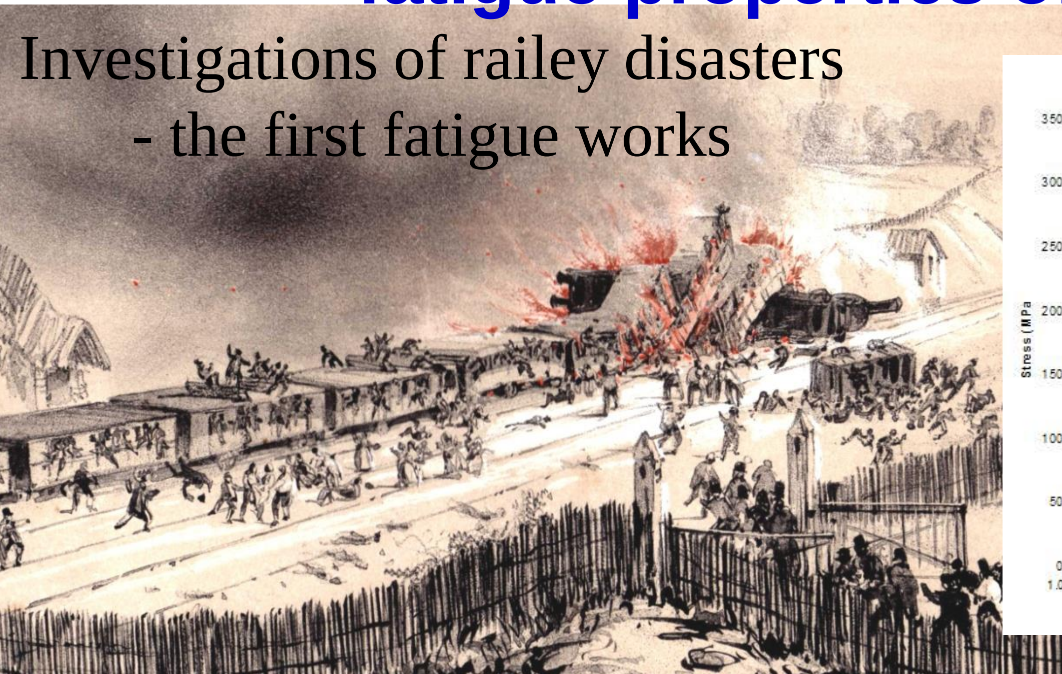


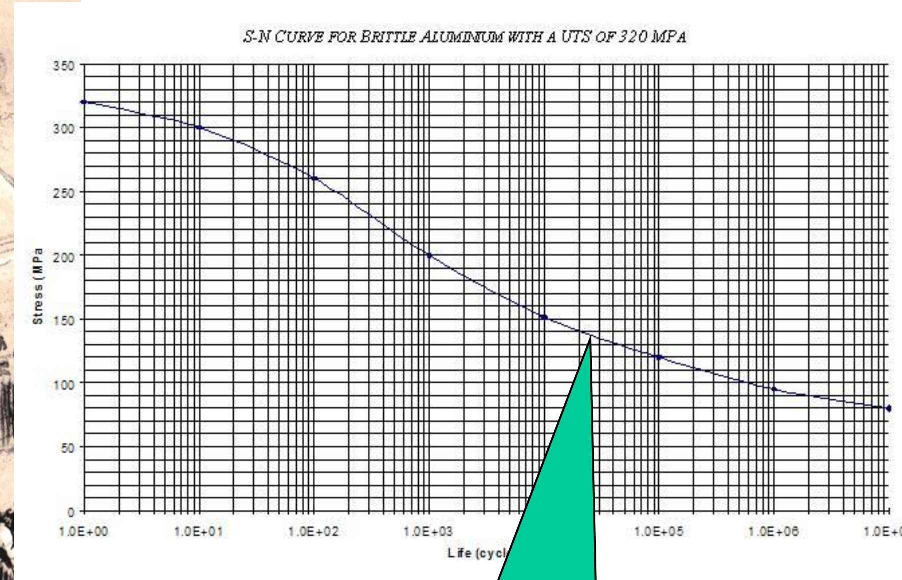


Early 20th Century
Begining of materials & design structures investigations regarding problem of fatigue

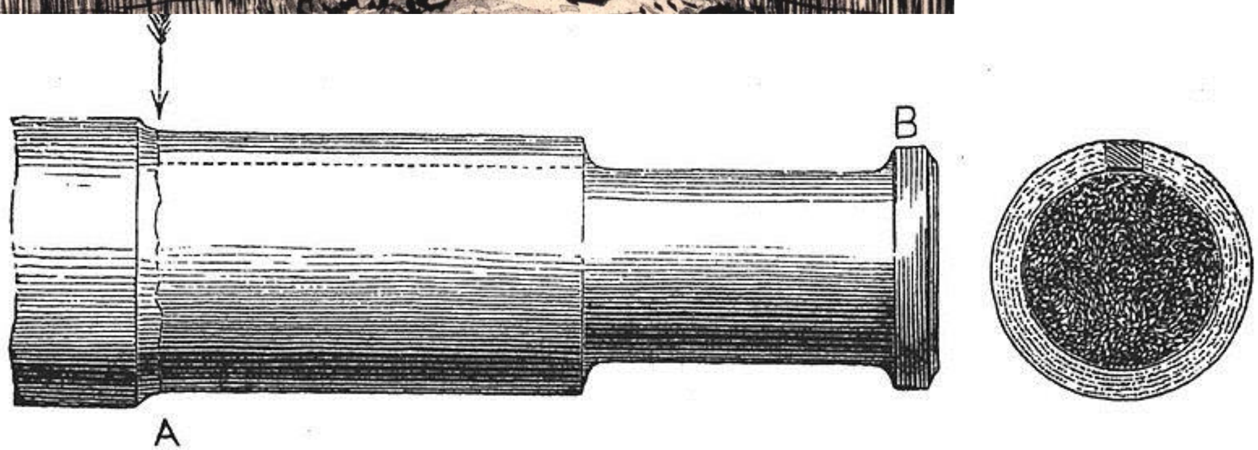
Industrial revolution - raise of interest regarding fatigue properties of the materials

Investigations of railey disasters
- the first fatigue works





Wöhler curve
(S-N curve)



Works of **August Wöhler** (22 June 1819 - 21 March 1914)

Aeronautics,1950s - impulse for considering fatigue as a crucial problem of technical safety

Series of catastrofic accidents of the first pasanger jet - raise of interest in subject of fatigue properties of the aeronautical structures

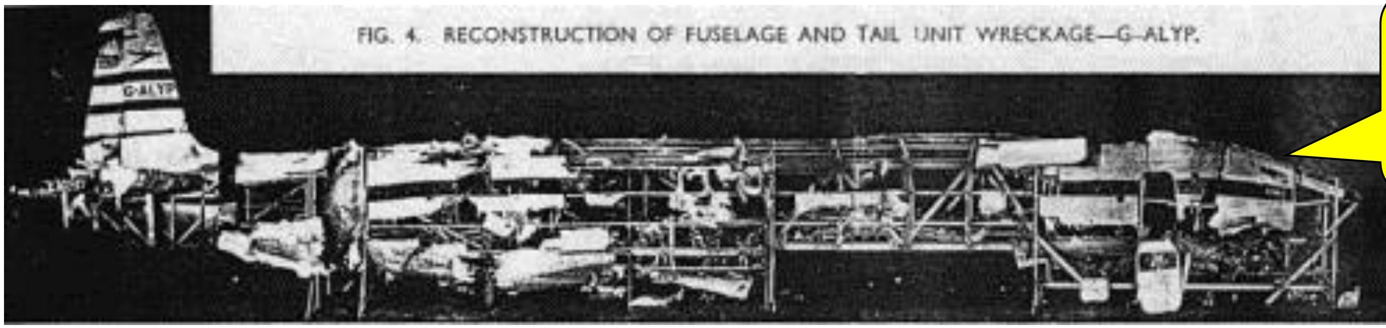
The **de Havilland Comet** was the world's first commercial jet airliner to reach production.[N 1] Developed and manufactured by de Havilland, it first flew in 1949 and was considered a landmark in British aeronautical design. After introduction into commercial service, the initial Comet versions suffered from catastrophic metal fatigue, causing two well-publicised accidents.

The Comet had to be withdrawn and was redesigned. The Comet 4 series subsequently enjoyed a long and productive career of over 30 years, although sales never fully recovered.

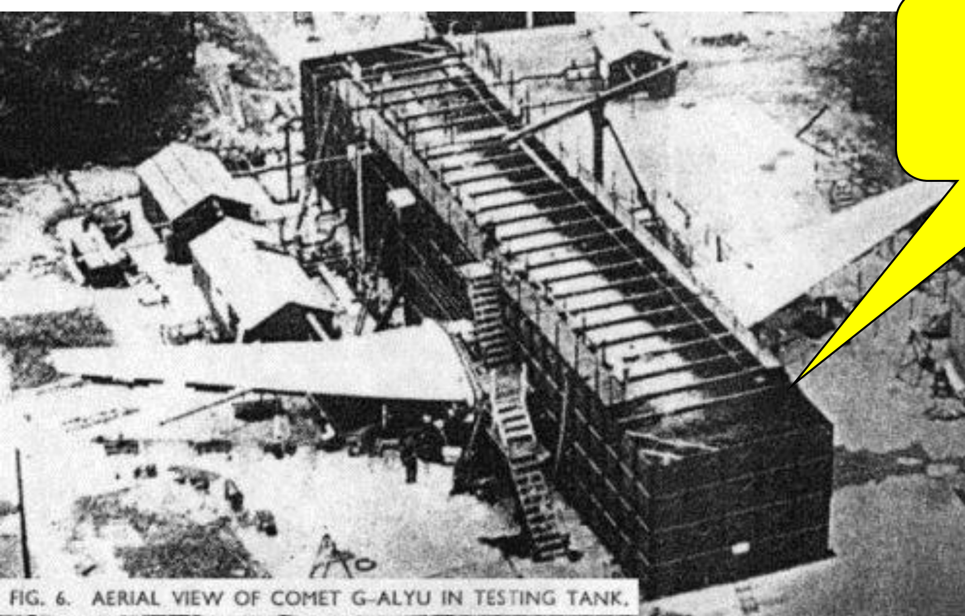
Accidents and incidents of the DH-106 COMET

- 26 October 1952: Comet 1 G-ALYZ of BOAC crashed on takeoff from Rome-Ciampino Airport, Italy
- 3 March 1953: Comet 1 CF-CUN of Canadian Pacific Airlines stalled on takeoff at Karachi, Pakistan
- 2 May 1953: Comet 1 G-ALYV of BOAC crashed at Calcutta, India
- 25 June 1953: Comet 1 F-BGSC of Union Aeromaritime de Transport skidded off a runway at Dakar, Senegal, damaged beyond repair
- 15 July 1953: A BOAC Comet landed at Juhu Aerodrome instead of Santacruz Airport, Bombay. The aircraft was flown out some nine days later
- 10 January 1954: Comet 1 G-ALYP of BOAC, operating Flight 781, crashed into the sea south of Elba, Italy
- 8 April 1954: Comet 1 G-ALYY of BOAC, operating a charter as South African Airways Flight 201, crashed into the sea north of Stromboli, Italy
- 13 September 1957: Comet 2R XK663 of No. 192 Squadron RAF damaged beyond repair in a hangar fire

De Havilland DH-106 *Comet*

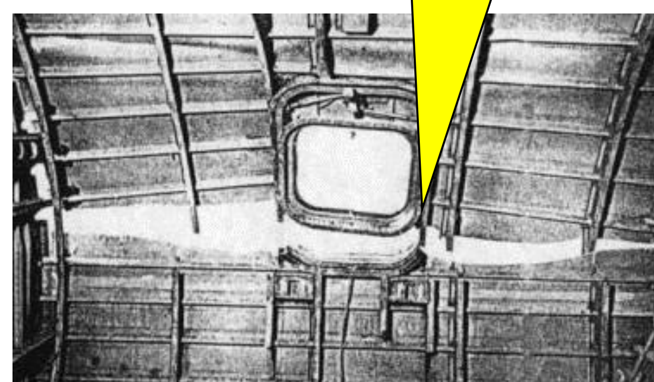


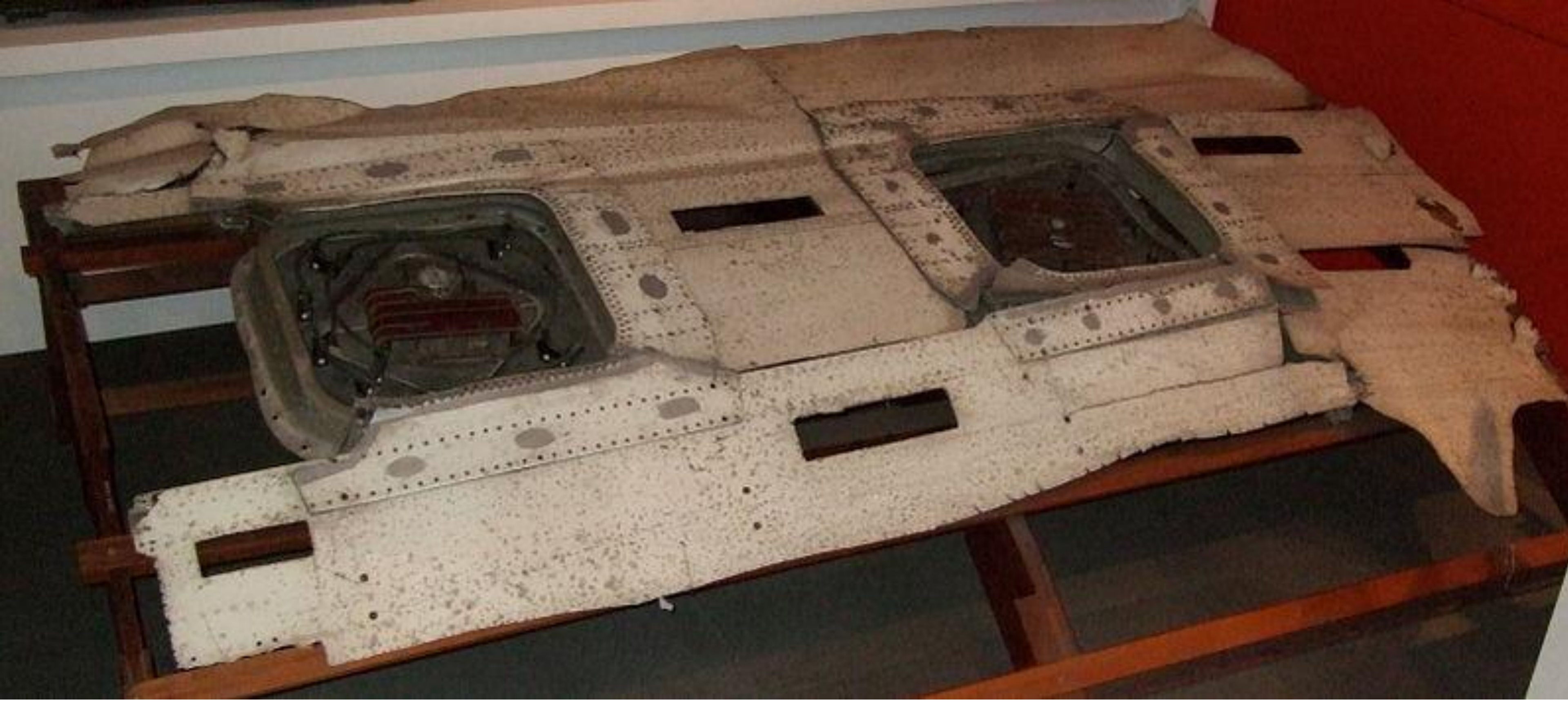
Investigations of the reasons



Fatigue tests

Fatigue damage !!!



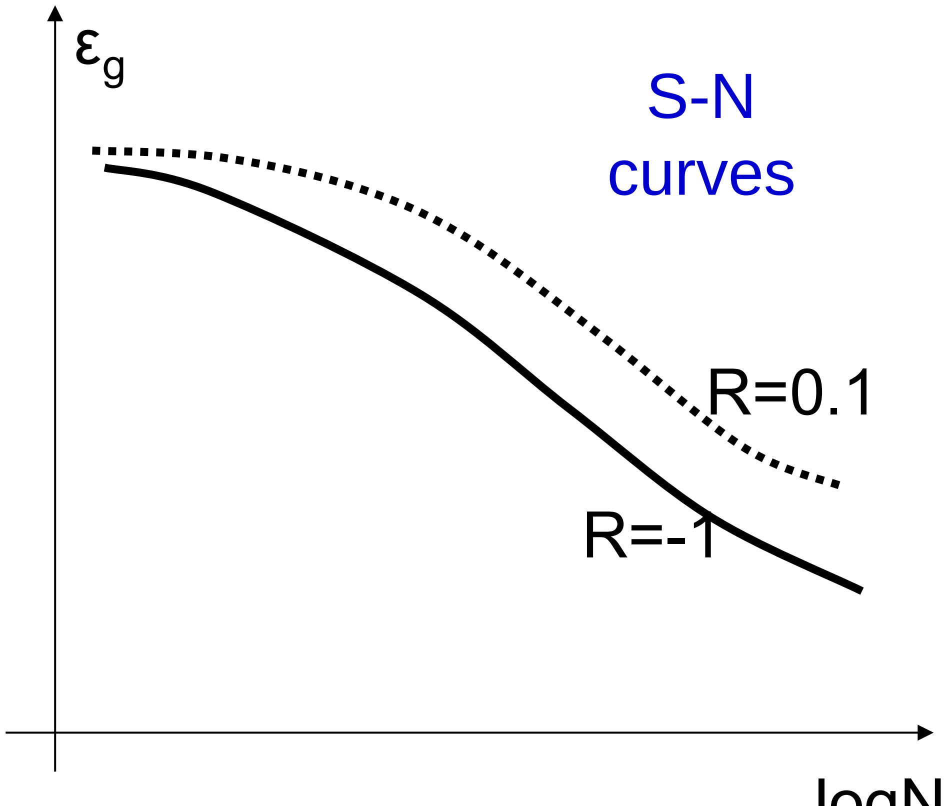


Fuselage of de Havilland Comet Airliner G-ALYP

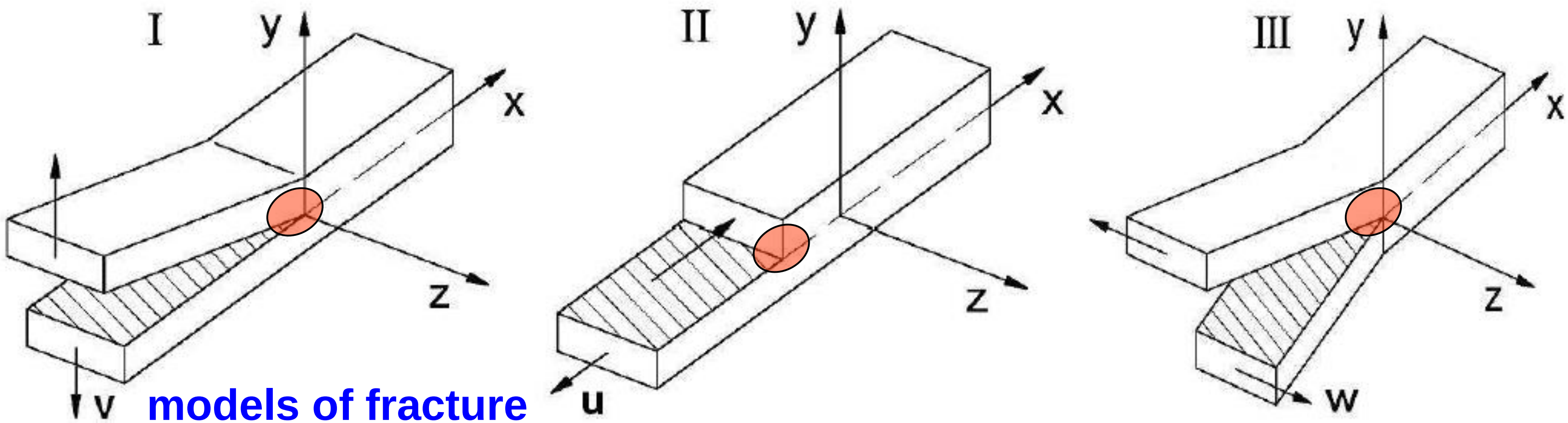
Method I – accumulation of fatigue damage

Oryginal Palmgren – Miner formula

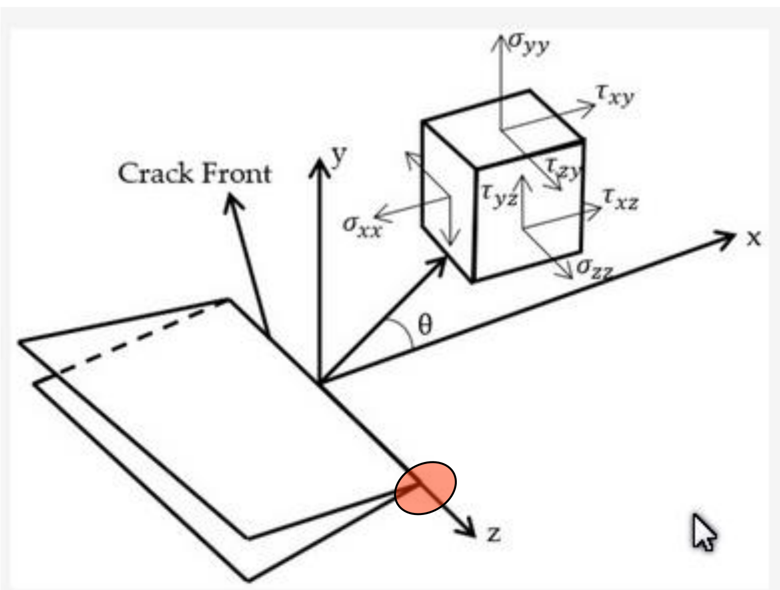
$$D = \sum_{i=1}^{l} \frac{n_i}{N_i} = 1$$



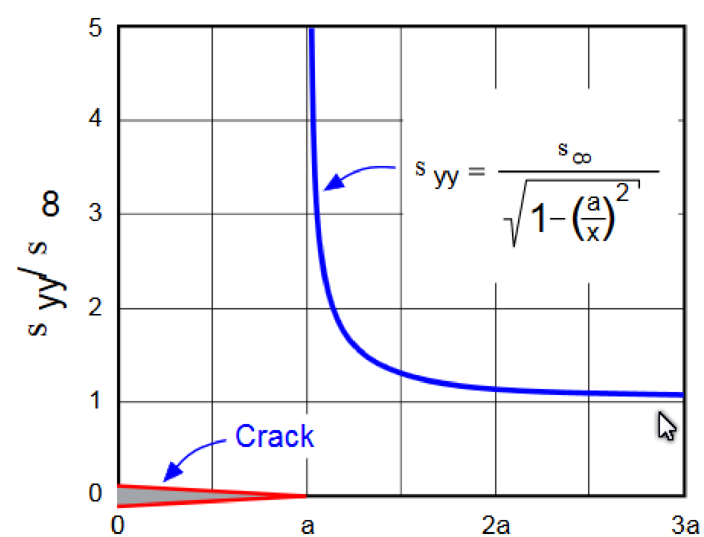
Method II – study of crack development – critical length of the crack, probability of detection



models of fracture



https://www.mdpi.com/1996-1944/12/7/1042



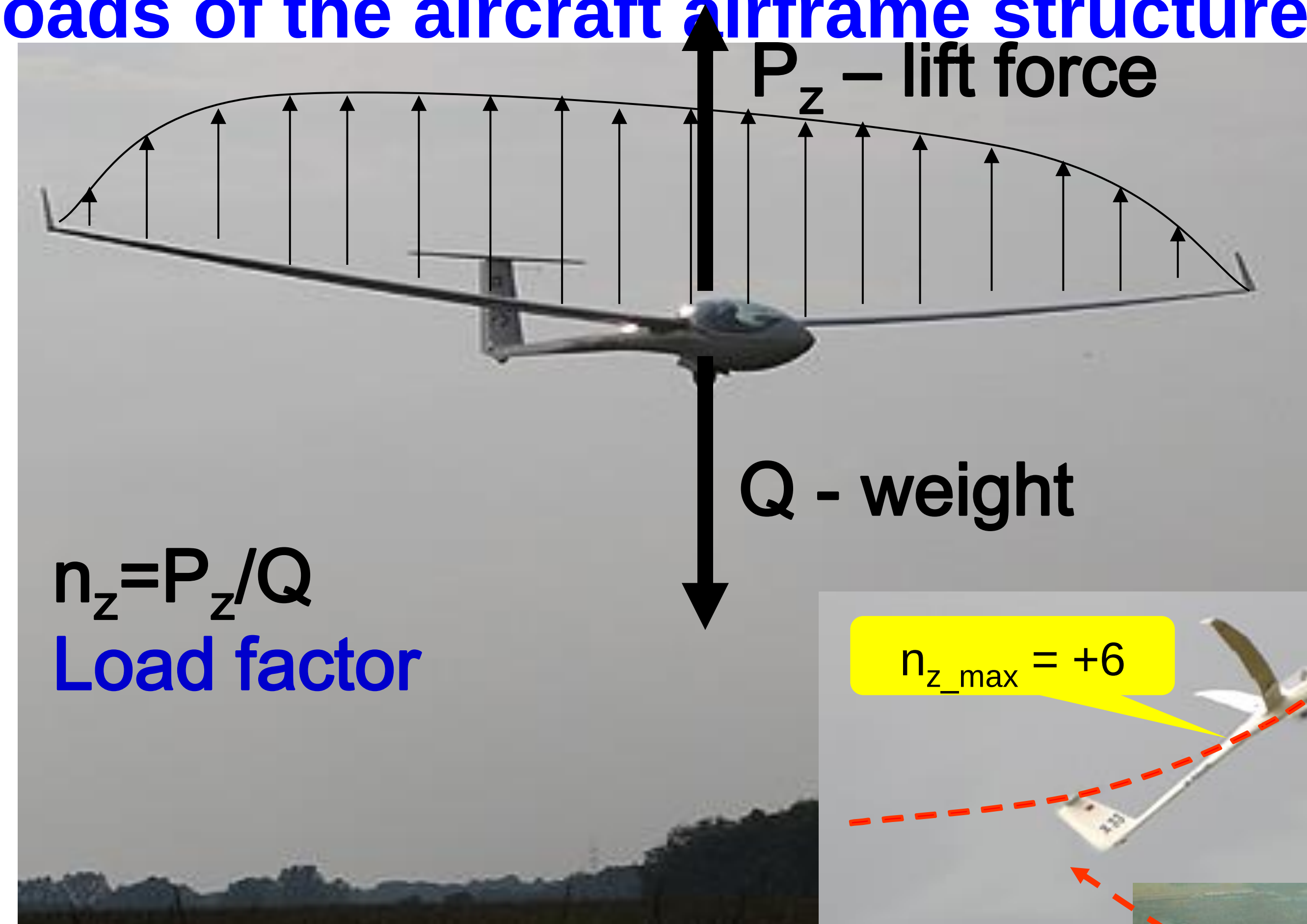
$$K = \sigma_\infty \sqrt{\pi a}$$

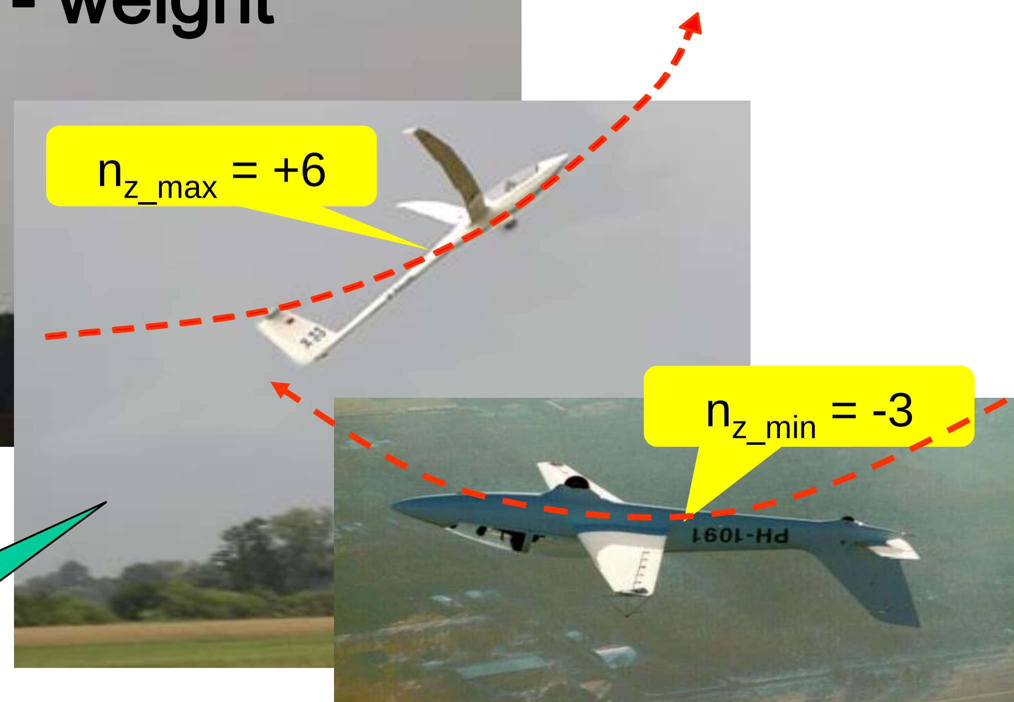
Stress Intensity Factor

https://www.fracturemechanics.org/sif.html

Introduced by George R Irwin, 1957

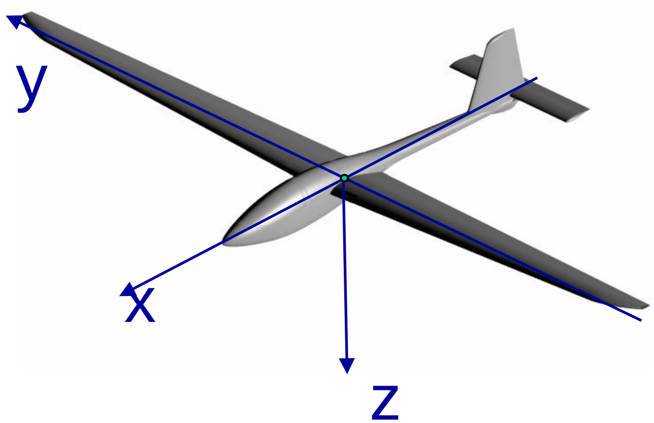
Loads of the aircraft airframe structure & Load Factor



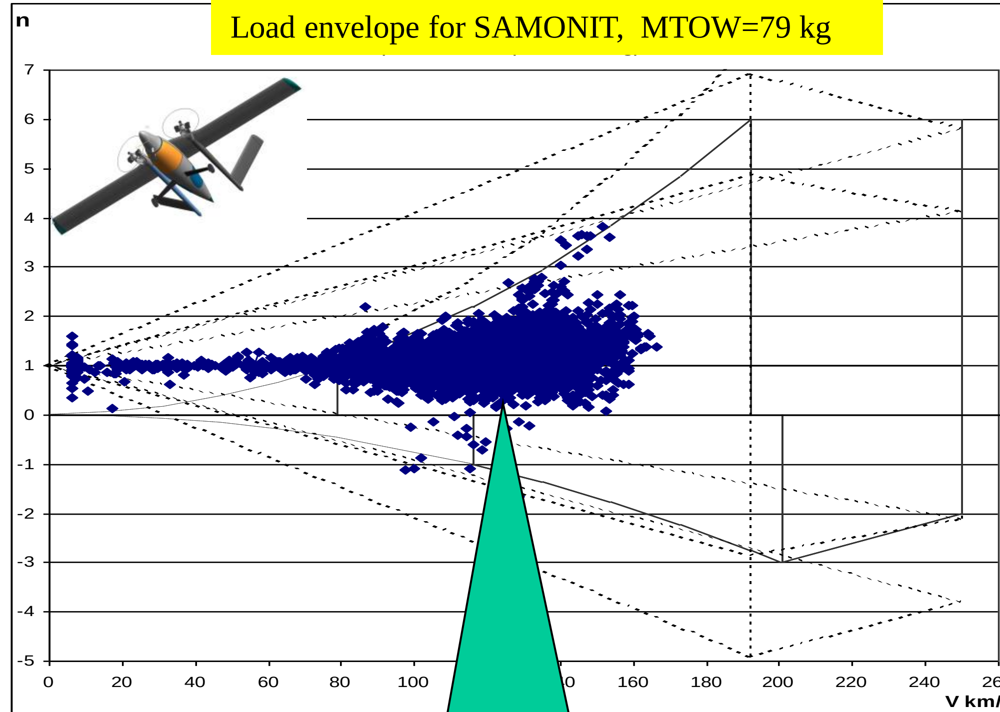


Design limit for load factor of the glider

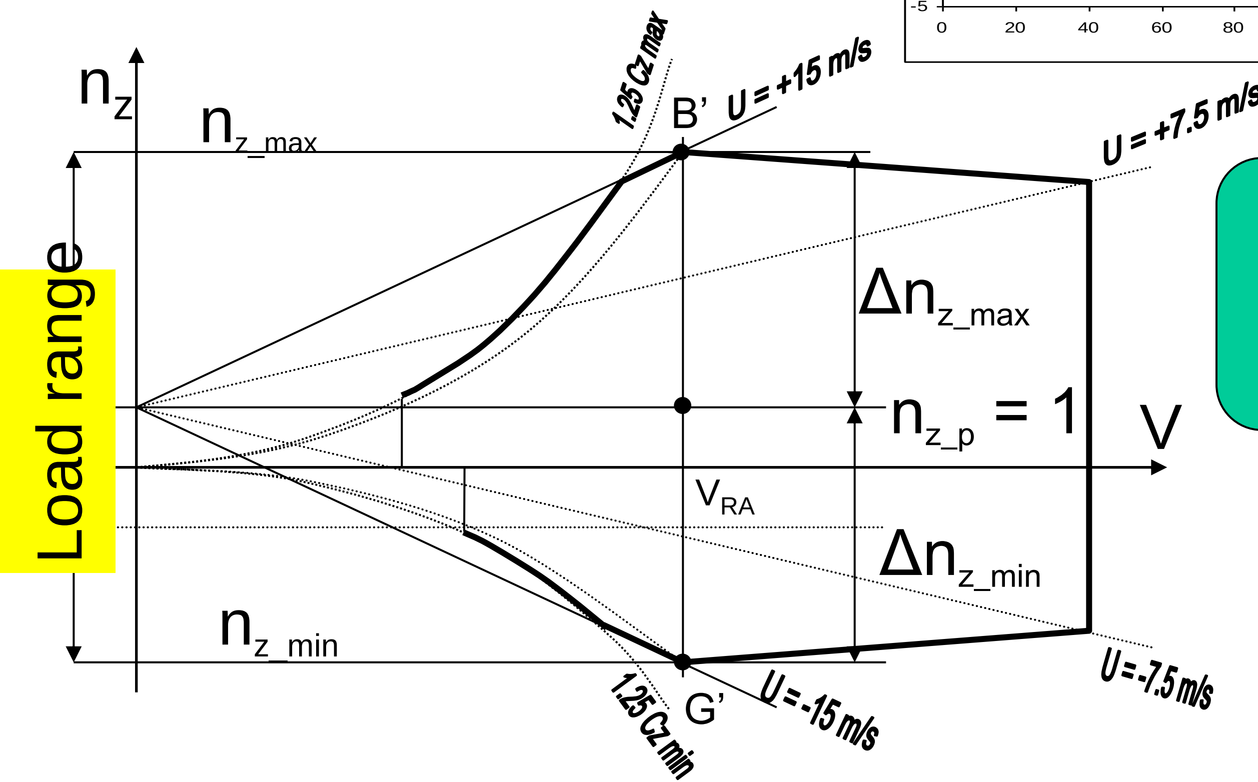
What force is acting on the wing ?



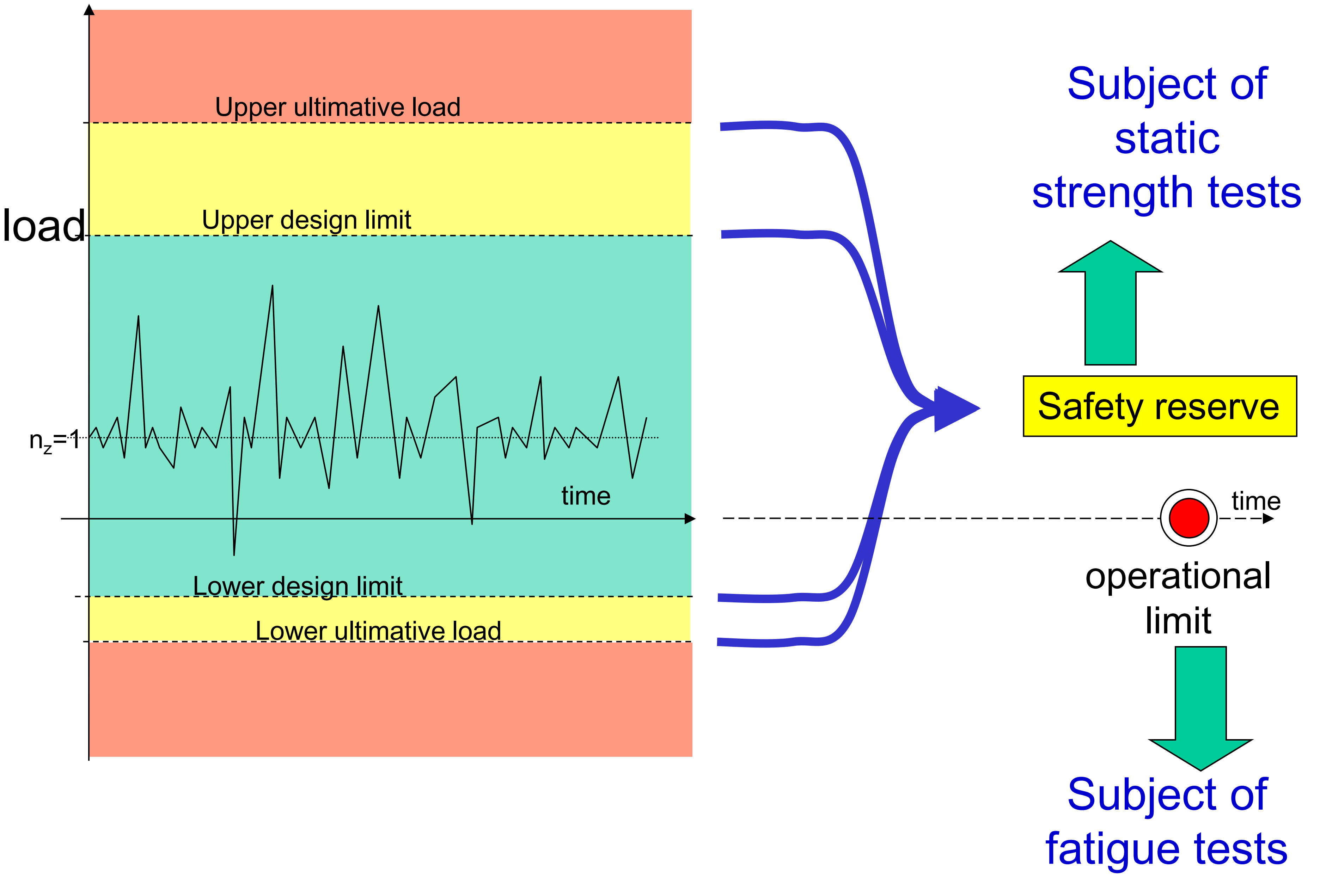
Aircraft load envelope



Evidence of loads recorded during flight-tests sesion

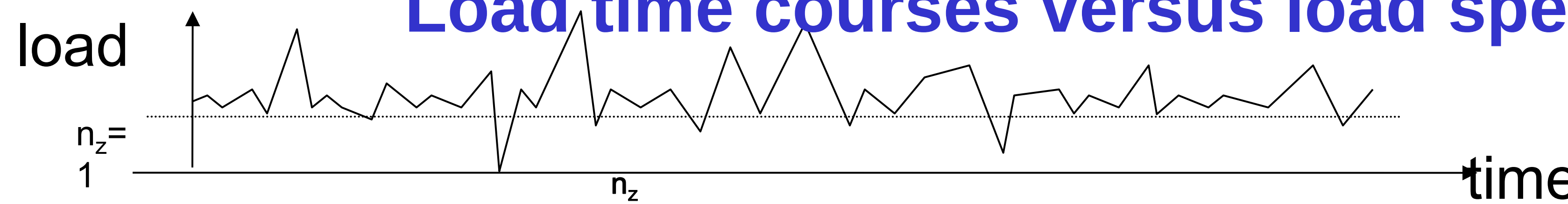


Glider loads - requirements for certification tests

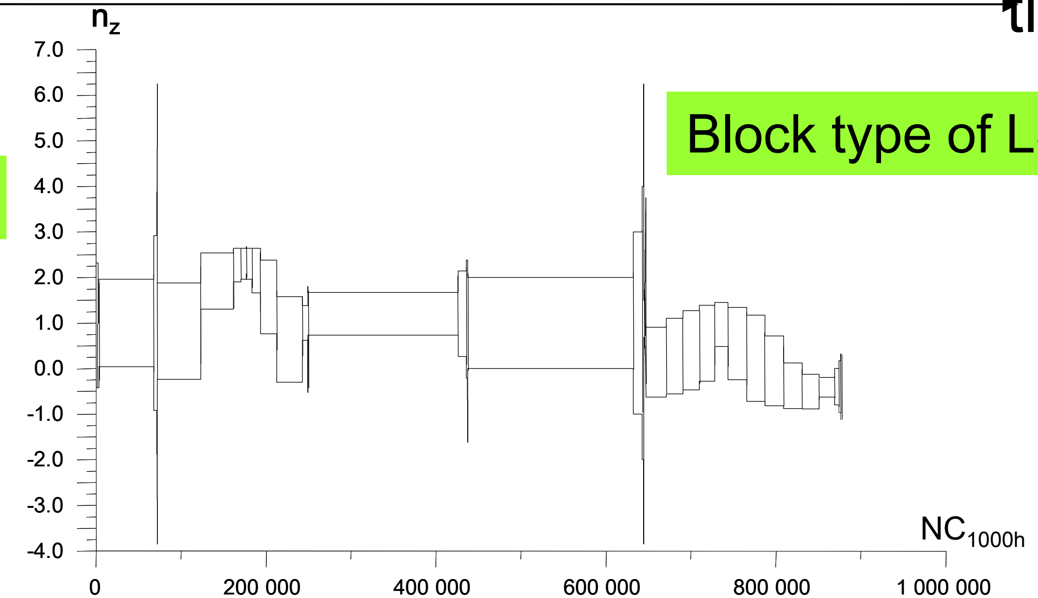


Load Spectra (LS)
LS as a statistics of load incremets apperances - methods of presentation

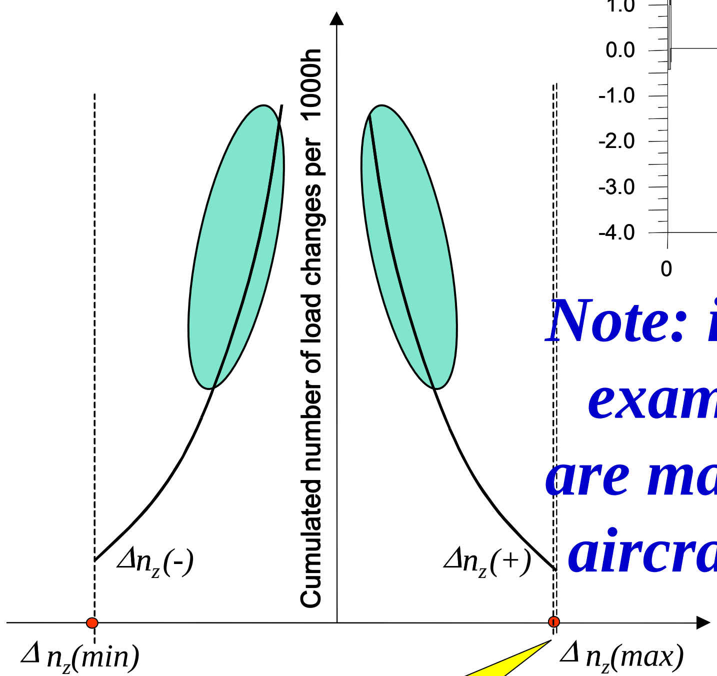
Load time courses versus load spectra



Block type of LS



Incremental type of LS



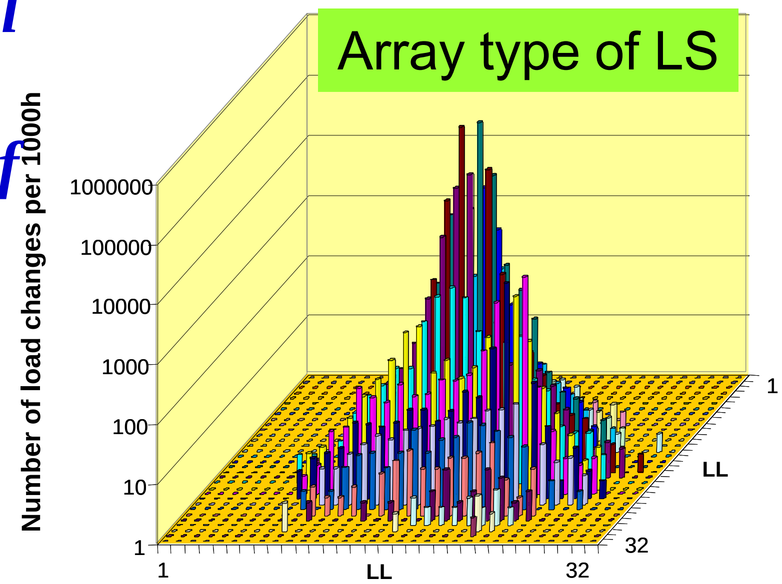
Extreme values according design limit

Note: in this figure all examples of the LS are made for 1000h of aircraft operation!!!

TM = 1000 h

Can be different for other types of aircrafts!

Array type of LS



How to prove the fatigue safety ???

Fatigue stand of the glider wing spar

$$TS = TP \cdot k_r = TM \cdot k_k \cdot k_r$$

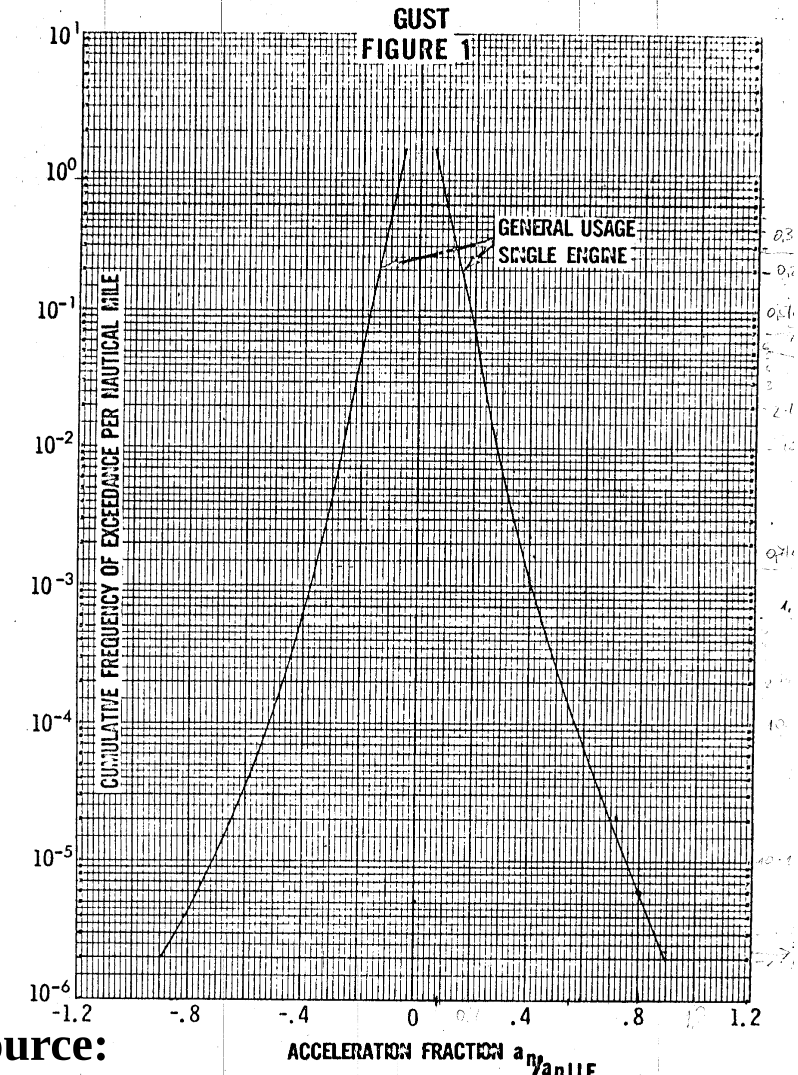
TS – operation period simulated on the fatigue stand as a proof of fatigue-safety

TP – postulated operation life

TM – time for which the LS was estimated (modelled period by load spectrum)

k_r scatter factor,

k_k ratio between modelled period by load spectrum and postulated operation life



Example of load spectra presentation

(classic way!)

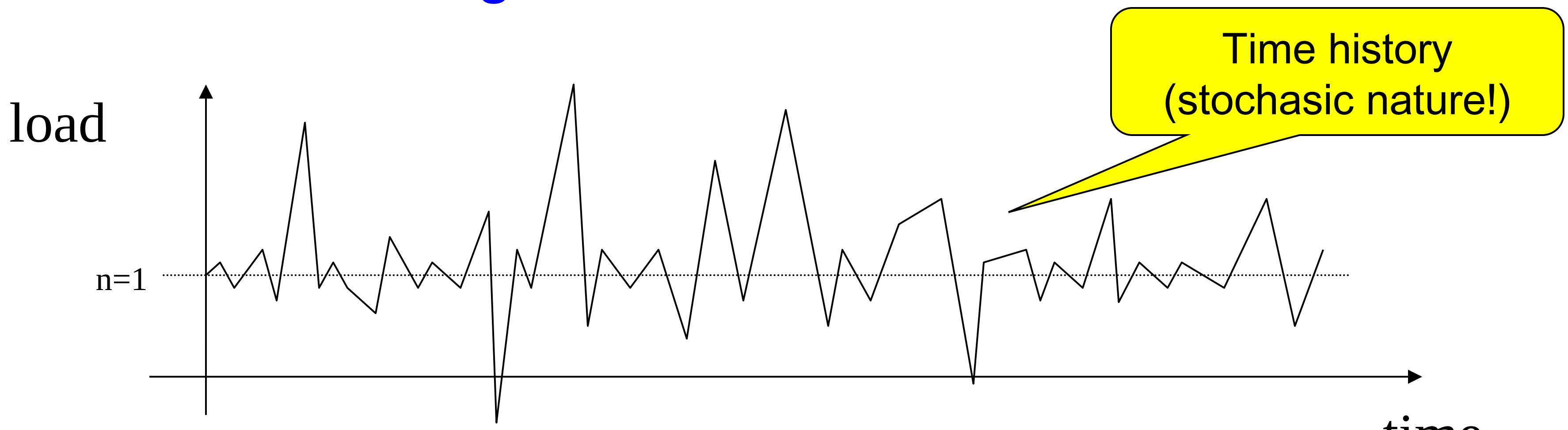
Source:

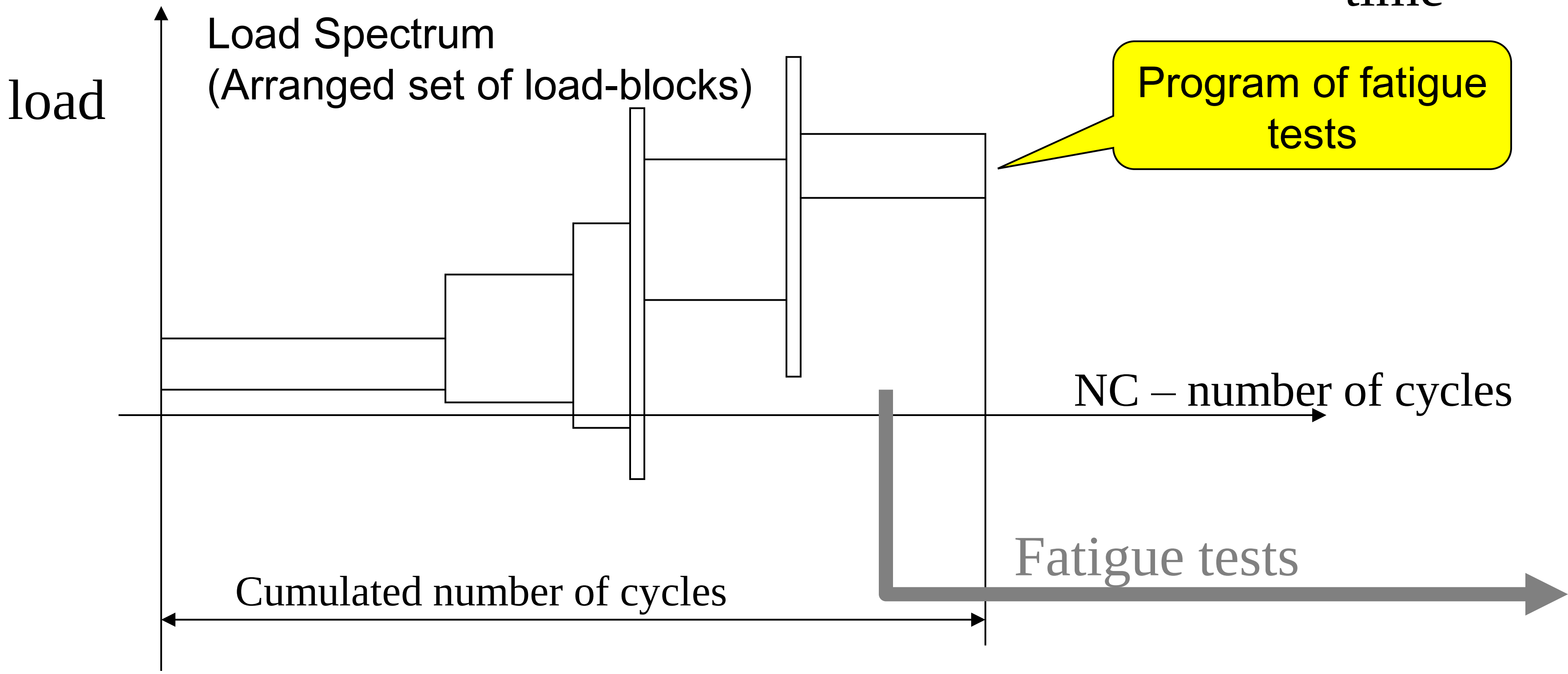
Engineering and Manufacturing Division Airframe Branch

Fatigue evaluation of wing and associated structure on small airplanes

Report No. AFS-120-73-2, sponsored by Department of Transportation, Federal Aviation Administration 1973

Loads acting on aircraft structure

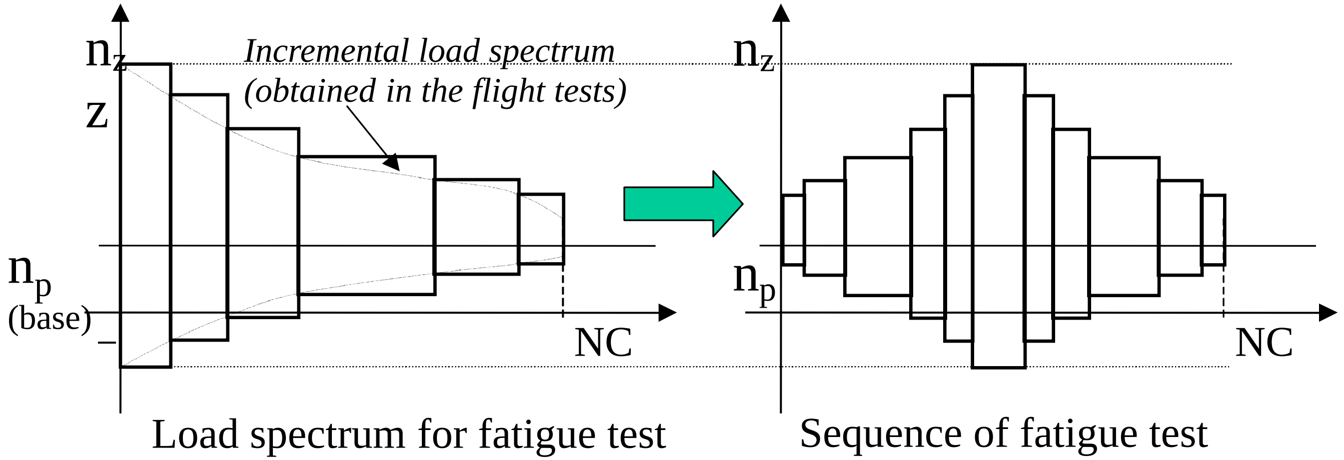




(In case of the glider NC= about 1 000 000 load cycles for 1000 flight hours)

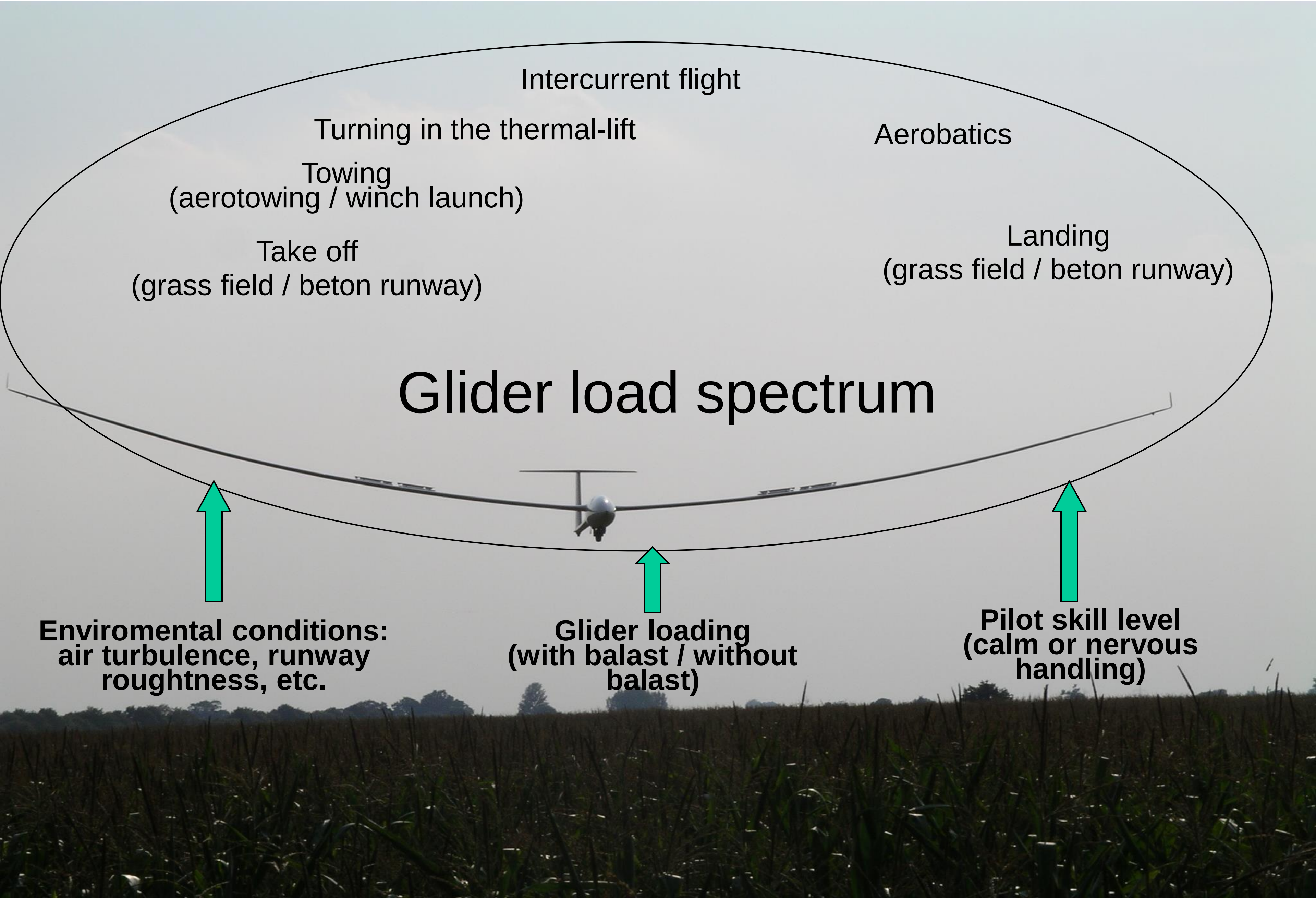
Can the set of the load-cycles arranged in the blocks substitute the real loads with they stochastic nature???

Is the damage caused by both loads realisation the same ???



The way of fatigue test program setting
(compensation of constant amplitude cycles fatigue effect)

Factors having influence on the Load Spectrum



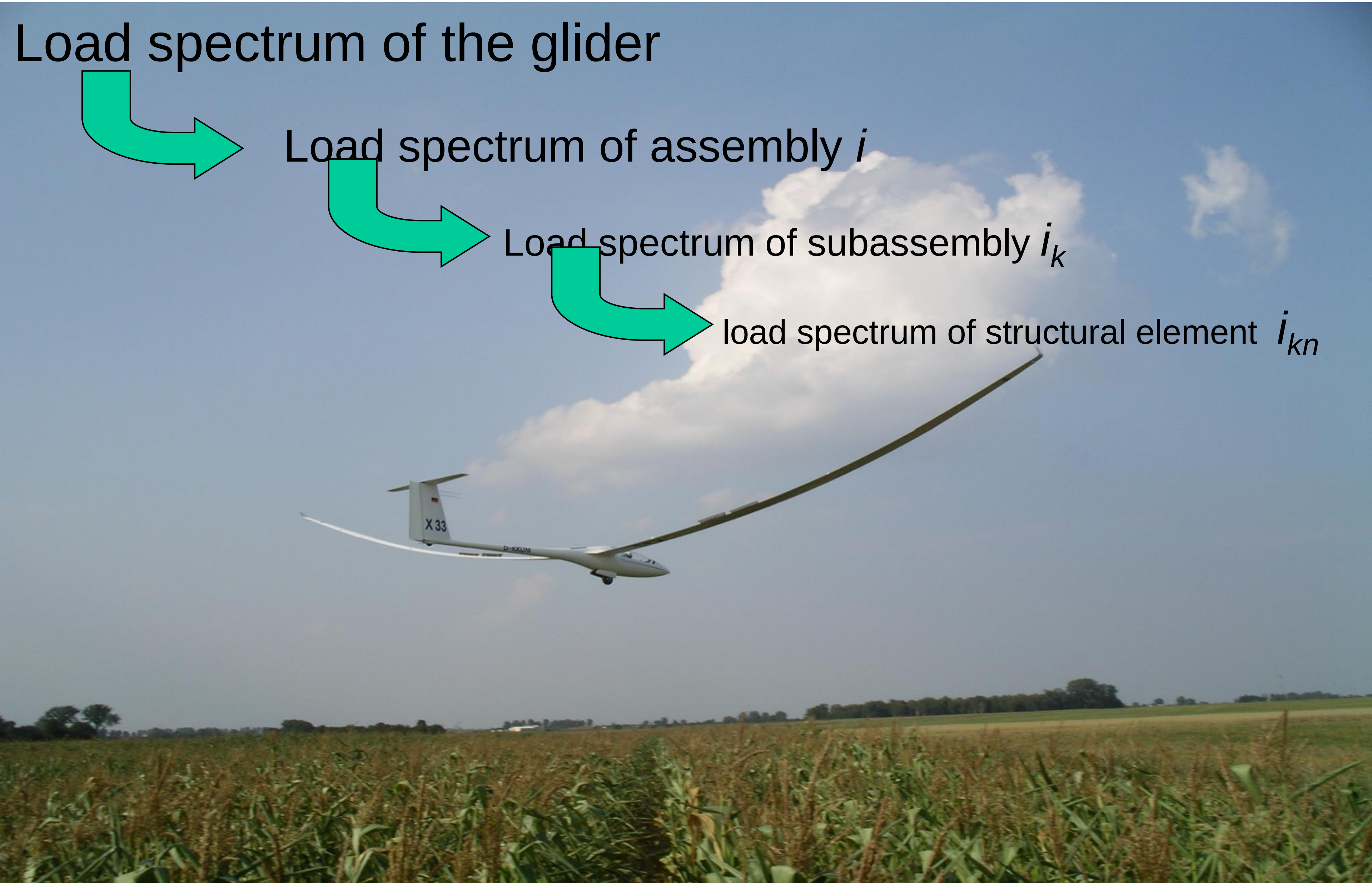
Load Spectrum and the aircraft stucture

Load spectrum of the glider

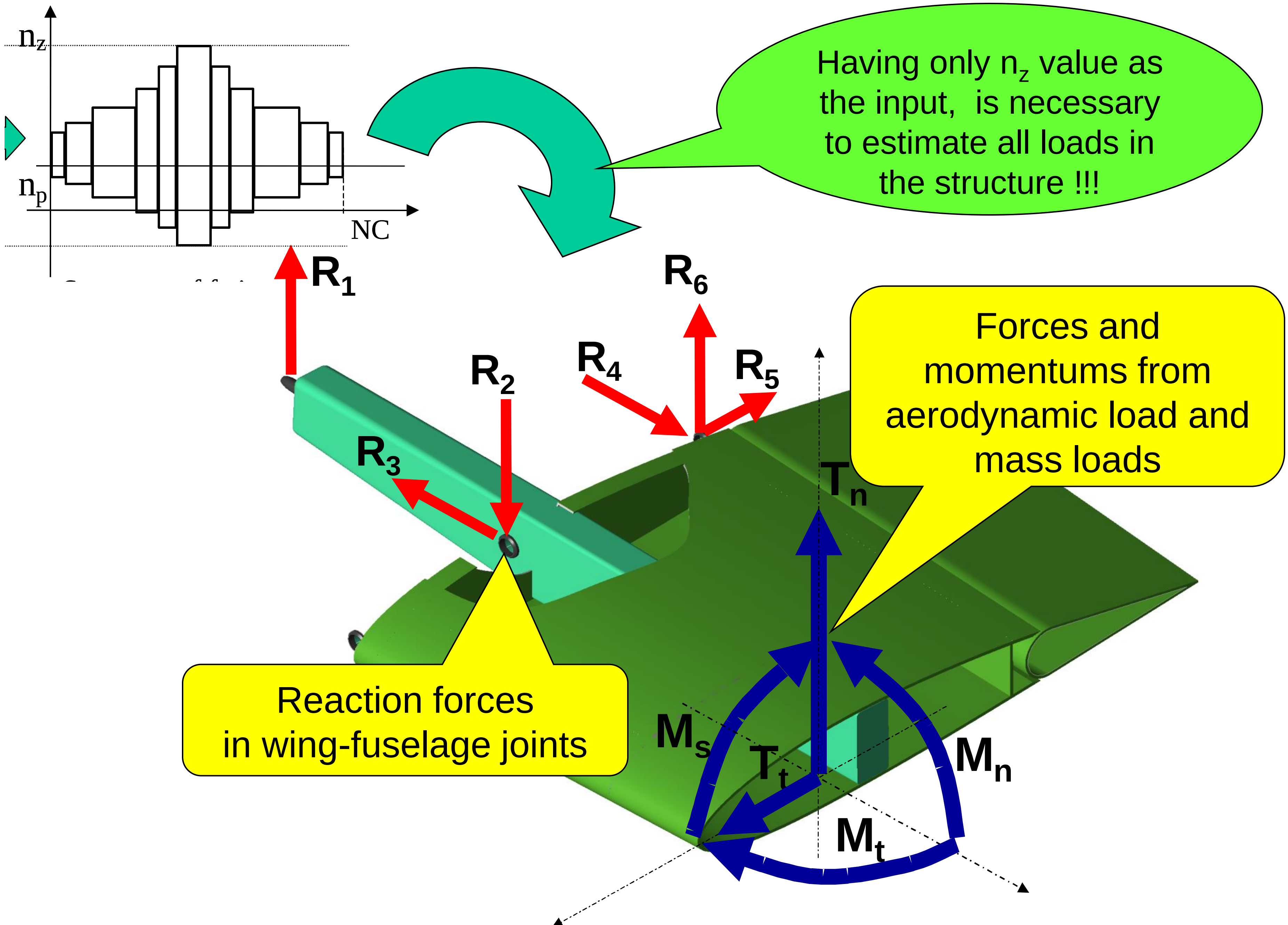
Load spectrum of assembly *i*

Load spectrum of subassembly i_k

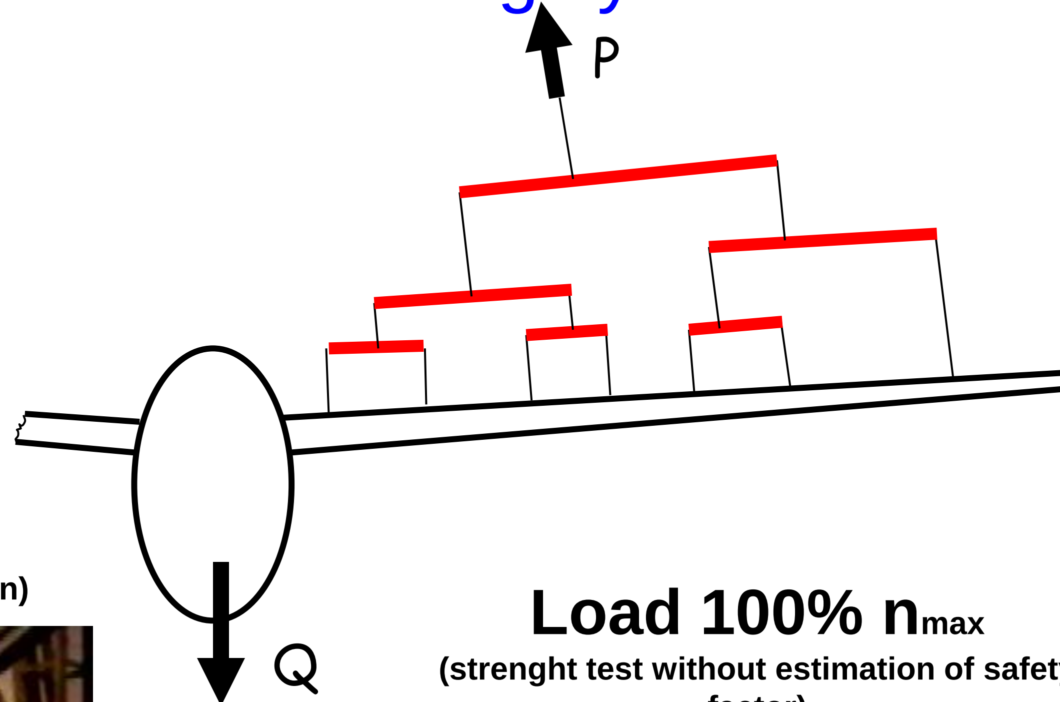
load spectrum of structural element i_{kn}



Load Spectrum and the aircraft stucture



Testing the structure - Loading systems



Load 150% n_{max}

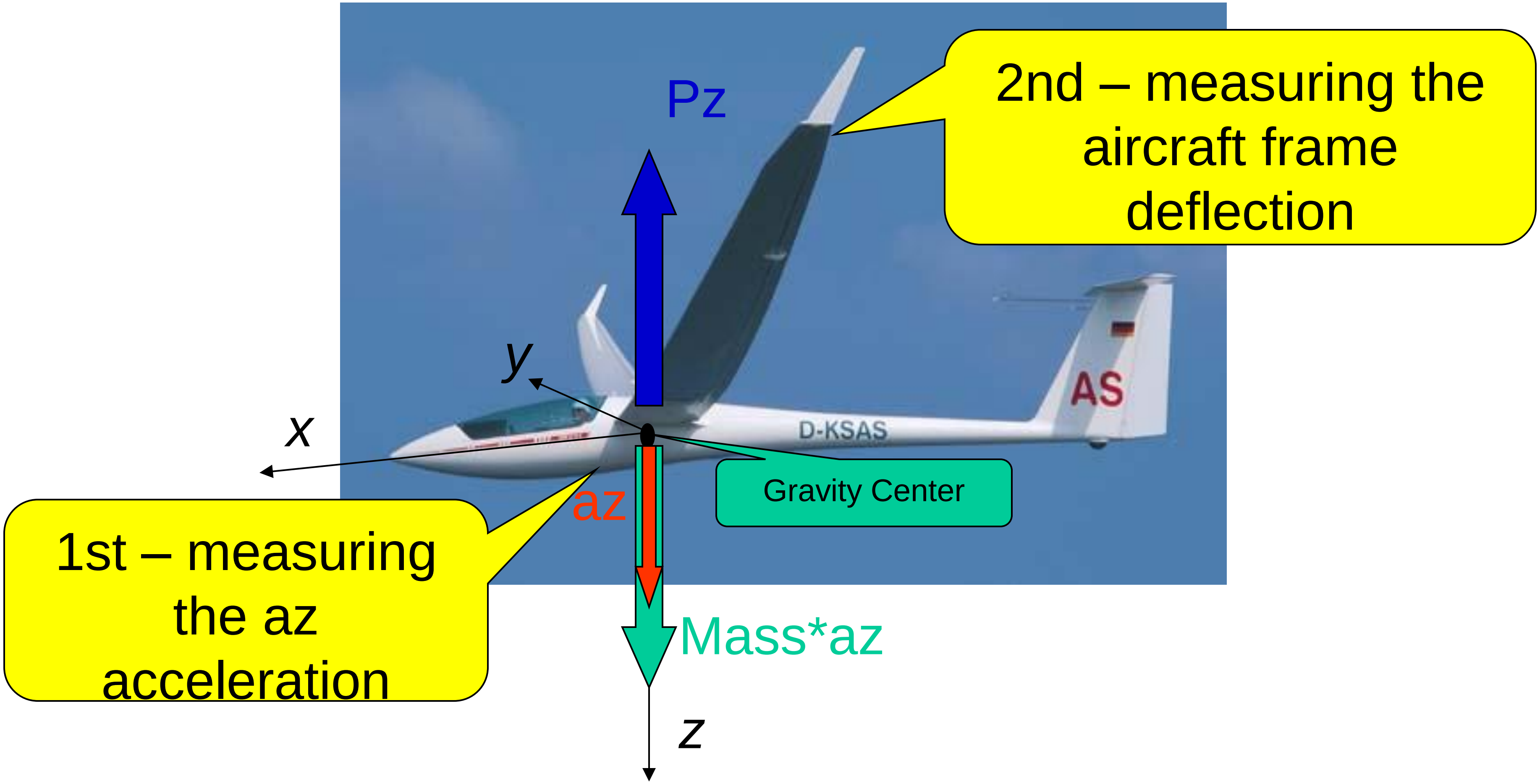
(Strenght test with estimation of safety margin)

Load 100% n_{max}

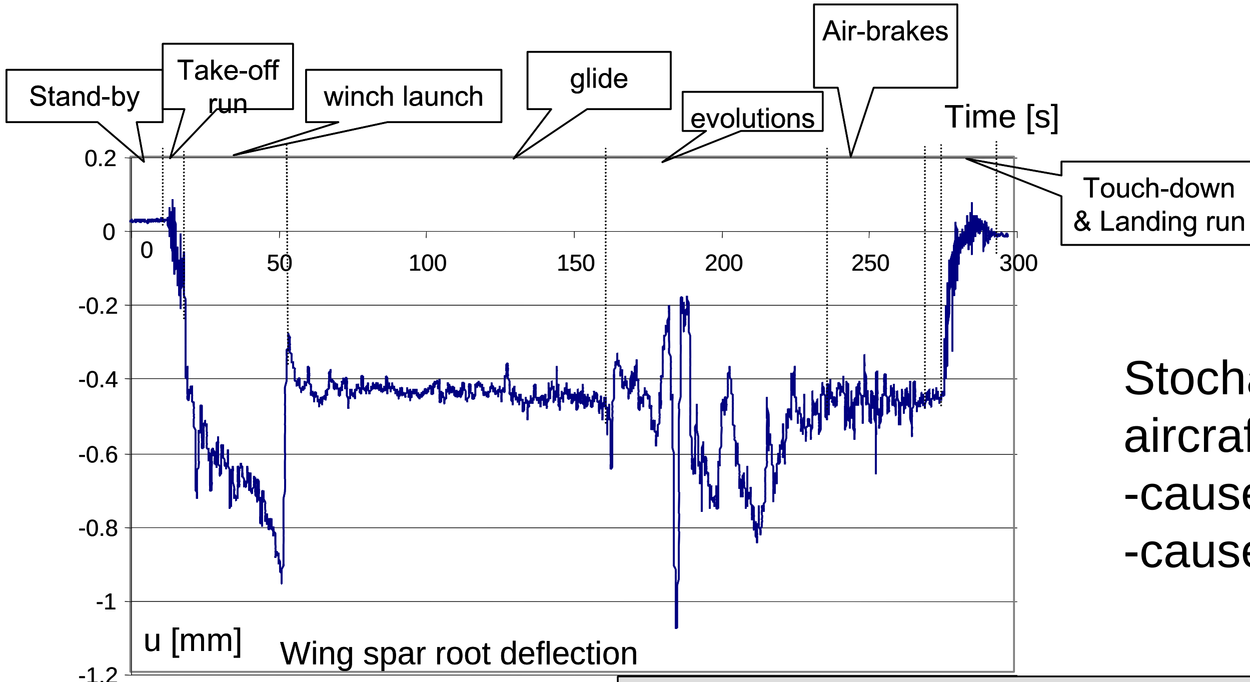
(strenght test without estimation of safety factor)

Investigations into load-spectra

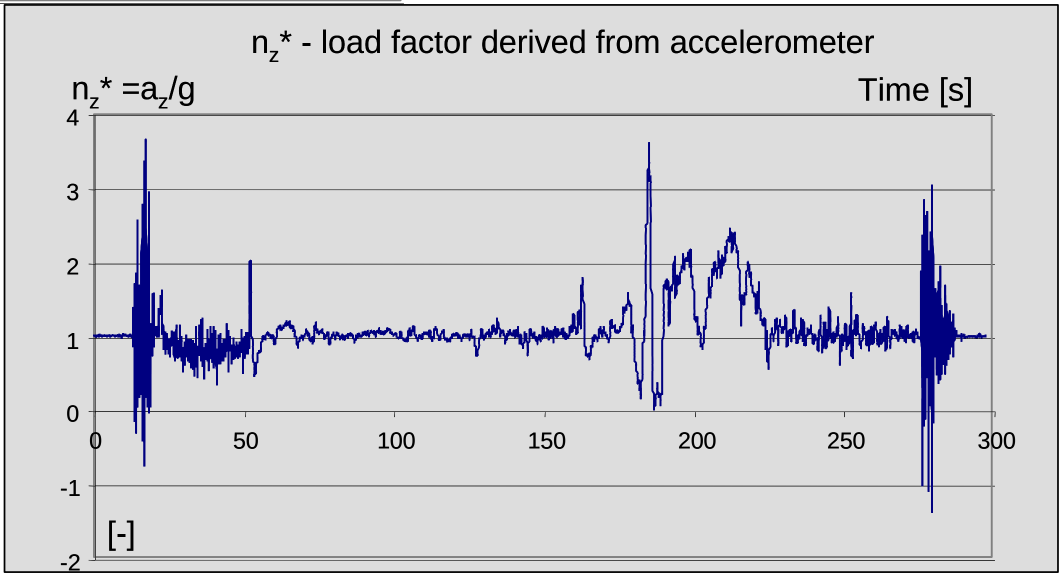
Methods of aircraft frame load measurements



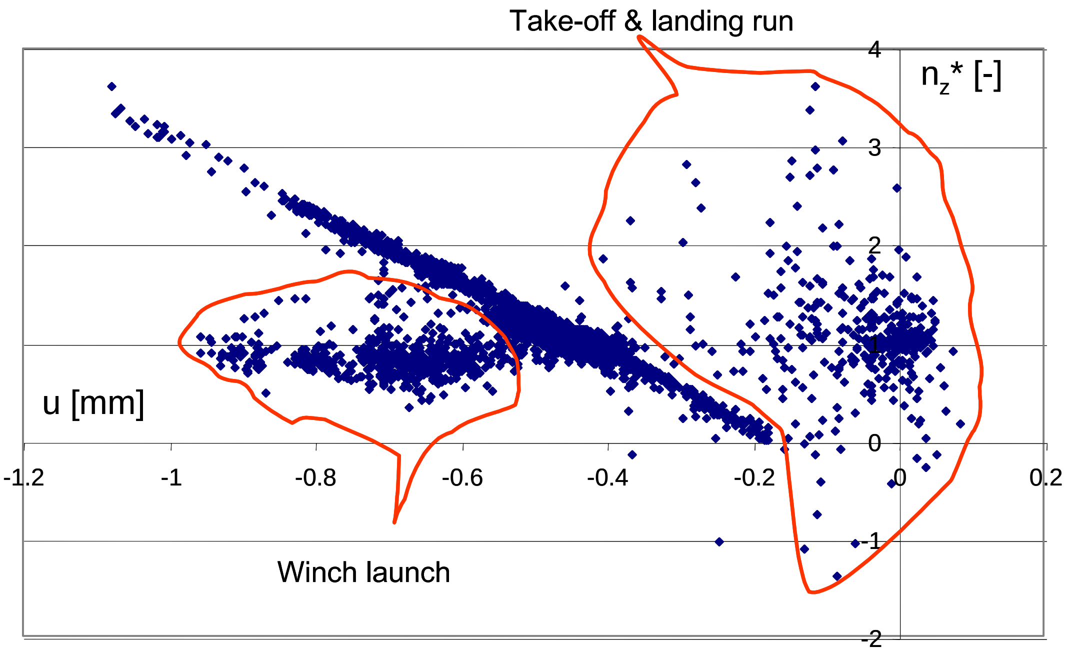
Comparision of signals recorded useing both measurement methods



Stochastic nature of aircraft loads:
-caused by pilot
-caused by turbulence



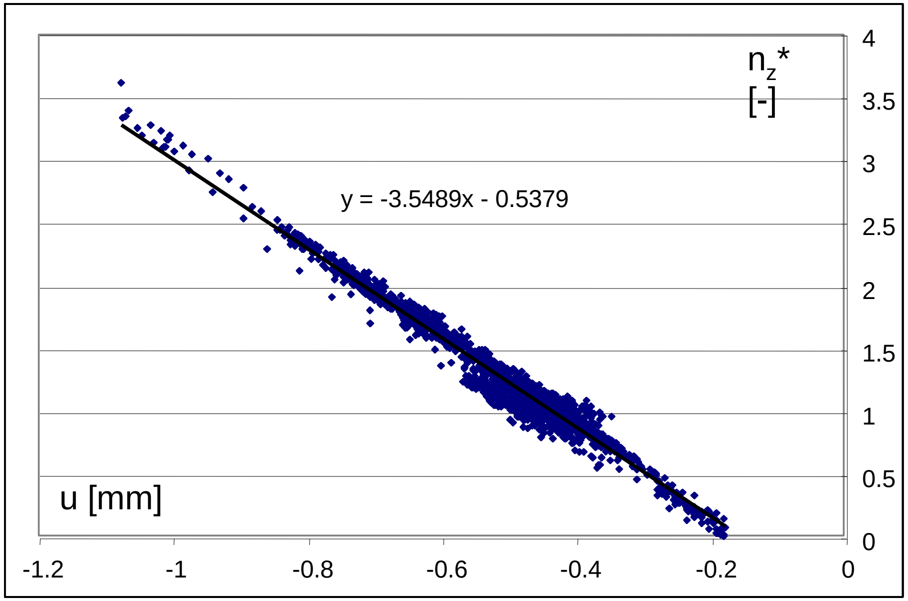
Correlation of the signals



Conclusion:

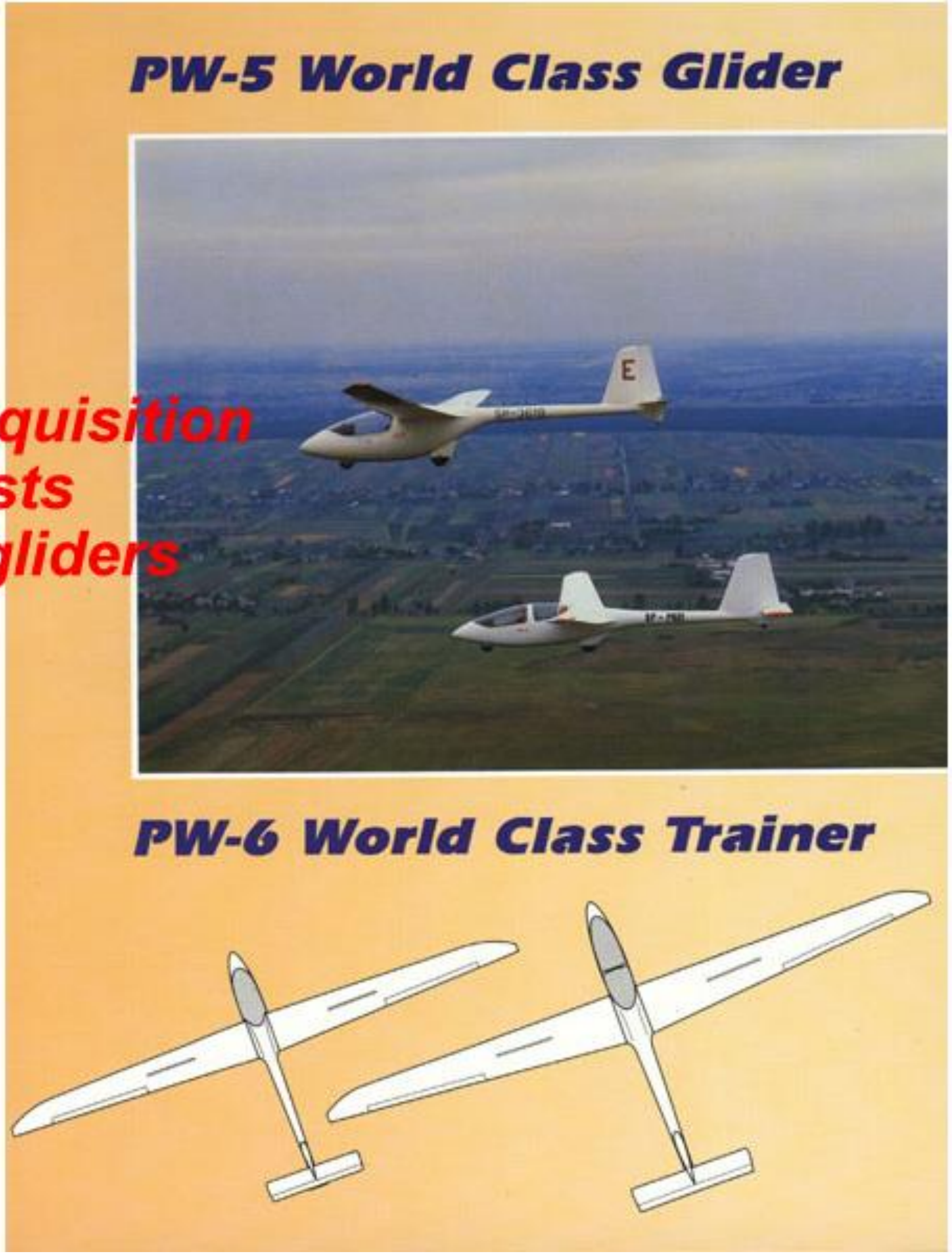
Acceleration and deflection signals are equivalent only in case of a free flight.

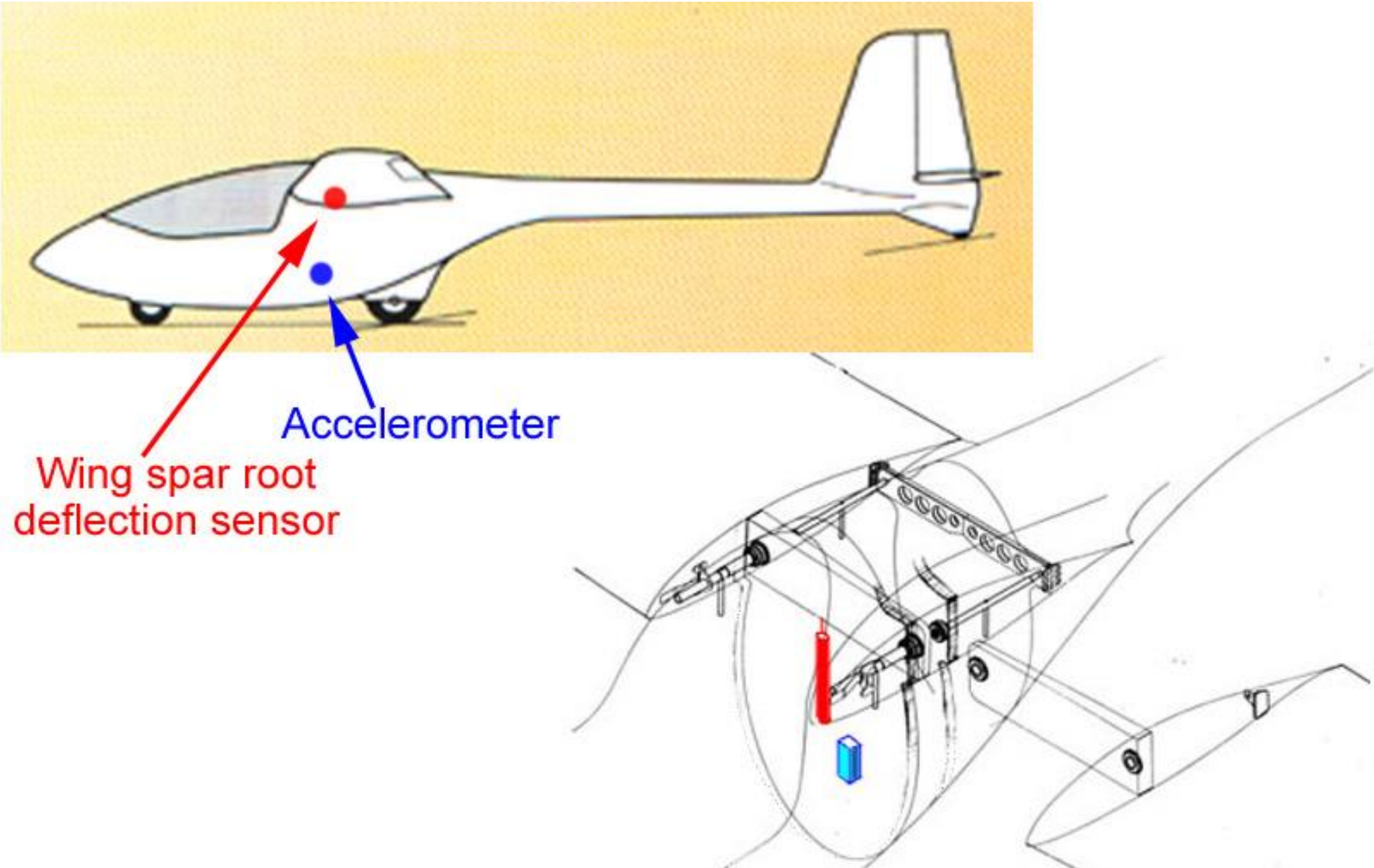
Acceleration signal is not usable in case of measuring loads during take-off or landing and during winch-towing.



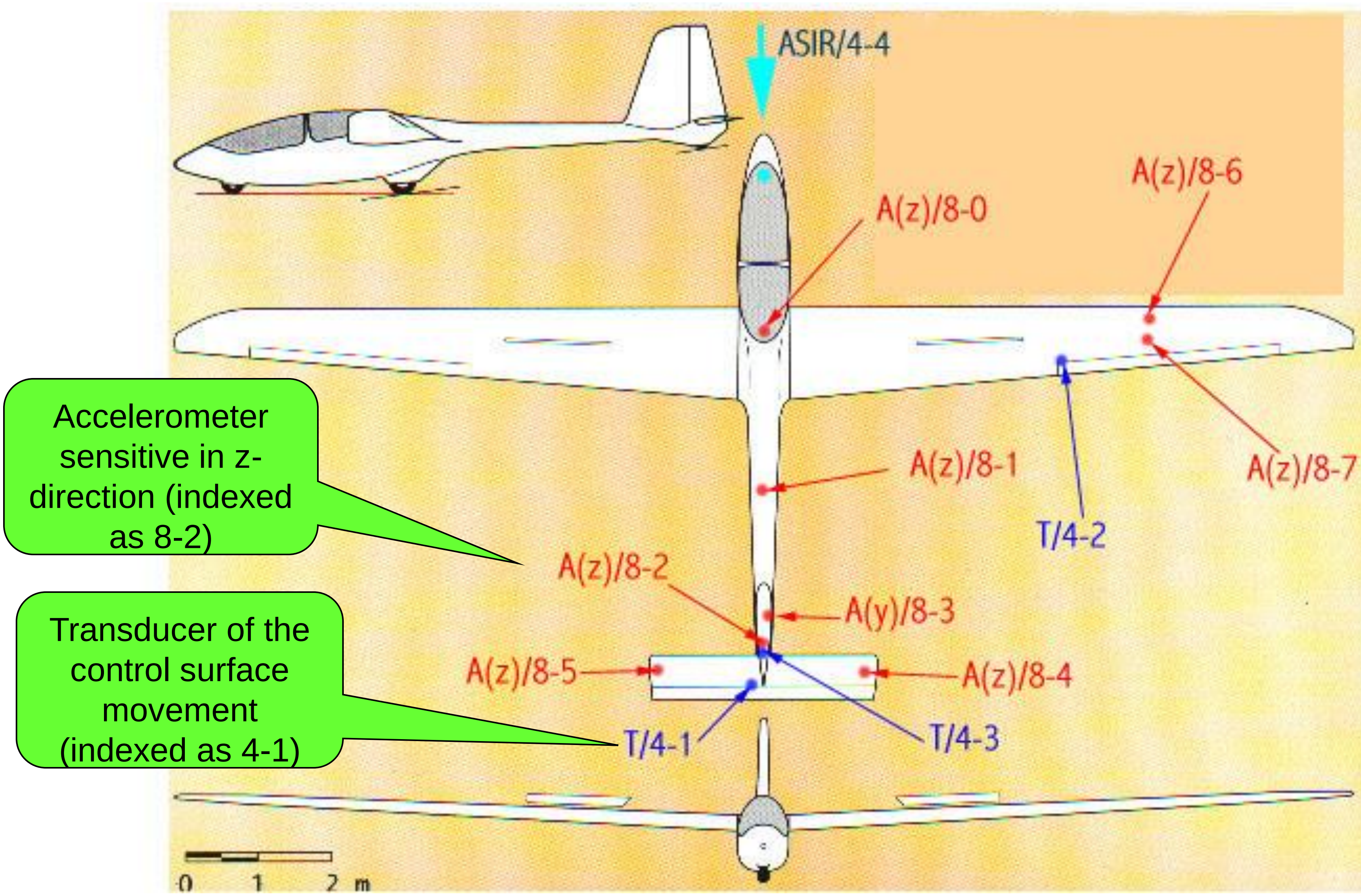
Example of instrumentation used for testing the gliders

The systems of data acquisition in certification tests of the PW-5 & PW-6 gliders



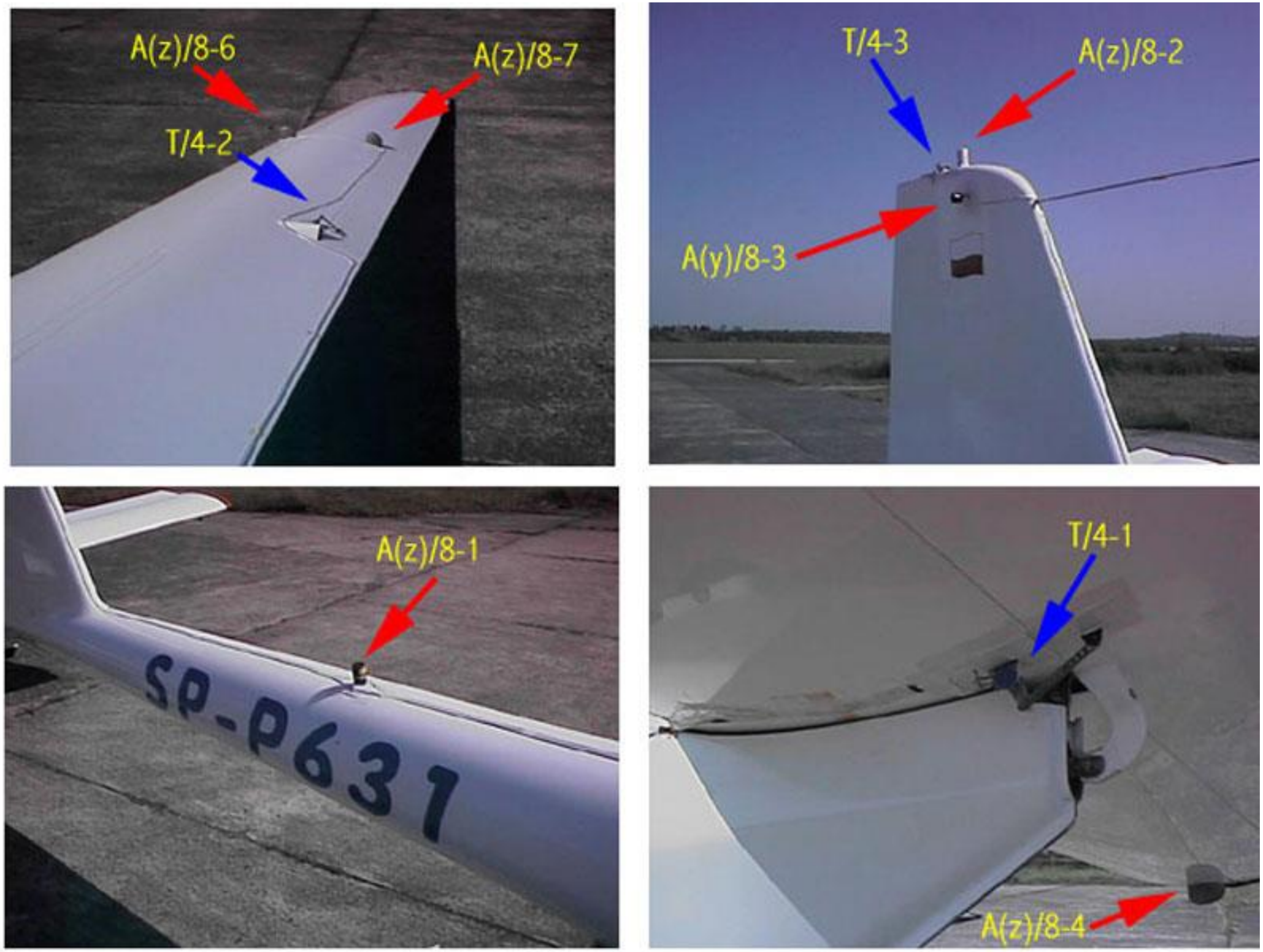


The set of measurement sensors beeing in use for load spectrum estimation



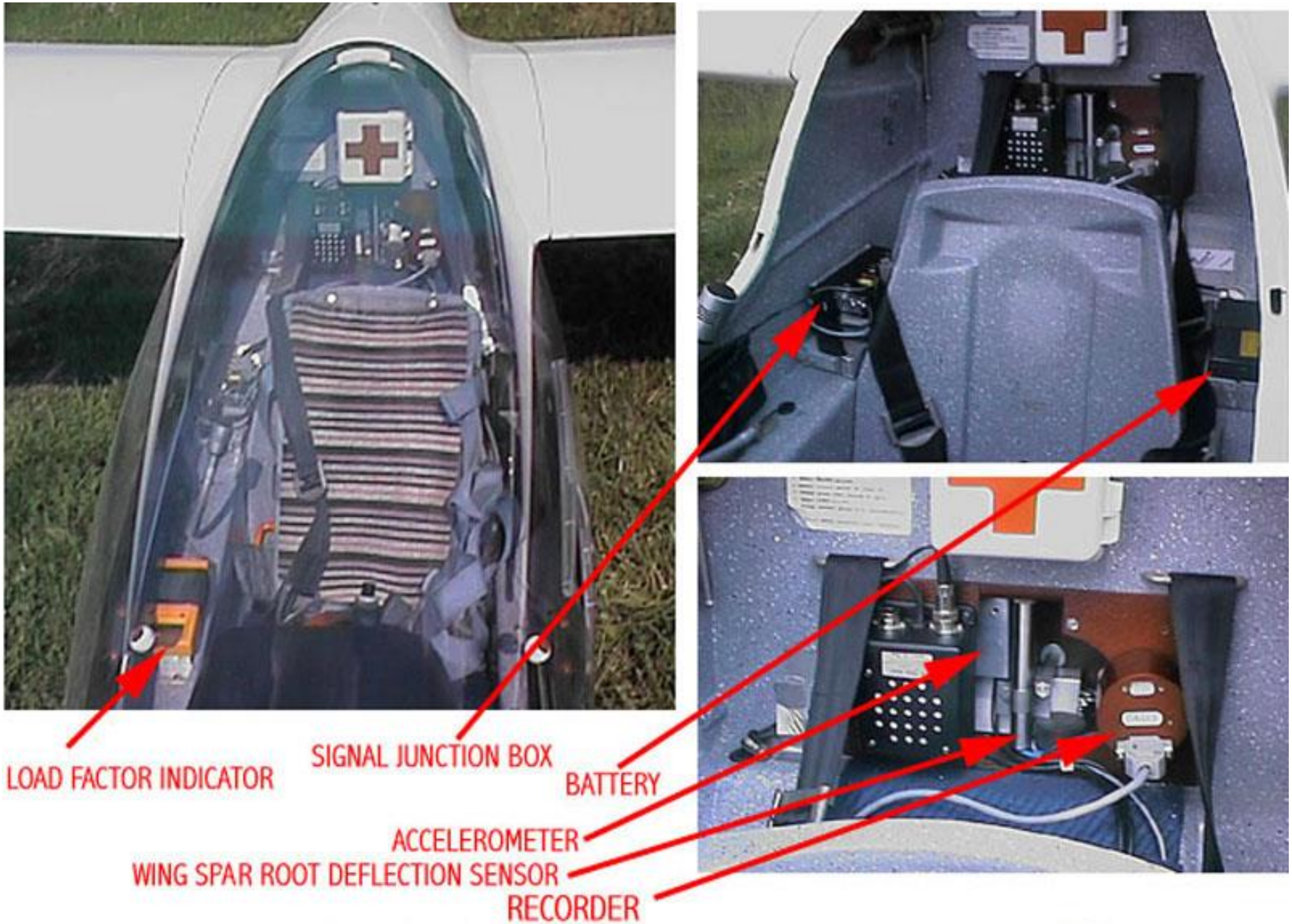
lacement of the sensors used for dynamic tests of the gliders (especially for flutter testing)

Details of the measurement equipment



Photos of accellerometers and deflection transducer fixed on the gli

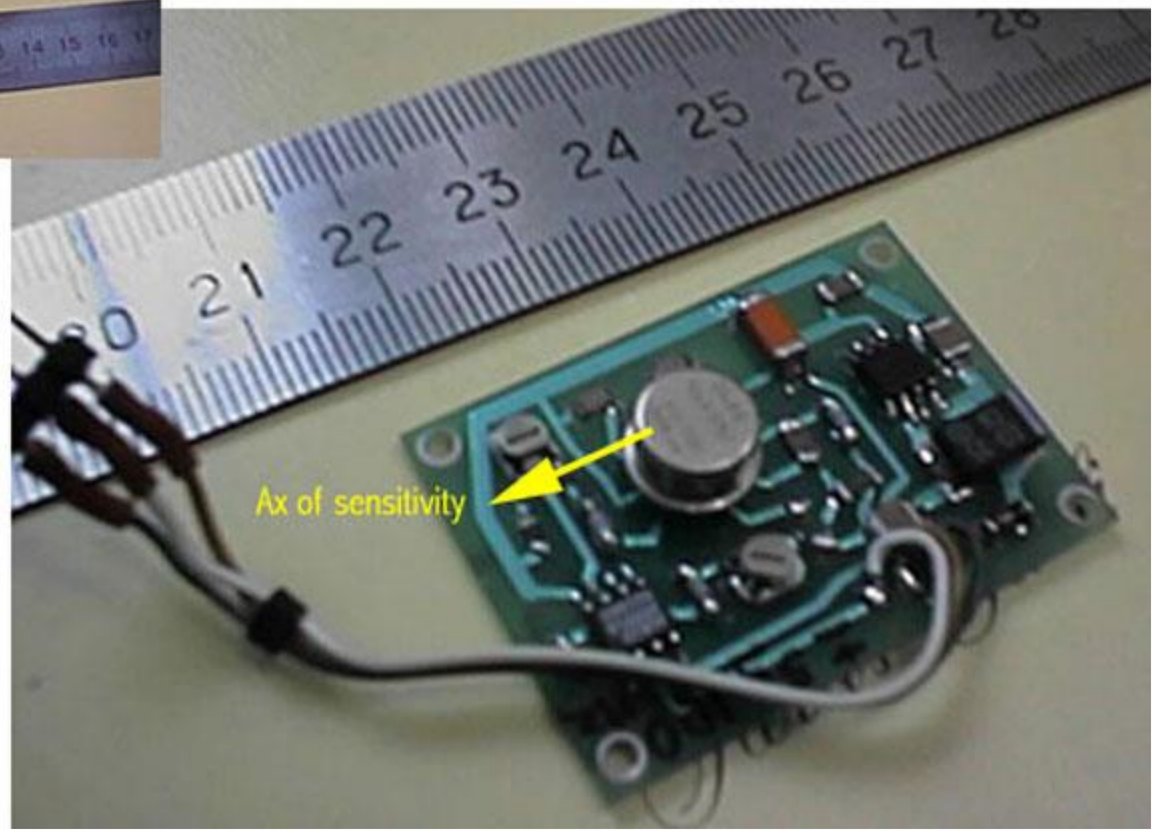
Details of the measurement equipment



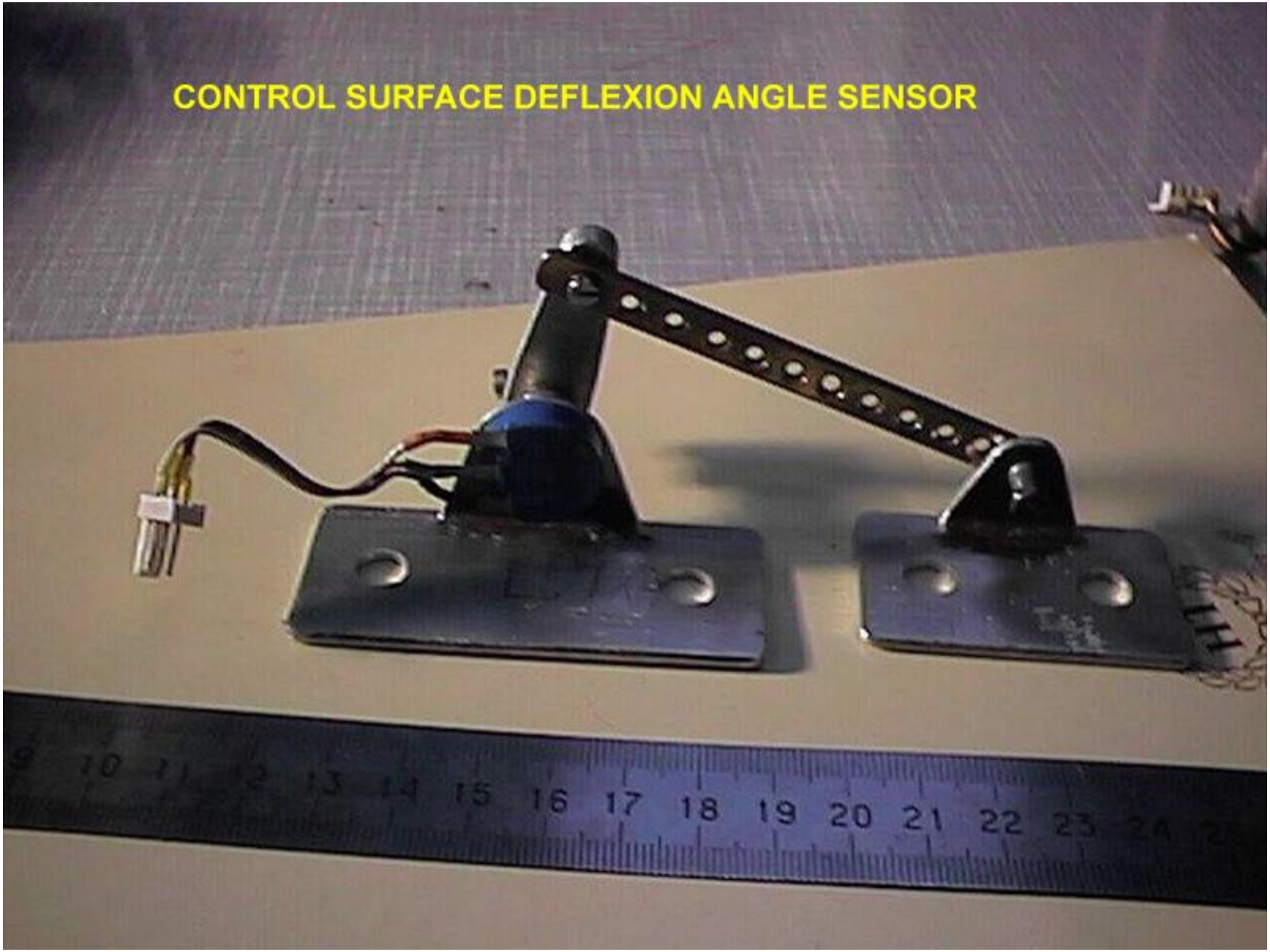
PW-5 Testing - LOCATION OF THE MEASUREMENT EQUIPMENT IN THE COCPIT

Details of the measurement equipment

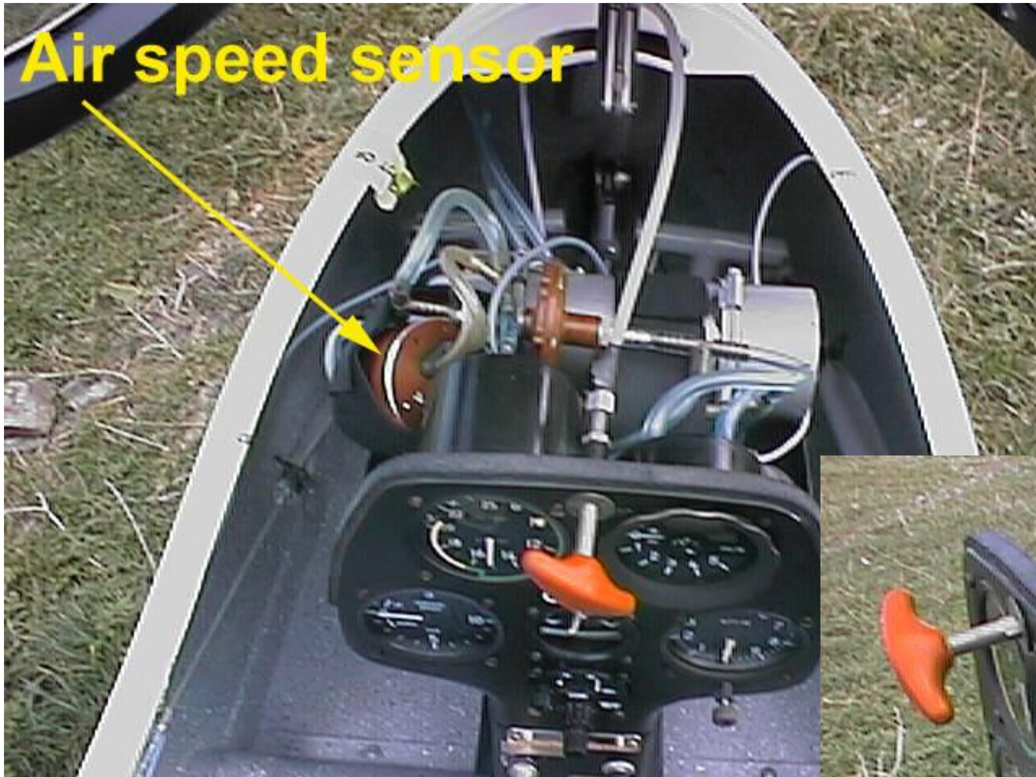
Accelerometer

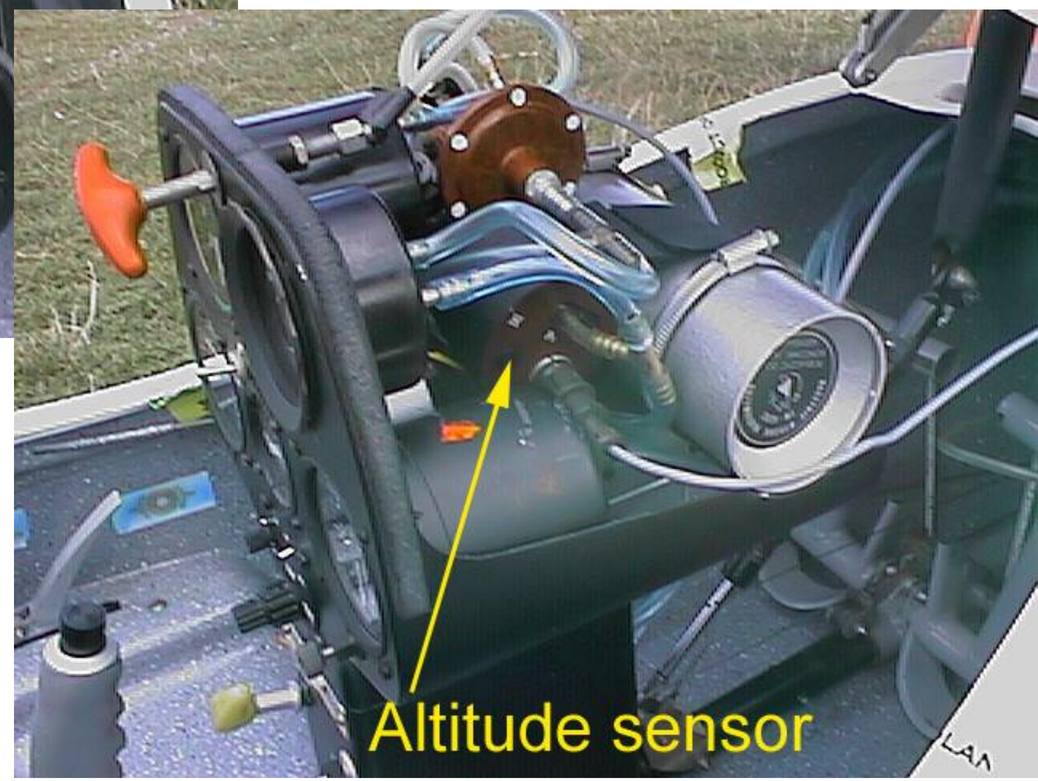


Details of the measurement equipment

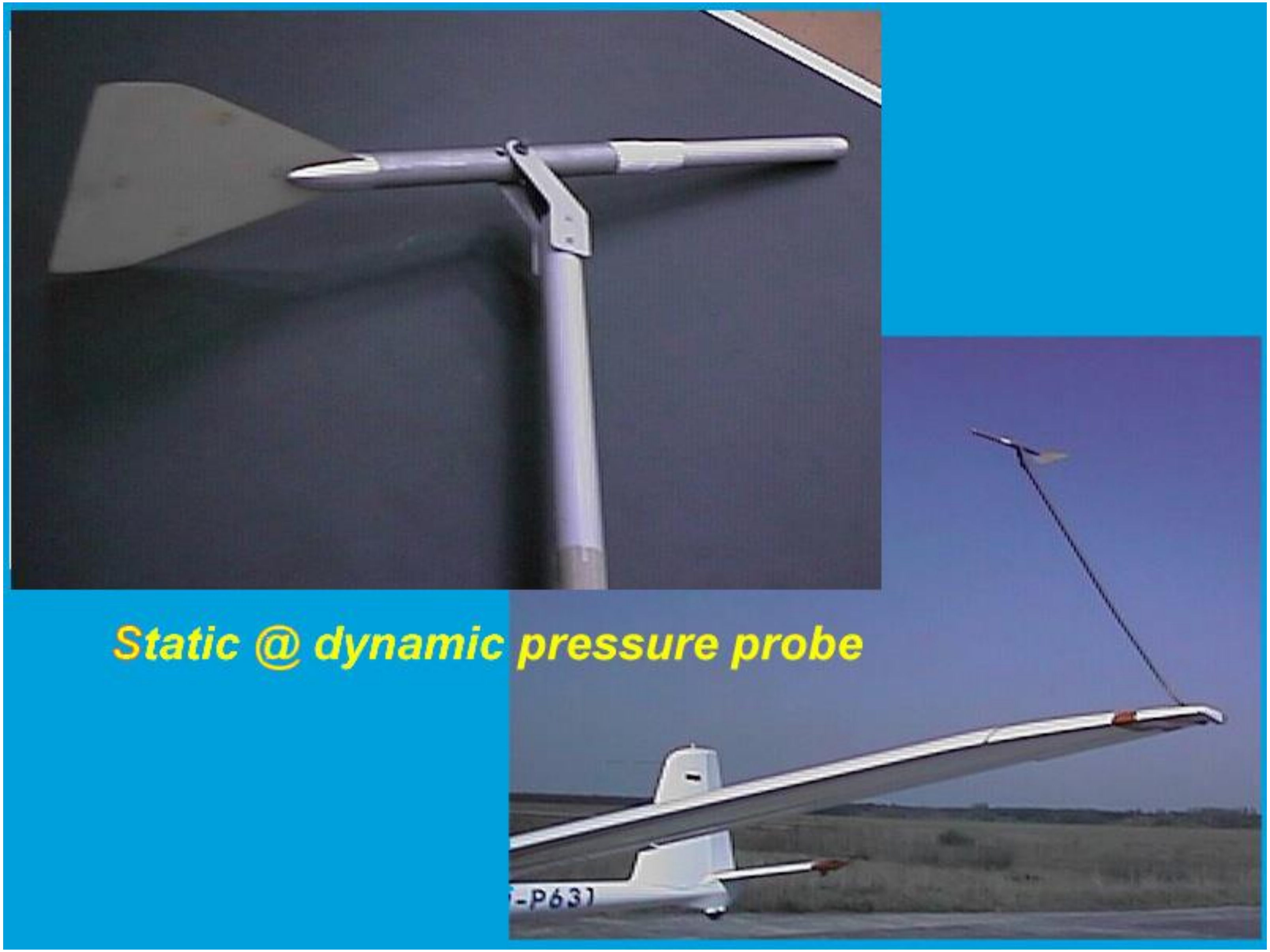


Details of the measurement equipment

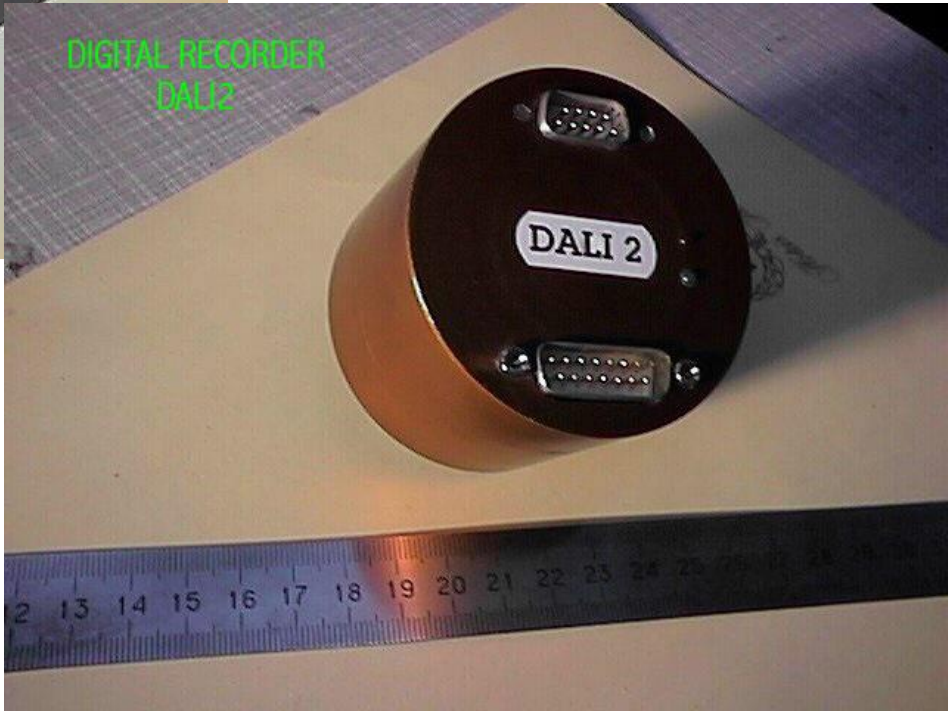




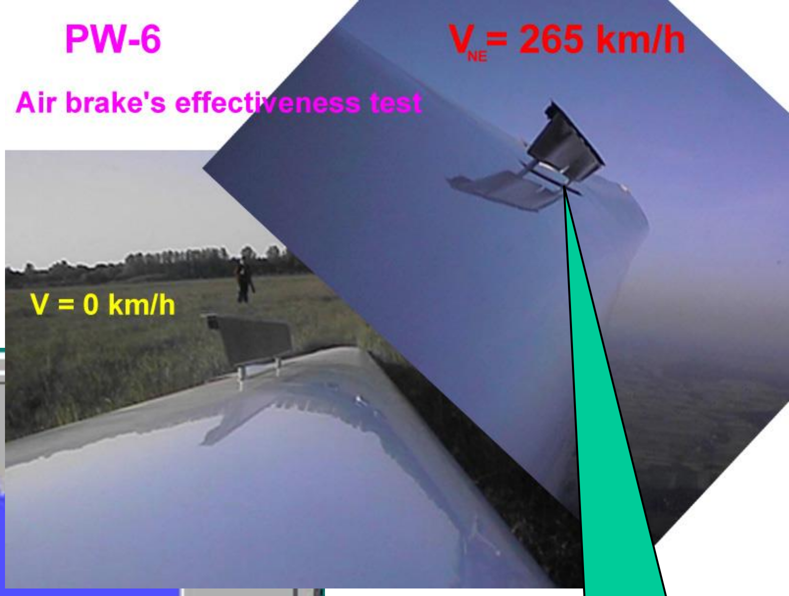
Details of the measurement equipment

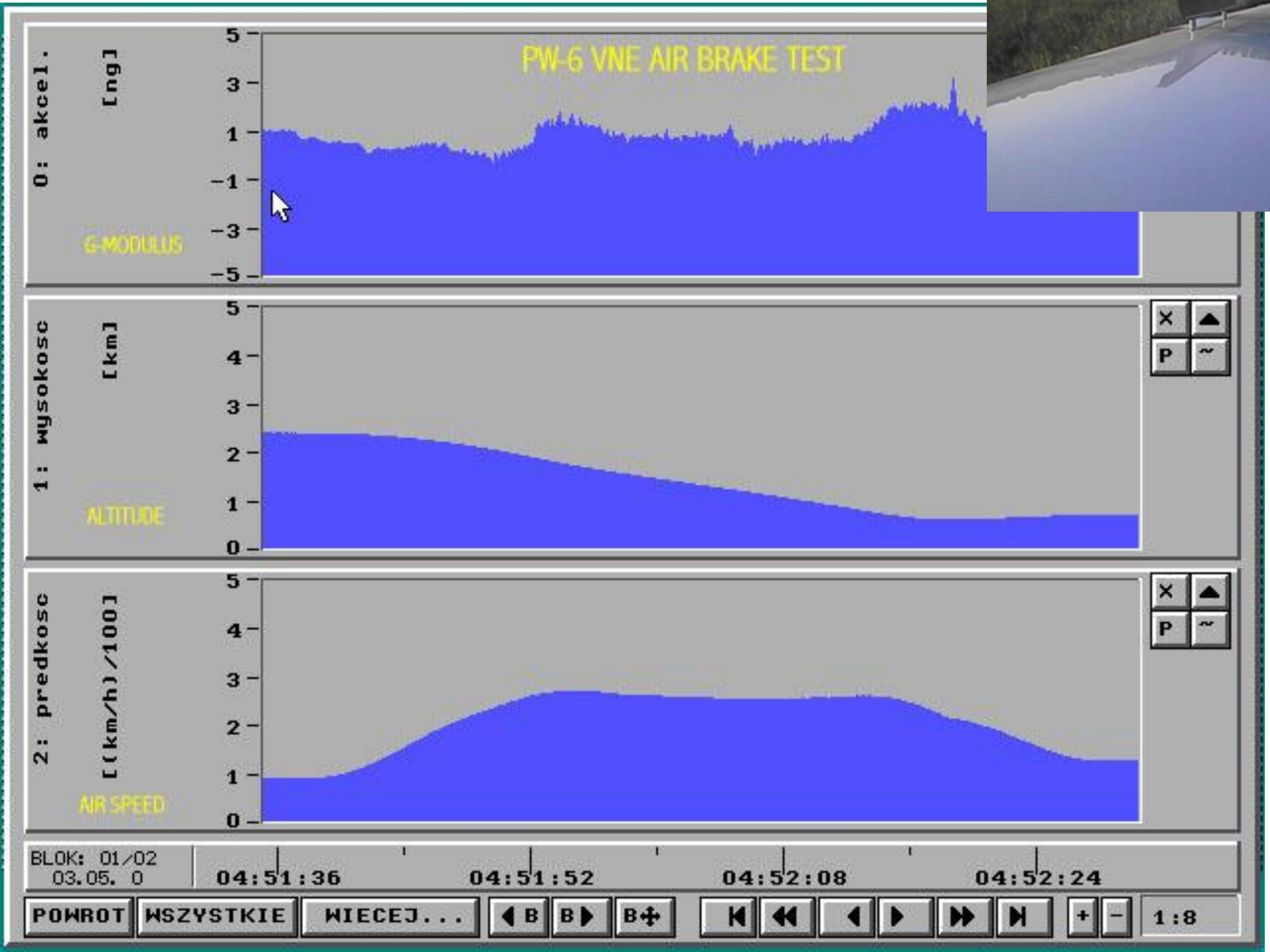


Details of the measurement equipment



Example of the signals recorded

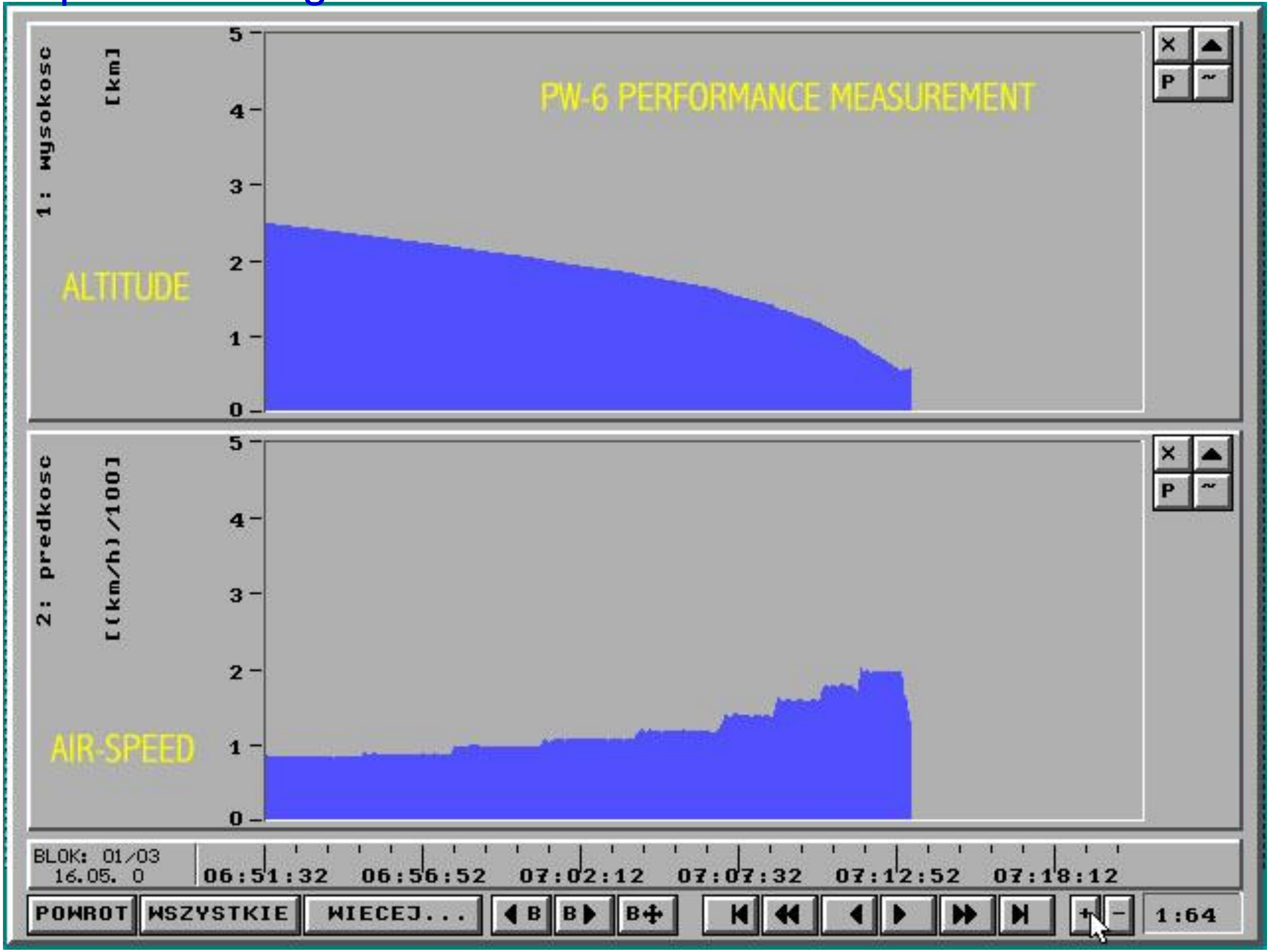




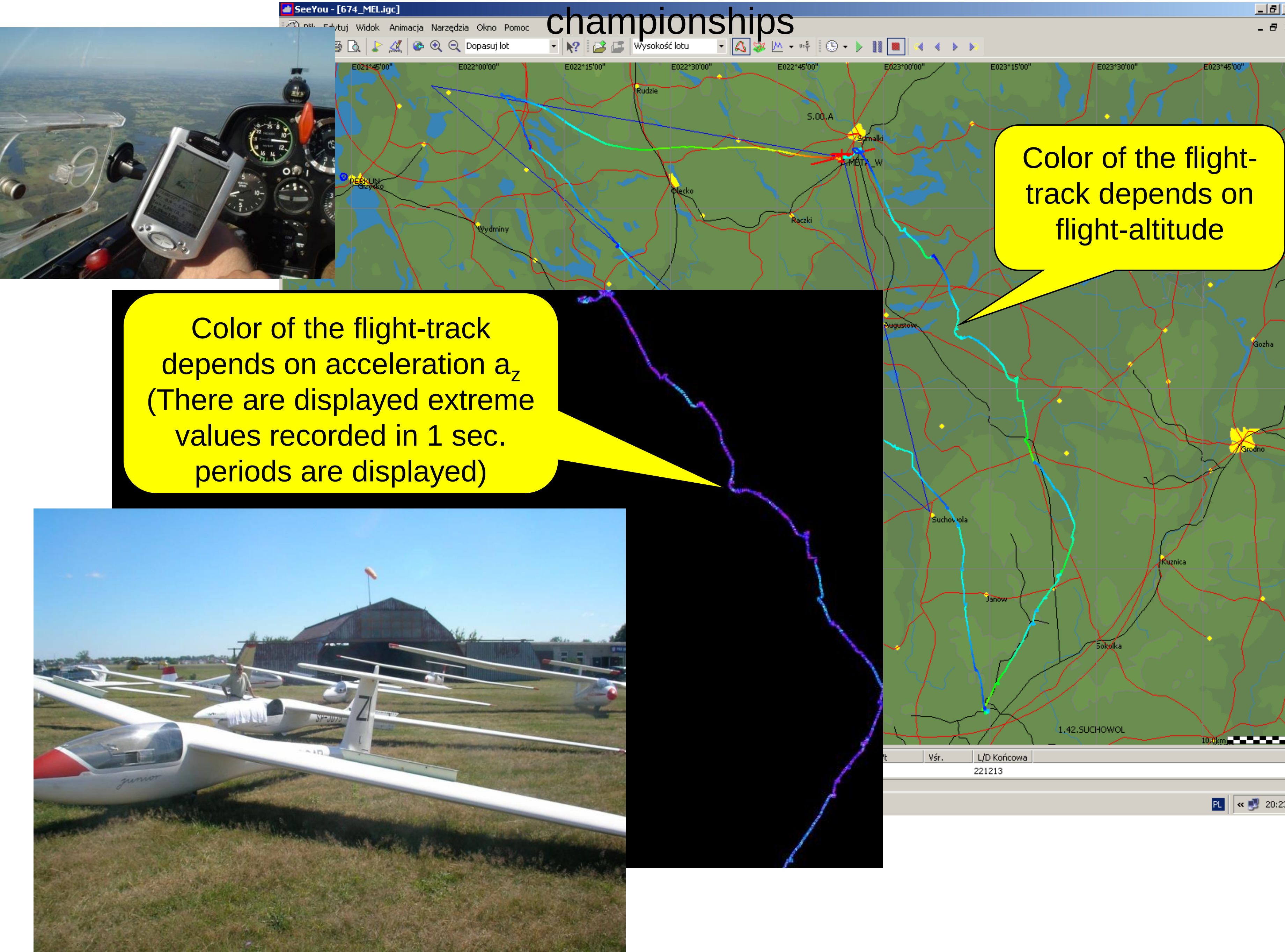
Effect of dynamic preassure

Example of the signals recorded

Example of the signals recorded



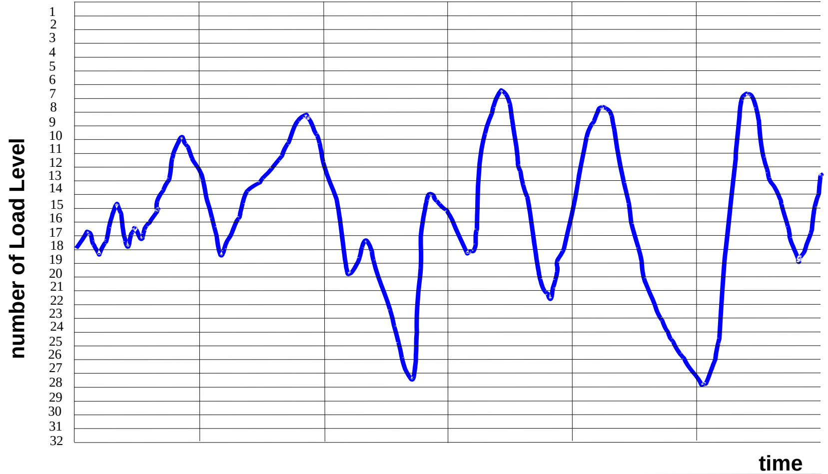
Visualisation of the load spectrum of the glider taking part in gliding championships



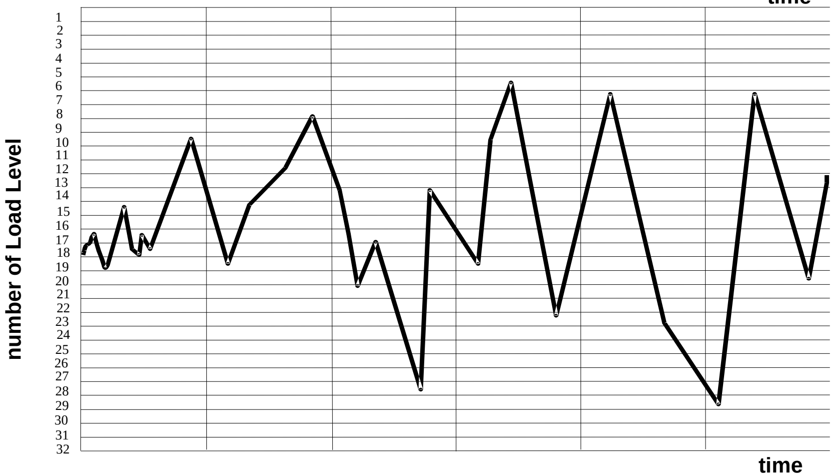
Color of the flight-track depends on flight-altitude

Color of the flight-track depends on acceleration a_z (There are displayed extreme values recorded in 1 sec. periods are displayed)

Load signals elaboration and determination of the LS

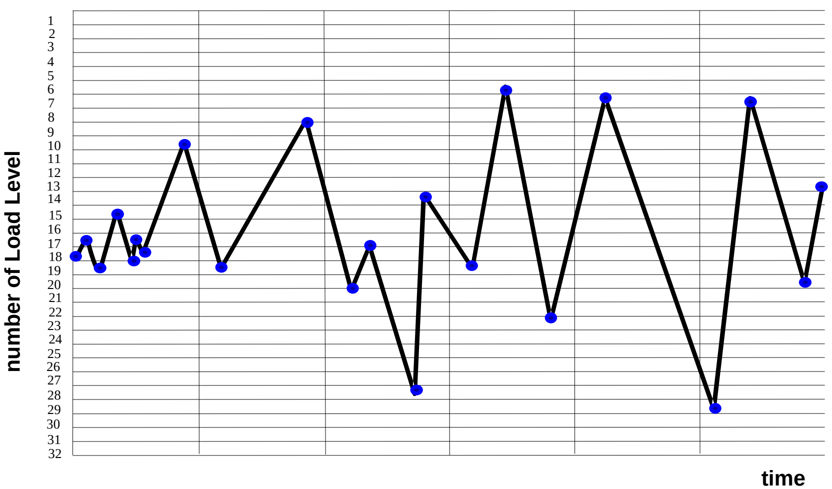


Load signal in a raw form (density of the blue dots depends on sampling frequency of the recorder



1st stage of filtration

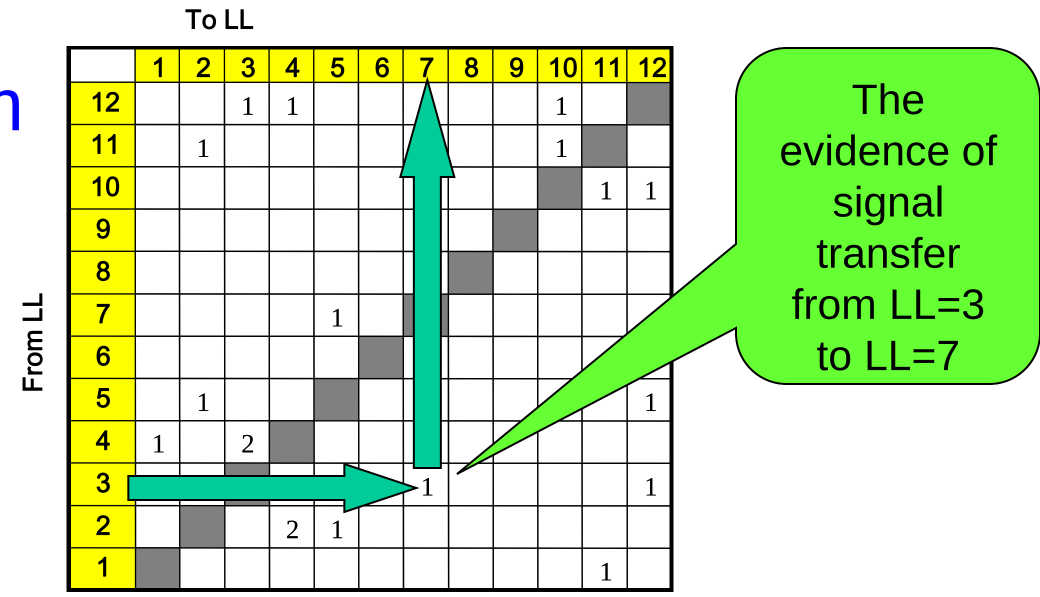
Transition from quasi-continous form of the signal to the form of chain of local extremes

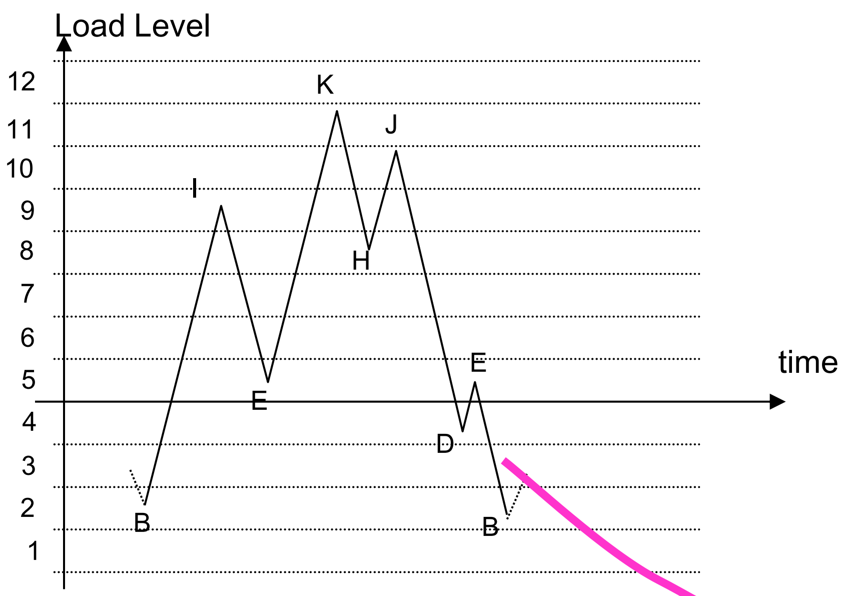


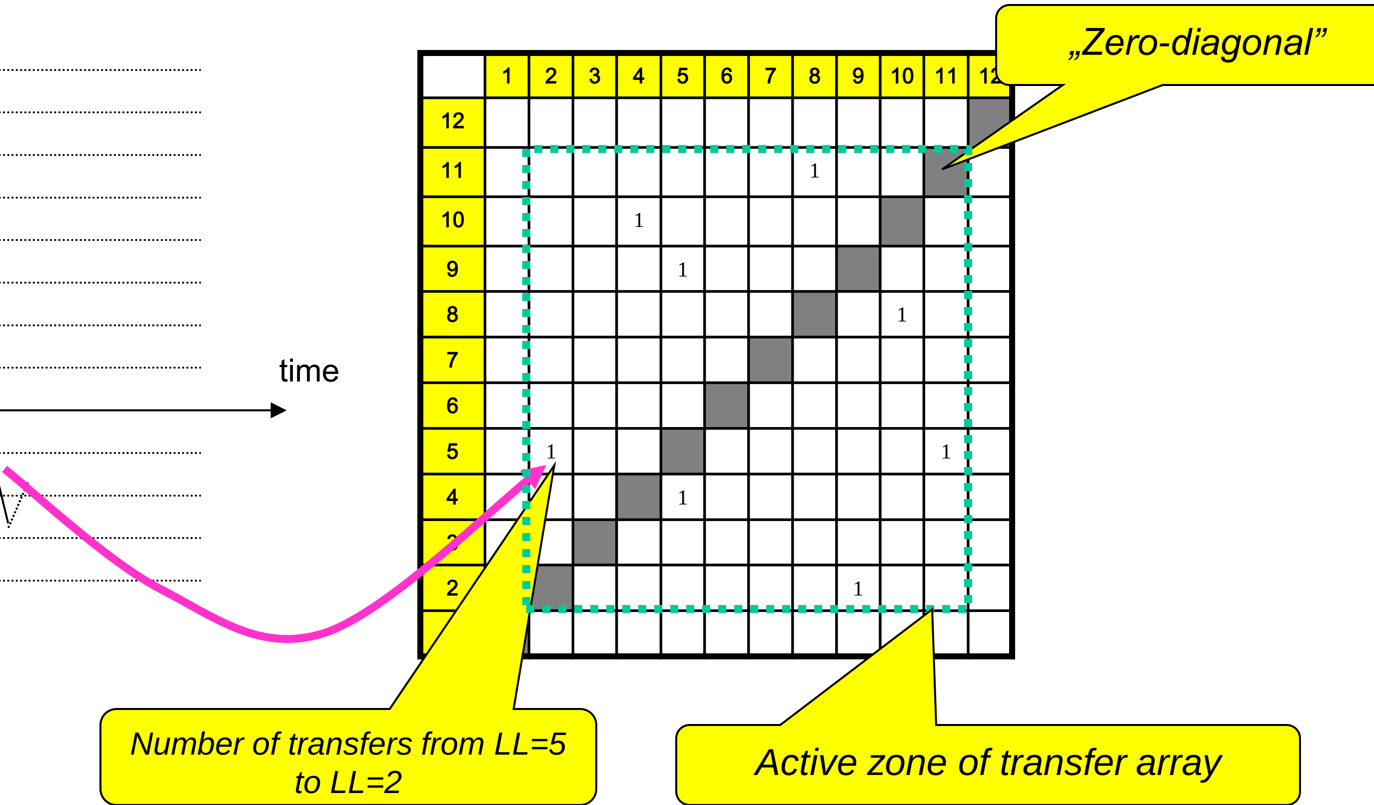
2nd stage of filtration

Load Spectrum in the form of a Transfer Array (TA)

The evidence how many signal transfers from i- Load Level to j- Load Level was noticed in the time history of the load signal







Standarisation of the Load Signal – Load Levels (LL)

Correlation between load factor n_z and load level LL

Example of standard applicable for load spectrum of the glider.
In this case an assumed number of load level is 32

$$\text{if } n_z = n_{z\_max} \text{ then } LL=3$$
$$\text{if } n_z = n_{z\_min} \text{ then } LL=31$$

Note:
LL=1, LL=2 and LL=32 are reserved for the loads exceeding operational limit

Example of the Transfer Array of a load signal recorded during flight of a glider

PO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
32																																
31																																
30																																
29																																
28																																
27																																
26																																
25																																
24																						5	74									
23																		1		1	3	8		74								
22																				1	3		8	5								
21											1					1			1	2		1	5									
20																	1	2	3		2	2										
19															1	1	9	108		2	1	1										
18															2	3	14		110	1												
17															4	11		15	7	1	1											
16														2	10		11	2	2	1												
15													1	6		12	4	1														
14													4		7			1														
13														4						1												
12																																
11																					1											
10																																
9																																
8																																
7																																
6																																
5																																
4																																
3																																
2																																
1																																

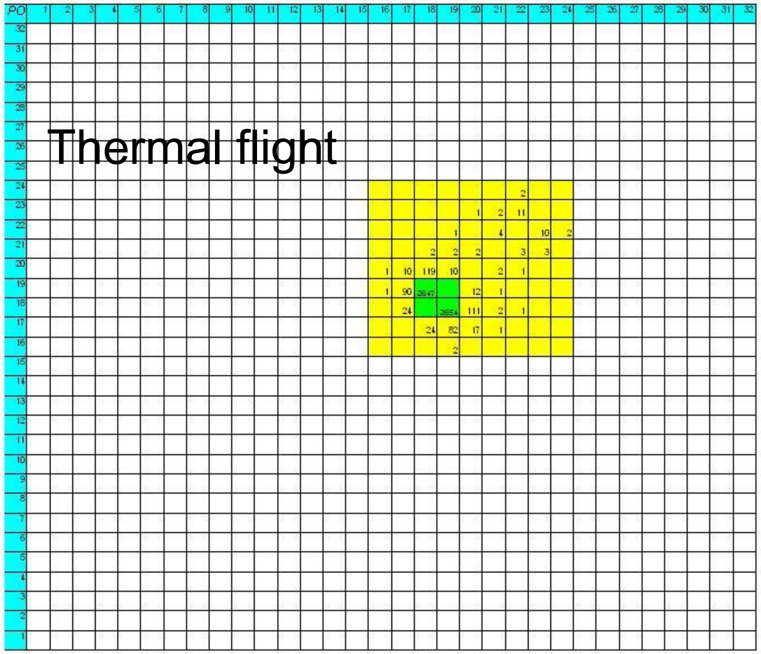
The highest load signal change !
(transfer from 21 LL to 11 LL)

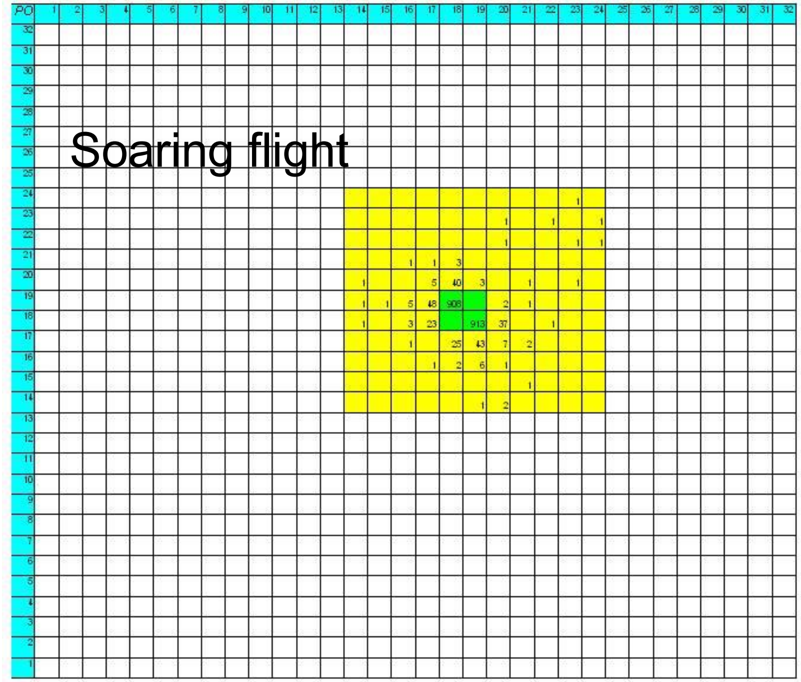
Properties & features of the Transfer Array

MF	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	22	23	24	25	26	27	28	29	3	31	32
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2	18	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	1	4	31	0	18	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	6	0	30	2	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	6	12	7	0	4	0	5	6	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	171	458	635	0	4	1	1	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	303	6747	0	690	1	1	0	0	1	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	256	0	[illegible]	469	7	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	207	316	[illegible]	14	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	12	7	[illegible]	0	2	1	0	1	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	[illegible]	0	0	0	0	0	0	0	1	2	[illegible]	[illegible]	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	1	0	[illegible]	[illegible]	0	0	0	0	0	0	0	0
13	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	[illegible]	[illegible]	0	0	0	0	0	0	0
12	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0
11	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0
10	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

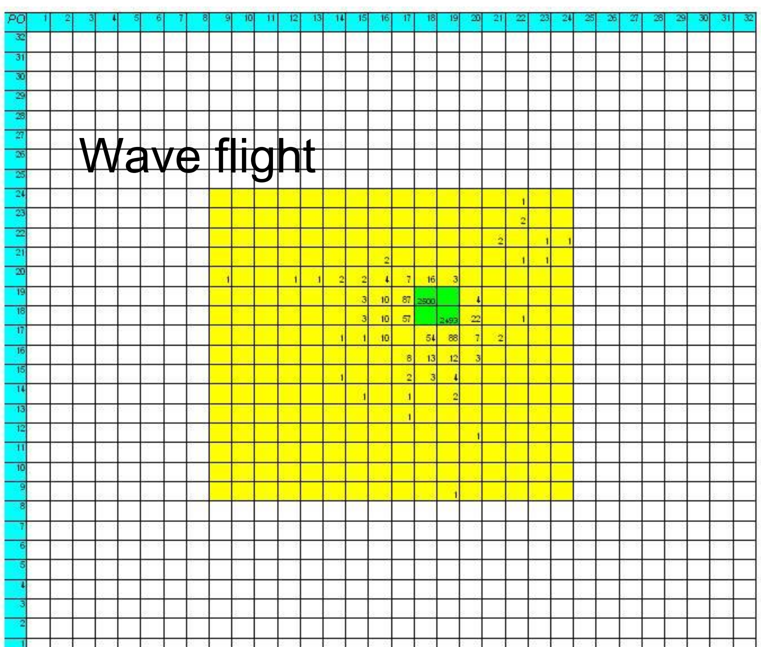
Active zone of transfer array

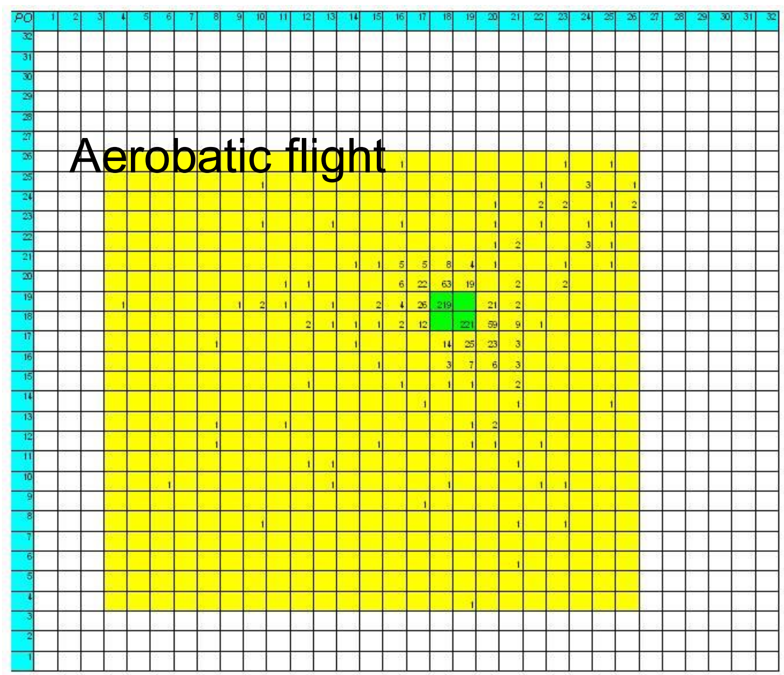
Small load oscillations near n_z=1

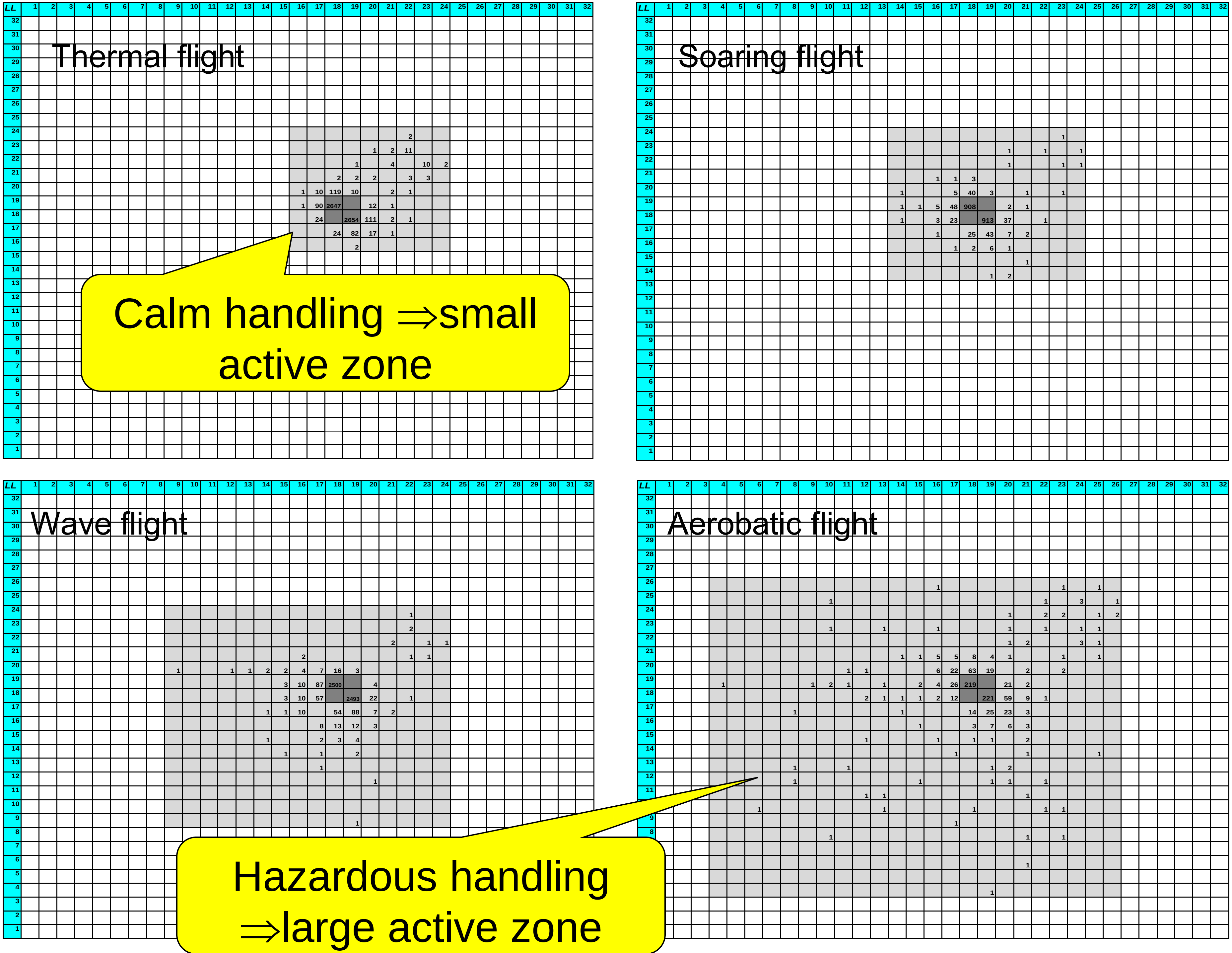




Examples of the glider LSs

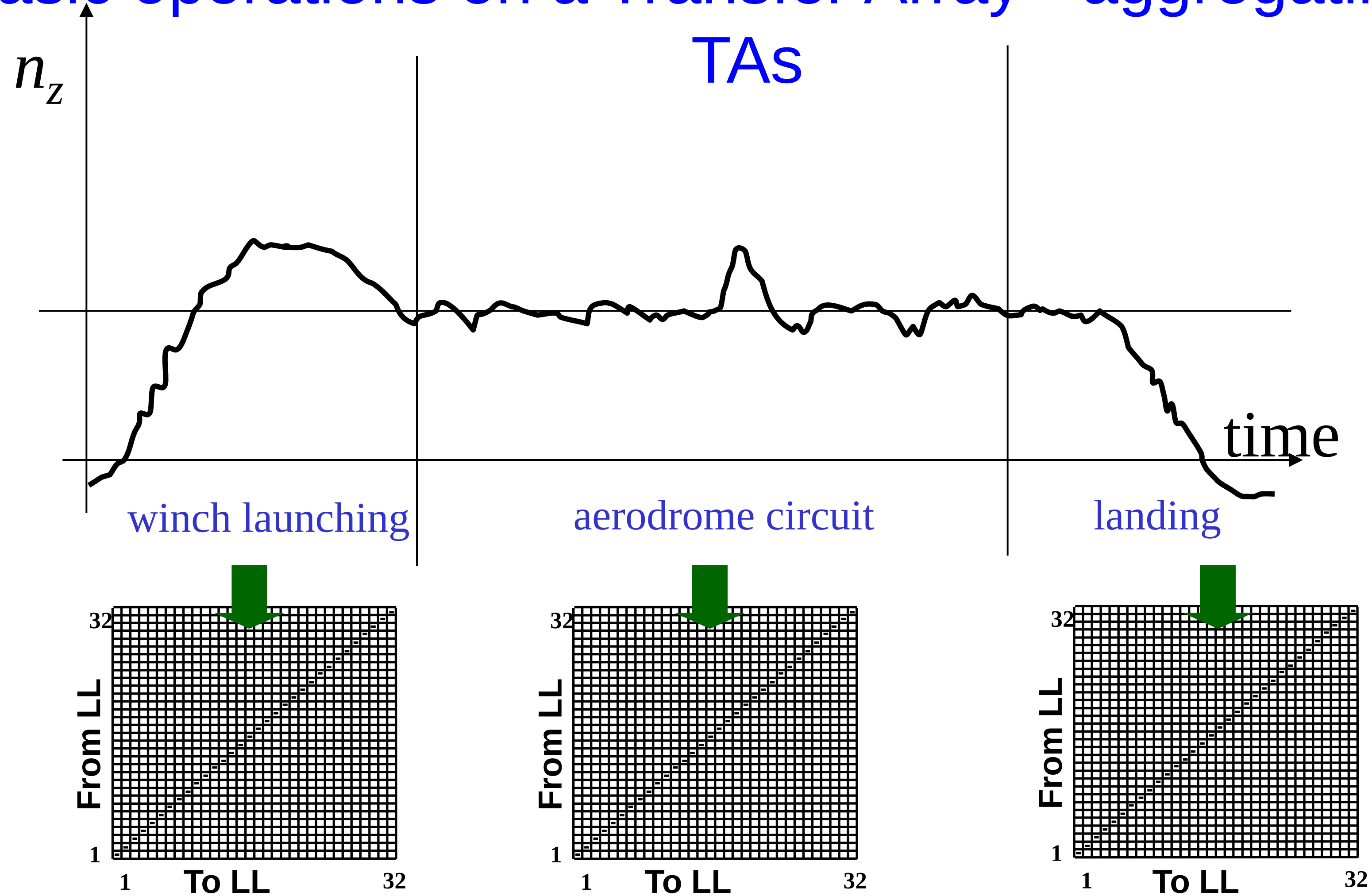






Thermal flight
Calm handling ⇒small active zone
Soaring flight
Wave flight
Aerobatic flight
Hazardous handling ⇒large active zone

Basic operations on a Transfer Array - aggregating the TAs



$TA_{\text{full flight}} = TA_{\text{winch launching}} + TA_{\text{aerodrome circuit}} + TA_{\text{landing}}$

$$TA_{i,j\ full\_flight} = \sum TA_{i,j\ flight\_components}$$

Basic operations on a Transfer Array - enveloping the set pf TAs

Transfer Array TA1

				1			-
			8	7	12	-	
		8	9	7	-	25	
		14	8	-			
		12	-	33	2	16	22
	2	-	34	2	7	14	
	-		13	2	1		
-		8					

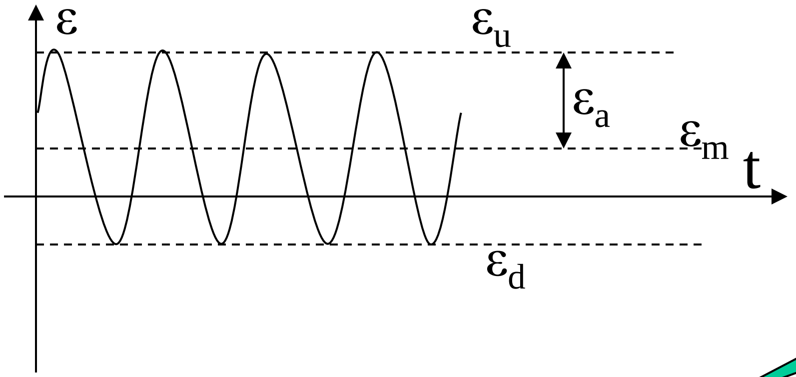
Transfer Array TA2

							-
				5		-	
		2	24		-		13
			8	-		7	
		12	-		18		22
		-		2	26	14	
	-		13		1		
-	1						

Envelope of TA1&TA2

				1			-
			8	7	12	-	
		8	24	7	-	25	13
		14	8	-		7	
		12	-	33	18	16	22
	2	-	34	2	26	14	
	-		13	2	1		
-	1	8					

Index of TA cell versus the load oscilation parameters



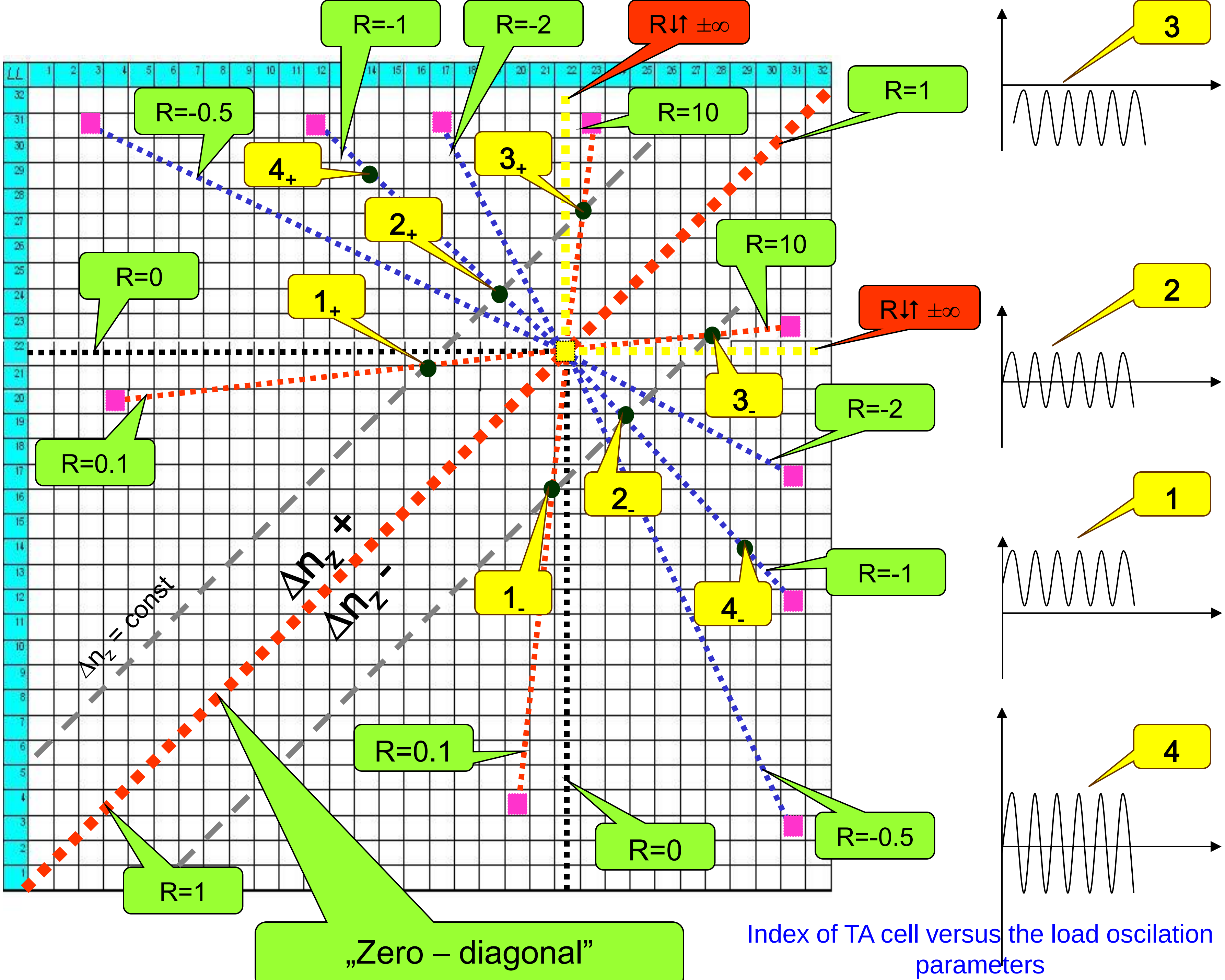
Characterization factors of load oscilations (or deformation oscilations)

$$R = \frac{\varepsilon_d}{\varepsilon_u}$$

Coefficient of load cycle asymetry

$$\kappa = \frac{\varepsilon_m}{\varepsilon_a}$$

Coefficient of load cycle constancy



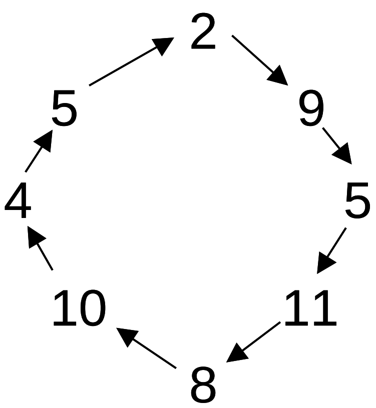
Index of TA cell versus the load oscilation parameters

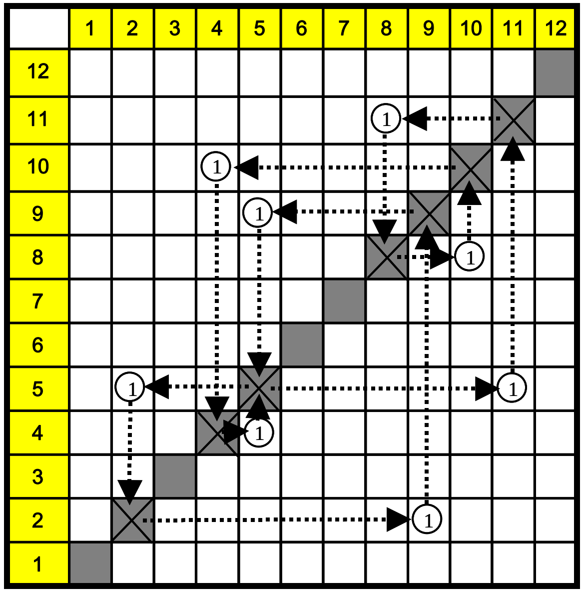
Distribution of R-values in the Transfer Array

R values	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
32	-0.50	-0.53	-0.55	-0.58	-0.62	-0.66	-0.70	-0.76	-0.82	-0.89	-0.97	-1.07	-1.19	-1.35	-1.55	-1.82	-2.21	-2.82	-3.87	-6.19	-15.45	31.18	7.76	4.43	3.10	2.39	1.94	1.63	1.41	1.24	1.11	
31	-0.45	-0.47	-0.50	-0.53	-0.56	-0.60	-0.64	-0.68	-0.74	-0.80	-0.87	-0.97	-1.08	-1.22	-1.40	-1.65	-2.00	-2.54	-3.50	-5.59	-13.96	28.16	7.01	4.00	2.80	2.15	1.75	1.47	1.27	1.12		1.11
30	-0.40	-0.42	-0.45	-0.47	-0.50	-0.53	-0.57	-0.61	-0.66	-0.71	-0.78	-0.86	-0.96	-1.09	-1.25	-1.47	-1.78	-2.27	-3.12	-4.99	-12.46	25.14	6.26	3.57	2.50	1.92	1.56	1.32	1.14		1.12	1.24
29	-0.35	-0.37	-0.39	-0.41	-0.44	-0.47	-0.50	-0.54	-0.58	-0.63	-0.69	-0.76	-0.85	-0.96	-1.10	-1.29	-1.57	-2.00	-2.75	-4.39	-10.96	22.12	5.51	3.14	2.20	1.69	1.38	1.16		1.14	1.27	1.41
28	-0.31	-0.32	-0.34	-0.36	-0.38	-0.40	-0.43	-0.46	-0.50	-0.54	-0.59	-0.65	-0.73	-0.83	-0.95	-1.12	-1.36	-1.73	-2.37	-3.79	-9.47	19.11	4.76	2.72	1.90	1.46	1.19		1.16	1.32	1.47	1.63
27	-0.26	-0.27	-0.29	-0.30	-0.32	-0.34	-0.36	-0.39	-0.42	-0.46	-0.50	-0.55	-0.62	-0.70	-0.80	-0.94	-1.14	-1.45	-2.00	-3.20	-7.97	16.09	4.00	2.29	1.60	1.23		1.19	1.38	1.56	1.75	1.94
26	-0.21	-0.22	-0.23	-0.25	-0.26	-0.28	-0.30	-0.32	-0.34	-0.37	-0.41	-0.45	-0.50	-0.56	-0.65	-0.76	-0.93	-1.18	-1.62	-2.60	-6.48	13.07	3.25	1.86	1.30		1.23	1.46	1.69	1.92	2.15	2.39
25	-0.16	-0.17	-0.18	-0.19	-0.20	-0.21	-0.23	-0.24	-0.26	-0.29	-0.31	-0.34	-0.38	-0.43	-0.50	-0.59	-0.71	-0.91	-1.25	-2.00	-4.98	10.05	2.50	1.43		1.30	1.60	1.90	2.20	2.50	2.80	3.10
24	-0.11	-0.12	-0.12	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.20	-0.22	-0.24	-0.27	-0.30	-0.35	-0.41	-0.50	-0.64	-0.87	-1.40	-3.49	7.04	1.75		1.43	1.86	2.29	2.72	3.14	3.57	4.00	4.43
23	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.09	-0.10	-0.11	-0.11	-0.12	-0.14	-0.15	-0.17	-0.20	-0.23	-0.29	-0.36	-0.50	-0.80	-1.99	4.02		1.75	2.50	3.25	4.00	4.76	5.51	6.26	7.01	7.76
22	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.05	-0.06	-0.07	-0.09	-0.12	-0.20	-0.50		4.02	7.04	10.05	13.07	16.09	19.11	22.12	25.14	28.16	31.18
21	0.03	0.03	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.07	0.08	0.09	0.10	0.12	0.14	0.18	0.25	0.40		-0.50	-1.99	-3.49	-4.98	-6.48	-7.97	-9.47	-10.96	-12.46	-13.96	-15.45
20	0.08	0.08	0.09	0.09	0.10	0.11	0.11	0.12	0.13	0.14	0.16	0.17	0.19	0.22	0.25	0.29	0.36	0.45	0.63		0.40	-0.20	-0.80	-1.40	-2.00	-2.60	-3.20	-3.79	-4.39	-4.99	-5.59	-6.19
19	0.13	0.14	0.14	0.15	0.16	0.17	0.18	0.20	0.21	0.23	0.25	0.28	0.31	0.35	0.40	0.47	0.57	0.73		0.63	0.25	-0.12	-0.50	-0.87	-1.25	-1.62	-2.00	-2.37	-2.75	-3.12	-3.50	-3.87
18	0.18	0.19	0.20	0.21	0.22	0.23	0.25	0.27	0.29	0.31	0.34	0.38	0.42	0.48	0.55	0.65	0.79		0.73	0.45	0.18	-0.09	-0.36	-0.64	-0.91	-1.18	-1.45	-1.73	-2.00	-2.27	-2.54	-2.82
17	0.23	0.24	0.25	0.26	0.28	0.30	0.32	0.34	0.37	0.40	0.44	0.48	0.54	0.61	0.70	0.82		0.79	0.57	0.36	0.14	-0.07	-0.29	-0.50	-0.71	-0.93	-1.14	-1.36	-1.57	-1.78	-2.00	-2.21
16	0.27	0.29	0.30	0.32	0.34	0.36	0.39	0.41	0.45	0.49	0.53	0.59	0.65	0.74	0.85		0.82	0.65	0.47	0.29	0.12	-0.06	-0.23	-0.41	-0.59	-0.76	-0.94	-1.12	-1.29	-1.47	-1.65	-1.82
15	0.32	0.34	0.36	0.38	0.40	0.43	0.45	0.49	0.53	0.57	0.63	0.69	0.77	0.87		0.85	0.70	0.55	0.40	0.25	0.10	-0.05	-0.20	-0.35	-0.50	-0.65	-0.80	-0.95	-1.10	-1.25	-1.40	-1.55
14	0.37	0.39	0.41	0.43	0.46	0.49	0.52	0.56	0.61	0.66	0.72	0.79	0.88		0.87	0.74	0.61	0.48	0.35	0.22	0.09	-0.04	-0.17	-0.30	-0.43	-0.56	-0.70	-0.83	-0.96	-1.09	-1.22	-1.35
13	0.42	0.44	0.46	0.49	0.52	0.55	0.59	0.63	0.68	0.74	0.81	0.90		0.88	0.77	0.65	0.54	0.42	0.31	0.19	0.08	-0.04	-0.15	-0.27	-0.38	-0.50	-0.62	-0.73	-0.85	-0.96	-1.08	-1.19
12	0.47	0.49	0.52	0.55	0.58	0.62	0.66	0.71	0.76	0.83	0.91		0.90	0.79	0.69	0.59	0.48	0.38	0.28	0.17	0.07	-0.03	-0.14	-0.24	-0.34	-0.45	-0.55	-0.65	-0.76	-0.86	-0.97	-1.07
11	0.52	0.54	0.57	0.60	0.64	0.68	0.73	0.78	0.84	0.91		0.91	0.81	0.72	0.63	0.53	0.44	0.34	0.25	0.16	0.06	-0.03	-0.12	-0.22	-0.31	-0.41	-0.50	-0.59	-0.69	-0.78	-0.87	-0.97
10	0.56	0.59	0.63	0.66	0.70	0.74	0.80	0.85	0.92		0.91	0.83	0.74	0.66	0.57	0.49	0.40	0.31	0.23	0.14	0.06	-0.03	-0.11	-0.20	-0.29	-0.37	-0.46	-0.54	-0.63	-0.71	-0.80	-0.89
9	0.61	0.64	0.68	0.72	0.76	0.81	0.86	0.93		0.92	0.84	0.76	0.68	0.61	0.53	0.45	0.37	0.29	0.21	0.13	0.05	-0.03	-0.11	-0.18	-0.26	-0.34	-0.42	-0.50	-0.58	-0.66	-0.74	-0.82
8	0.66	0.69	0.73	0.77	0.82	0.87	0.93		0.93	0.85	0.78	0.71	0.63	0.56	0.49	0.41	0.34	0.27	0.20	0.12	0.05	-0.02	-0.10	-0.17	-0.24	-0.32	-0.39	-0.46	-0.54	-0.61	-0.68	-0.76
7	0.71	0.75	0.79	0.83	0.88	0.94		0.93	0.86	0.80	0.73	0.66	0.59	0.52	0.45	0.39	0.32	0.25	0.18	0.11	0.05	-0.02	-0.09	-0.16	-0.23	-0.30	-0.36	-0.43	-0.50	-0.57	-0.64	-0.70
6	0.76	0.80	0.84	0.89	0.94		0.94	0.87	0.81	0.74	0.68	0.62	0.55	0.49	0.43	0.36	0.30	0.23	0.17	0.11	0.04	-0.02	-0.08	-0.15	-0.21	-0.28	-0.34	-0.40	-0.47	-0.53	-0.60	-0.66
5	0.81	0.85	0.89	0.94		0.94	0.88	0.82	0.76	0.70	0.64	0.58	0.52	0.46	0.40	0.34	0.28	0.22	0.16	0.10	0.04	-0.02	-0.08	-0.14	-0.20	-0.26	-0.32	-0.38	-0.44	-0.50	-0.56	-0.62
4	0.85	0.90	0.95		0.94	0.89	0.83	0.77	0.72	0.66	0.60	0.55	0.49	0.43	0.38	0.32	0.26	0.21	0.15	0.09	0.04	-0.02	-0.08	-0.13	-0.19	-0.25	-0.30	-0.36	-0.41	-0.47	-0.53	-0.58
3	0.90	0.95		0.95	0.89	0.84	0.79	0.73	0.68	0.63	0.57	0.52	0.46	0.41	0.36	0.30	0.25	0.20	0.14	0.09	0.04	-0.02	-0.07	-0.12	-0.18	-0.23	-0.29	-0.34	-0.39	-0.45	-0.50	-0.55
2	0.95		0.95	0.90	0.85	0.80	0.75	0.69	0.64	0.59	0.54	0.49	0.44	0.39	0.34	0.29	0.24	0.19	0.14	0.08	0.03	-0.02	-0.07	-0.12	-0.17	-0.22	-0.27	-0.32	-0.37	-0.42	-0.47	-0.53
1		0.95	0.90	0.85	0.81	0.76	0.71	0.66	0.61	0.56	0.52	0.47	0.42	0.37	0.32	0.27	0.23	0.18	0.13	0.08	0.03	-0.02	-0.06	-0.11	-0.16	-0.21	-0.26	-0.31	-0.35	-0.40	-0.45	-0.50
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32

Load signal sequence restoring

During TA processing – the information about load signal sequence is lost.
Exact signal sequence restoring from the TA is possible only for very simple cases (short-closed-loop events).
In other cases the load sequence can be restored only in an aproximate way (on the basis of Markov chains theory)





MP ⇒ *MP''*

Markov chains

$$p_i(k) = \sum_{j \in S} p_j(k-1) \cdot MP'_{ji} \qquad \forall_i \in S$$

$$\left\{ p_i = \sum_{j \in S} p_j \cdot MP'_{ji} \qquad \forall_i \in S \right.$$

(Hidden Markow chains)

Rabiner L.R., *A tutorial on hidden Markov models and selected applications in speech recognition*, Proceedings of the IEEE 77(2), pp 257-286, 1989

Status defined by 2-parameters: s –Load Level, k – direction of signal change (binary: „up" or „down").

Example of signal sequence restoring

KONFERENCJA MECHANIKA W LOTNICTWIE

Input data

-KONRFNEJCEAMCEANHKI-AWLTIONTCWI-E-

29-11-15-14-18-6-14-5-10-3-5-1-13-3-5-1-14-8-11-9-29-1-23-12-20-9-15-14-20-3-23-9-5-29

PO	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	22	23	24	25	26	27	28	29	3	31	32
32																																
31																																
3																																
29	1				1						1																					
28																																
27																																
26																																
25																																
24																																
23									1			1																				
22																																
21																																
2			1						1																							
19																																
18						1																										
17																																
16																																
15														2																		
14					1			1										1		1												
13			1																													
12																				1												
11									1						1																	
1			1																													
9															1														2			
8											1																					
7																																
6														1																		
5	2									1																			1			
4																																
3					2																		1									
												1	1										1									

Output data

JCWI-E-KONRFNEJCEAMCWLTIONTCEANHKI-

Load sequence restoring - example

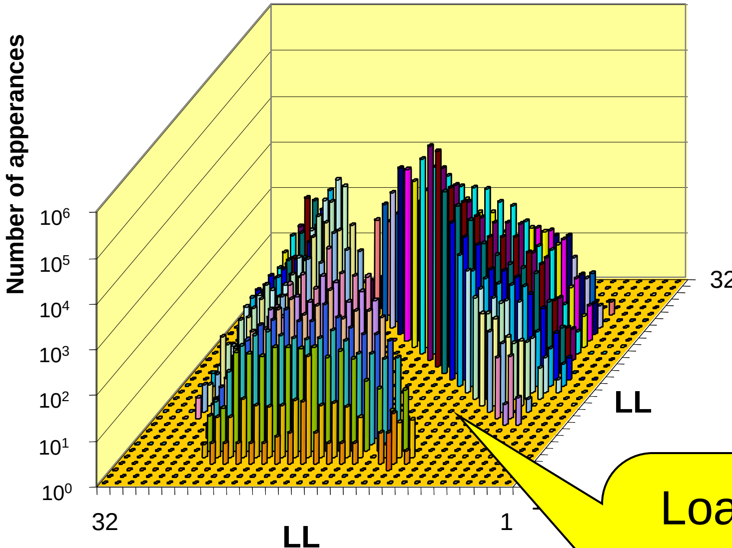
ASCII codes of the Load Levels

ASCII code of Load Levels

Load Level	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ASCII symbol	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Load Level	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
ASCII symbol	Q	R	S	T	U	V	W	X	Y	Z	#	$	-	*	!	+

KoSMOS – Load Spectrum Standard applied in Germany

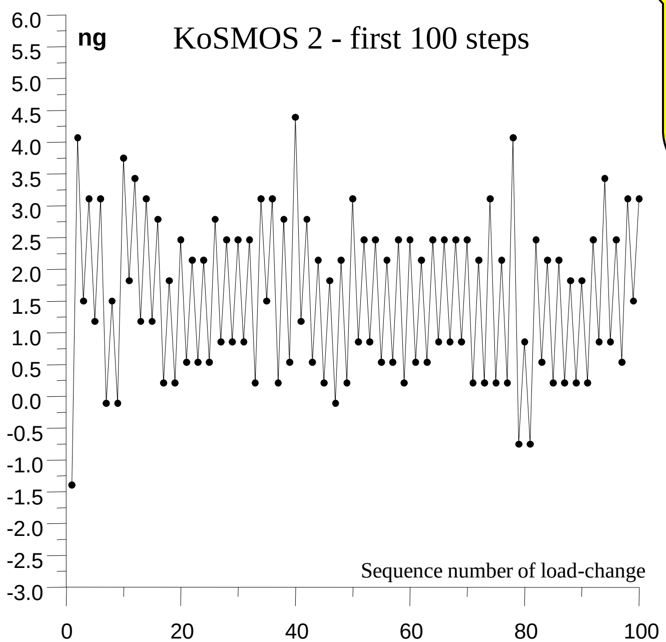
Kollektiv für Segelflugzeuge, Motorflugzeuge bis ca. 2 Abfulgmasse und Motor-Segler

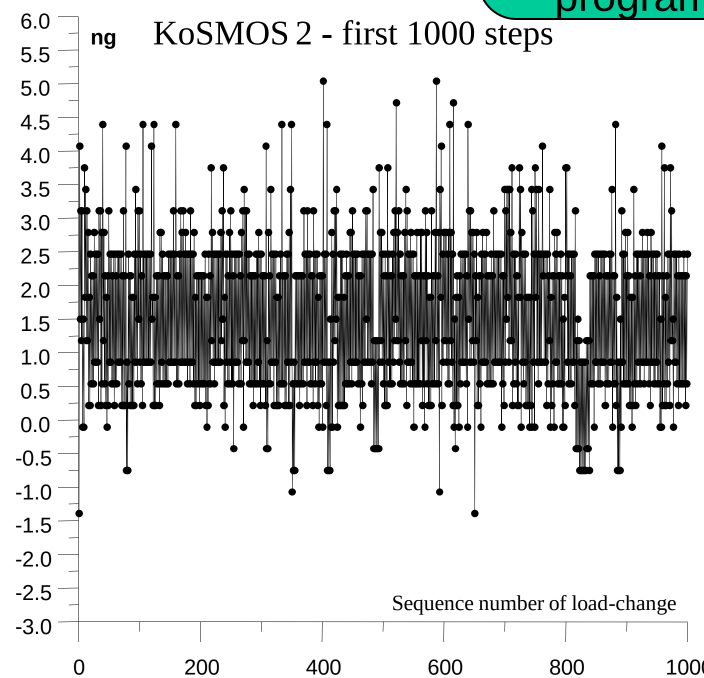



```
ZIQLRLVQVJPKRLRMUPUNTOTOTMSNSNSNULQLUMTHRMTOUPVOULSNSNTOTNUNTOTNSNS
NSNUOULUOUIXSXNTOUOUPUPUNSKSNTLQLSNTOUHSNSNSNSNSNSNSIQPUHUPUOTOTOUM
TMSNTOTOTOTOTNSNSNSNSLSNSHTOTOTNSLSMSLSNSMSNTNSNTLSNSNTMUPUOTOTOUOT
OTOTOTNUPVPUNTOTJRMSNTNSNSNSNSNSMRLQJUPVNSNTOTMSLTNTOWNSNSNSNTNTOTM
RLVKRLSLSNSNTOTOTOUOTOTNTNSMTNUNTOTOTOUIWRWMTOTKSNSNUNSNUPUPUOTNTHT
OTOUOUNSNUMUKSHYTXSXOTOTOTOUOTOTOTLSNSNULSNSNTOTOULSNTNSNUPVOTOTOVF
SNSNUHXSXSXQVMVNSLRLQKVPUPUNUNUNUPUOTNTOTOTMSMTLSNSNSNSNTOTOVOTNUNS
NSLQLSNSNSNTNSKWRWRWRWRWJSMRMSNTOUNUOUJSNTOTOTNSMRLQGRMRLSNTOTOTOTM
RKULSNSNTMSNTNVOTOTMTOTOTMRMUOTOVLRMTOUPUPULTOTOTMRFTOTMYKPIUNSMRMR
MSNTMTHRMSNUGVQWPUOUPVOTNSNSNSNSNTOVHQLSLSMRMSNZORMUPUOTOVNSMSNSNSM
TOTOTOTNTOTLSNSNSNSNSNSNVOTOUKSLQKPKSKR  JUNTNSNTOUPUJPKVMSNTNSNUPU
PUPVPUKVLSNVJPKSNTKSNSNSIONSNSNUNTORKVPUOT  MS
TNTOTNSNSNULWRWQWRXSXSXSXSXSXRWRWRXOTOTOTOV
NSNSKVOTOTHUPXSXSXQVLSNTNTMTOTMTOUPUPVP ...
```

Example of ASCII code of the fatigue test programme

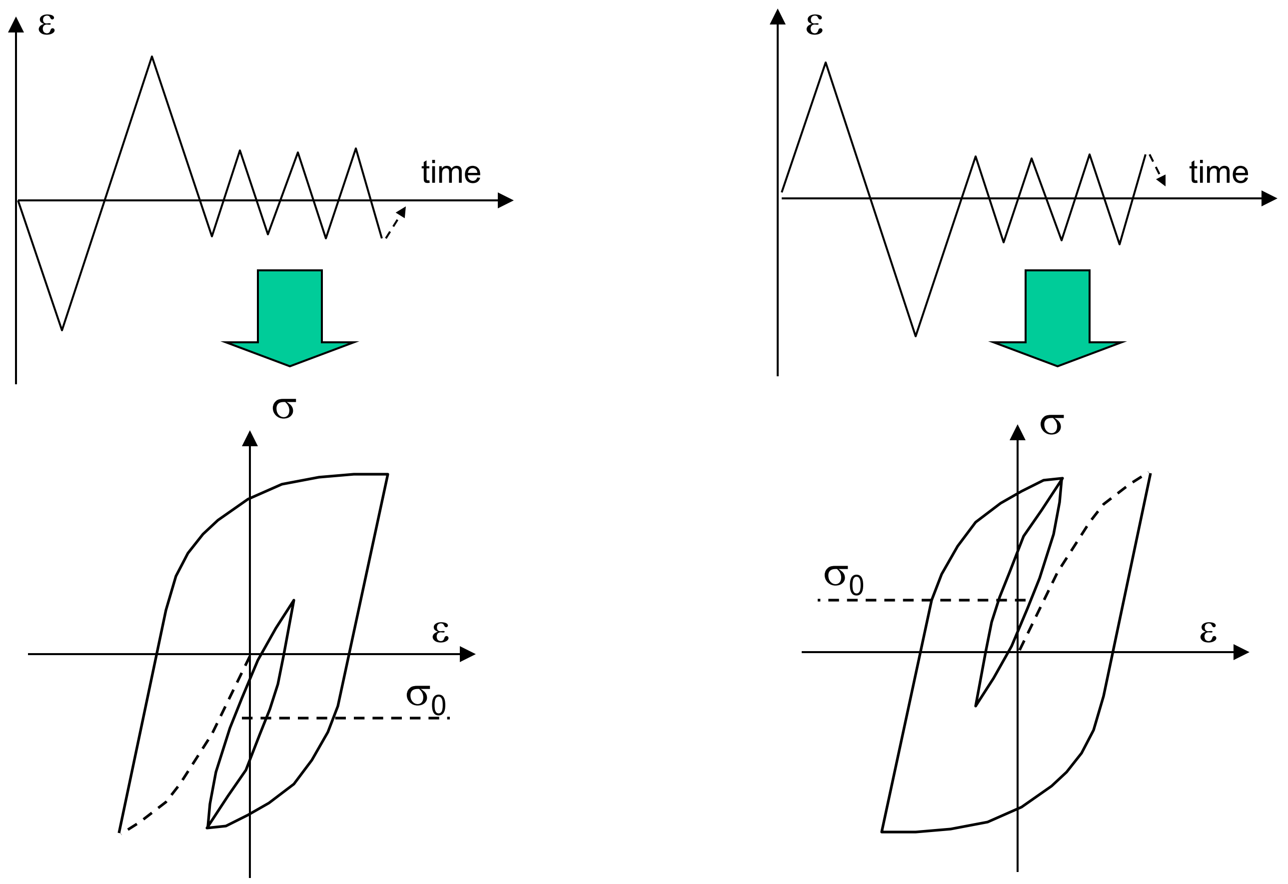
Load cycles near the „0-diagonal" are intentionaly neglected!!!





Algoritms of full-load-cycles counting

Importance of load-cycles sequence: example

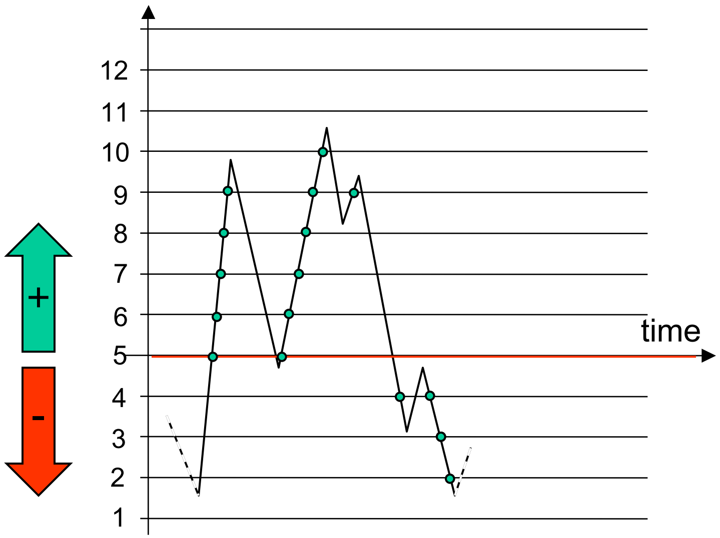


•Put the attention on the mean value (σ_0) of small hysteresis-loop
•It corresponds with mean value of the stress in critical cross-section of the material, caused by initial overloading
•The value and the sign depend on sequence of loading

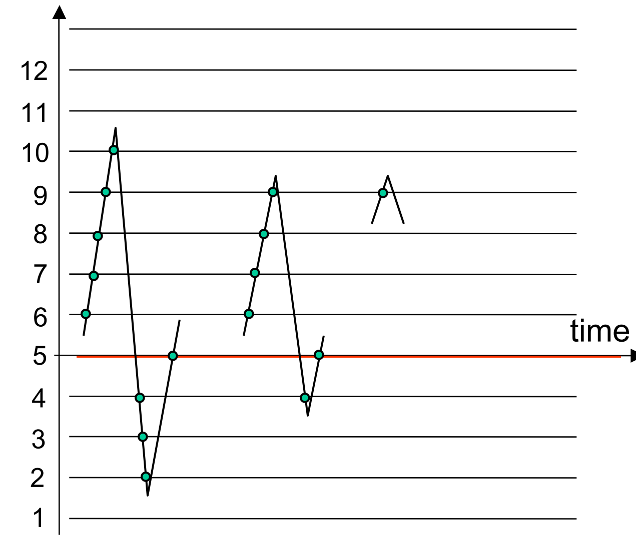
Algoritms of full-load-cycles counting

Counting of LL exceeding

Load Levels represented by lines



Load Levels represented by lines



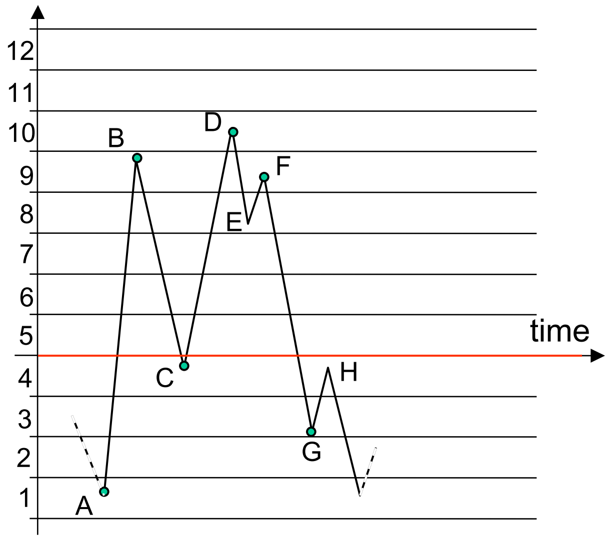
Load Level	Number of passes
1	0
2	1
3	1
4	2
5	2
6	2
7	2
8	2
9	3
10	1
11	0
12	0

- Designate load levels and reference load level
- For signal increase cases – begin the counting of LL exceeeding when signal is over reference load level
- For signal decrease cases – begin the counting of LL exceeding when signal is under reference load level
- Starting from extremal exceeded LL – complete the full load cycles

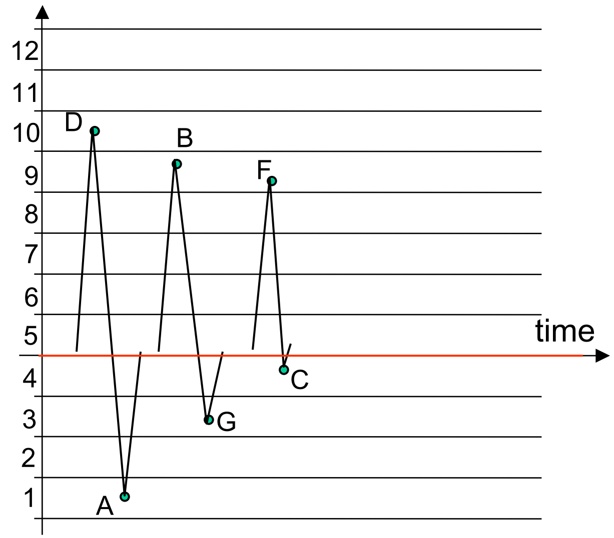
Algoritms of full-load-cycles counting

Counting of local extremes

Load Level - intervals



Load level - intervals



Load Level	Nomber of LE
1	1
2	0
3	1
4	1
5	0
6	0
7	0
8	0
9	2
10	1
11	0
12	0

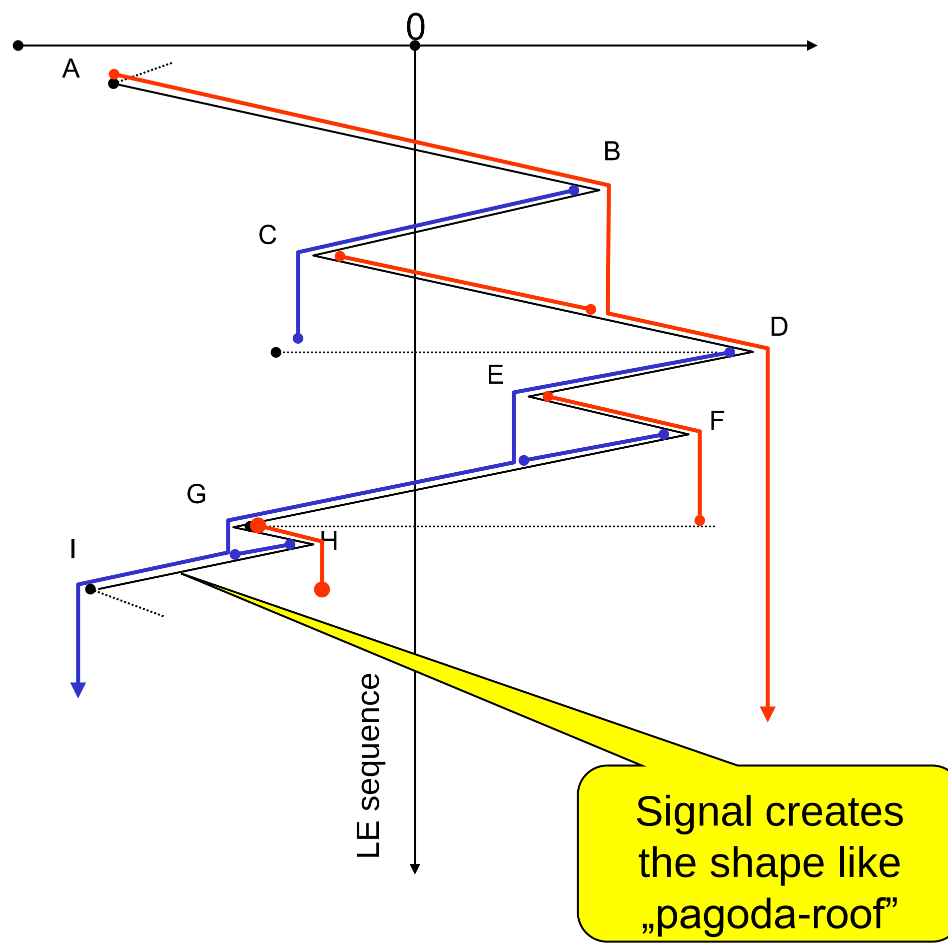
- Designate load levels and reference load level
- Mark all local ekstremes (LE) related with change of signal angle
- Ignore the LE created by signal changes, which do not exceed the reference LL
- Starting from extremal values of LE – complete the full load cycles

Rainflow Fatigue Cycle Counting

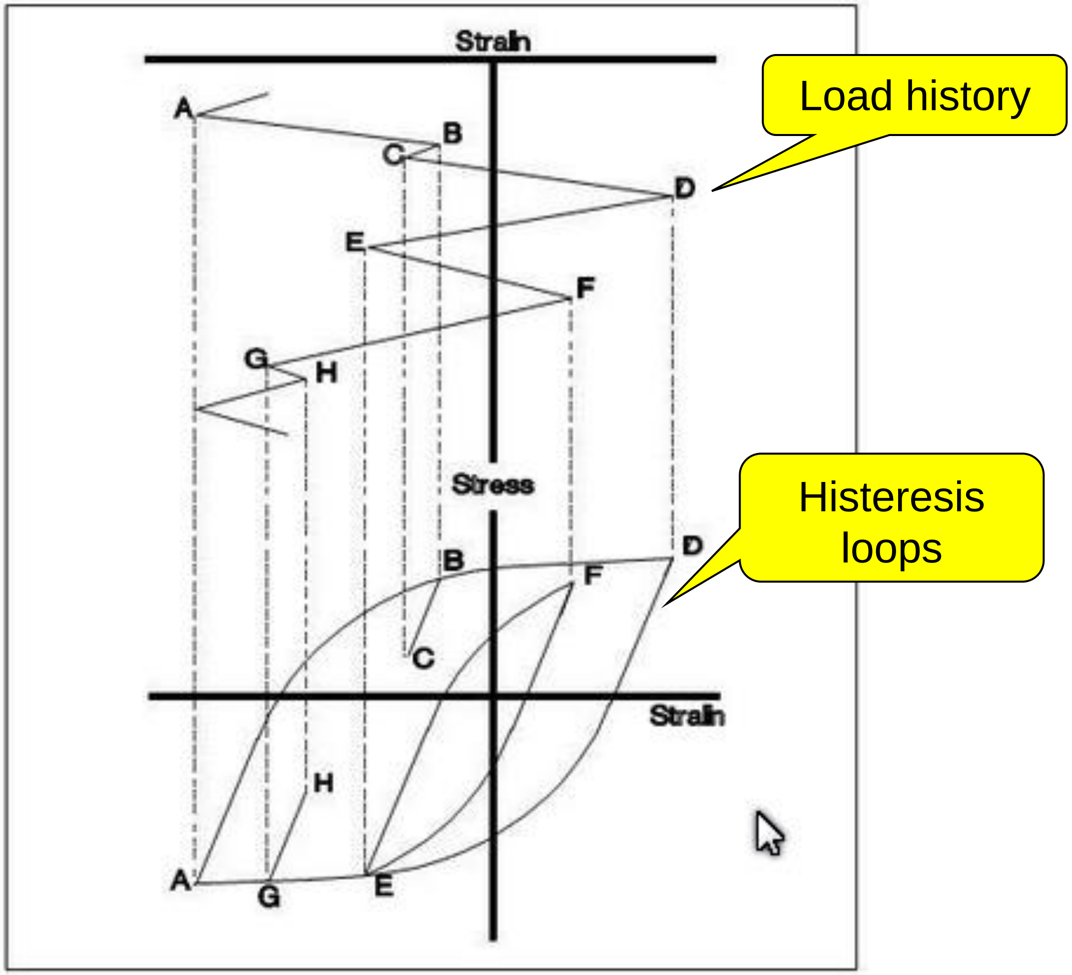
https://vibrationdata.wordpress.com/2012/10/31/rainflow-fatigue-cycle-counting/

Endo & Matsuishi (1968) developed the Rainflow Counting method by relating stress reversal cycles to streams of rainwater flowing down a Pagoda.

Rainflow Counting



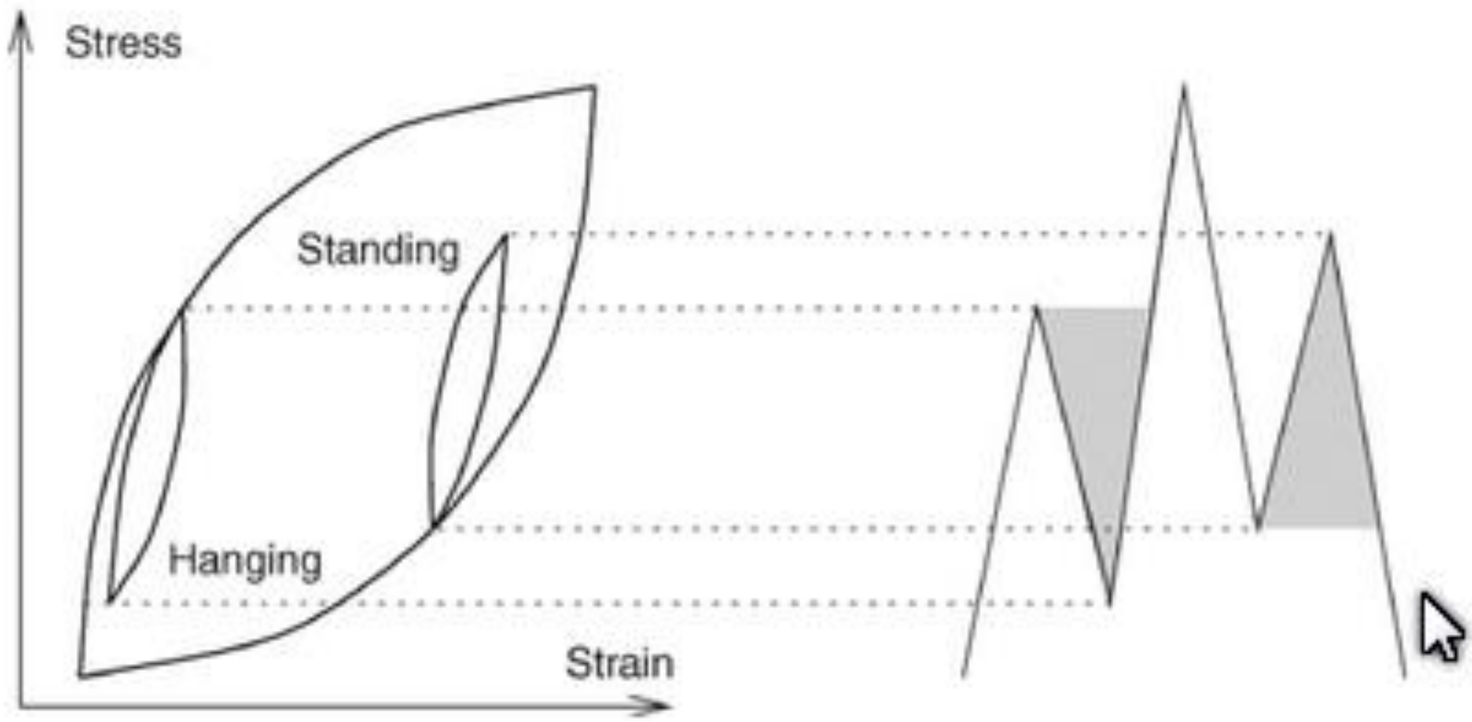
Identyfication of closed histeresis-loops



http://www.myshared.ru/slide/886624/

A-D, B-C, E-F, G-H
(similary to the tips of histeresis-loops)

Identyfication of closed histeresis-loops



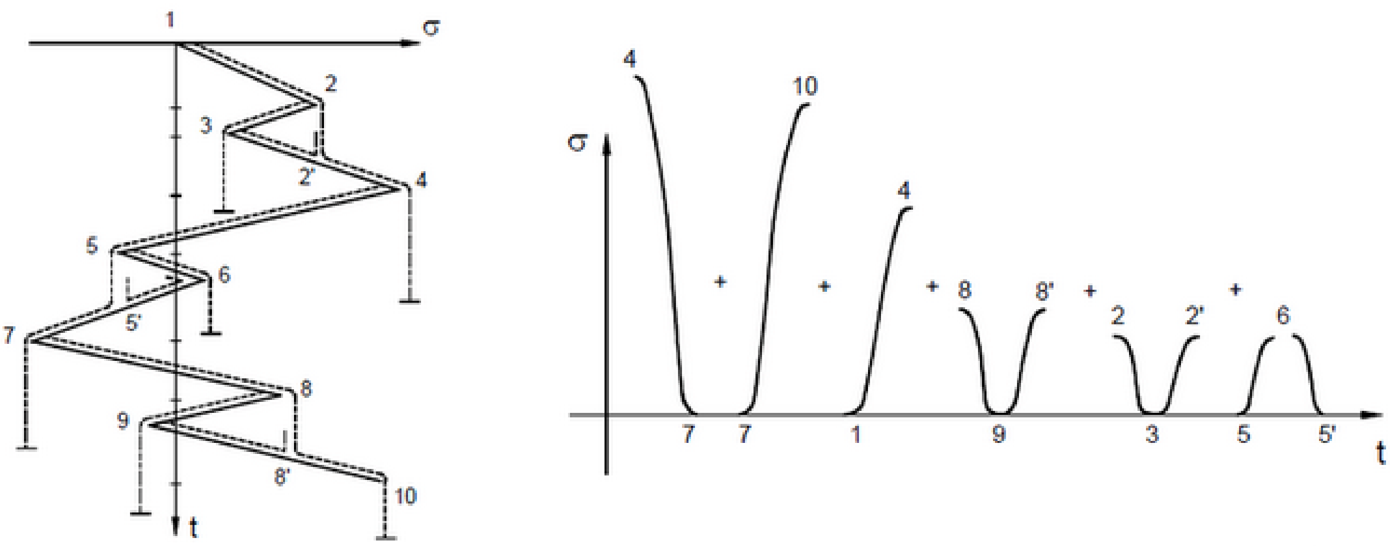
Source: ttps://training.dewesoft.com/online/course/fatigue-analysis
https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-92897-5_1076

Rainflow Counting alghoritm rule:

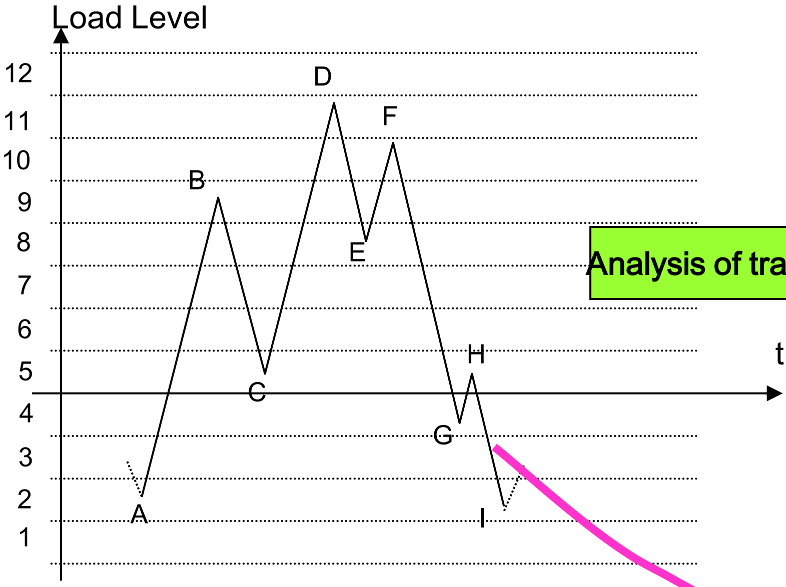
Water-stream has the source in each depression, and can flow until:

A/ meets the depression bigger than the depth of own source

B/ meets the flow, which drops from higher step of the „roof”



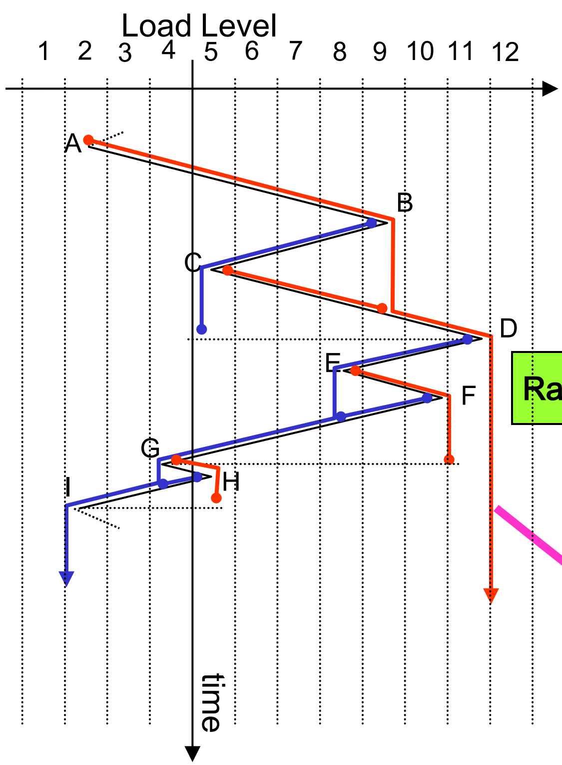
https://www.researchgate.net/figure/Rainflow-counting-method-a-peak-and-valley-stress-history-b-equivalent-stress-history_fig1_307935057



Analysis of transfers

	1	2	3	4	5	6	7	8	9	10	11	12
12												
11								1				
10				1								
9					1							
8										1		
7												
6												
5		1									1	
4					1							
3												
2									1			
1												

Result: Transfer Array



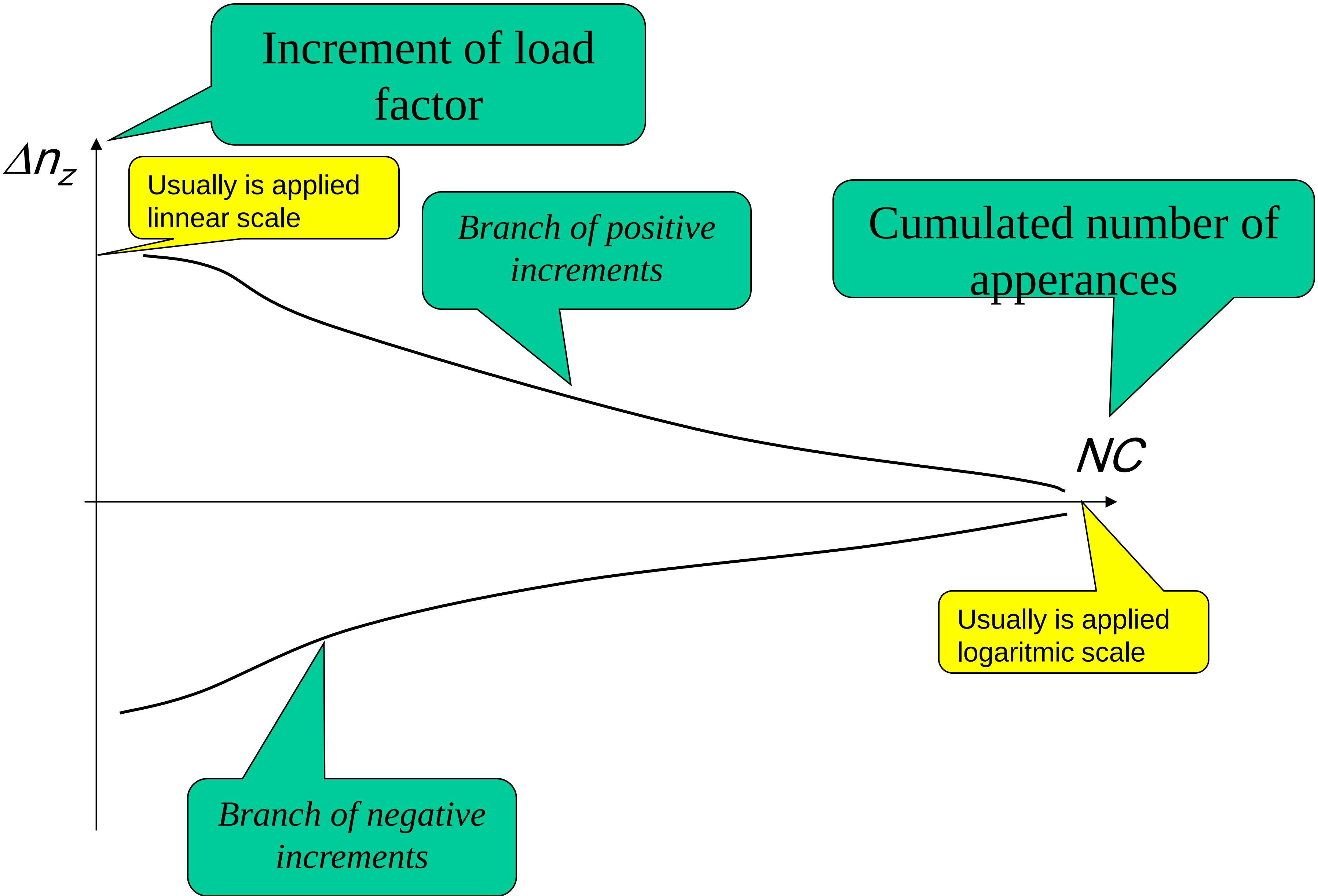
Rainflow Counting

	1	2	3	4	5	6	7	8	9	10	11	12
12												
11		1										
10								1				
9					1							
8										1		
7												
6												
5				1					1			
4					1							
3												
2											1	
1												

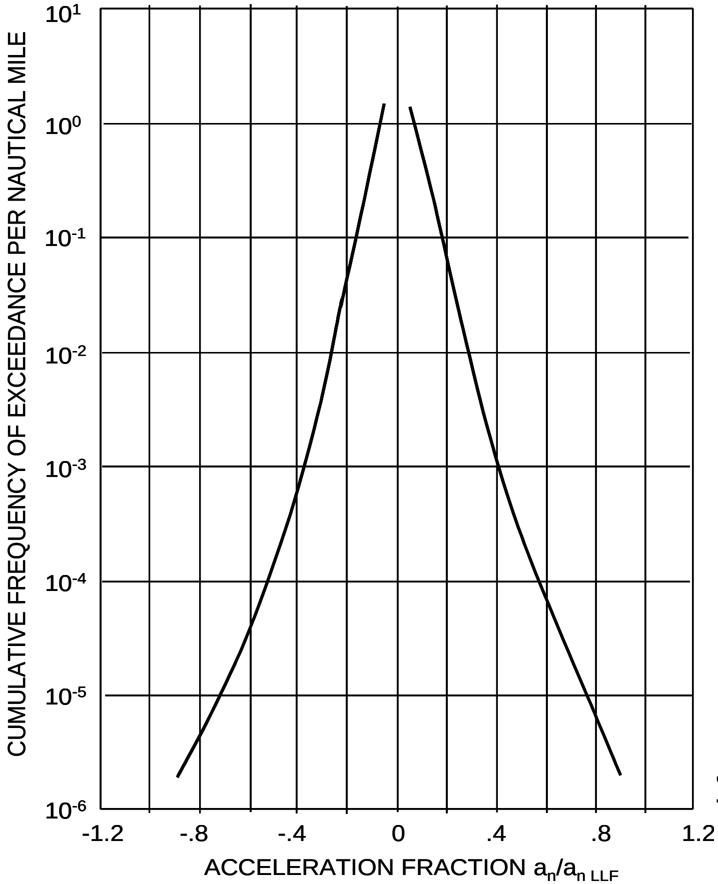
Result: Half-Cylces Array

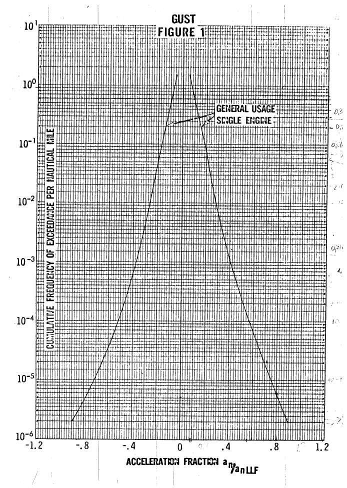
Half-Cycles Array and incremental load spectra

Incremantal load spectra (clasic form)



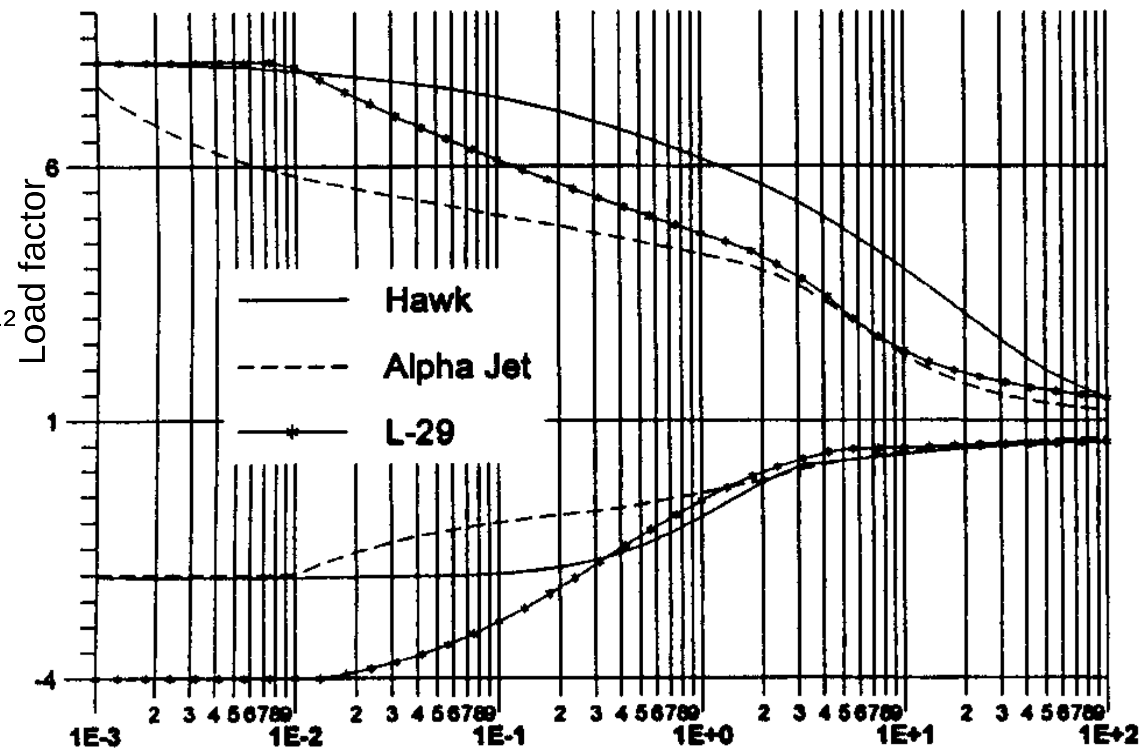
Incremantal load spectra (clasic form) - examples





Source:
Engineering and Manufacturing Division Airframe Branch

Fatigue evaluation of wing and associated structure on small airplanes
Report No. AFS-120-73-2, sponsored by Department of Transportation,
Federal Aviation Administration 1973



Transition from a Transfer Array to an incremental LS

Input-data
((MicroPilot logdata)

↓

Implementation of Load Levels and Filtration

↓

Chain of Local Extremes

↓

Rainflow Counting Alghoritm

↓

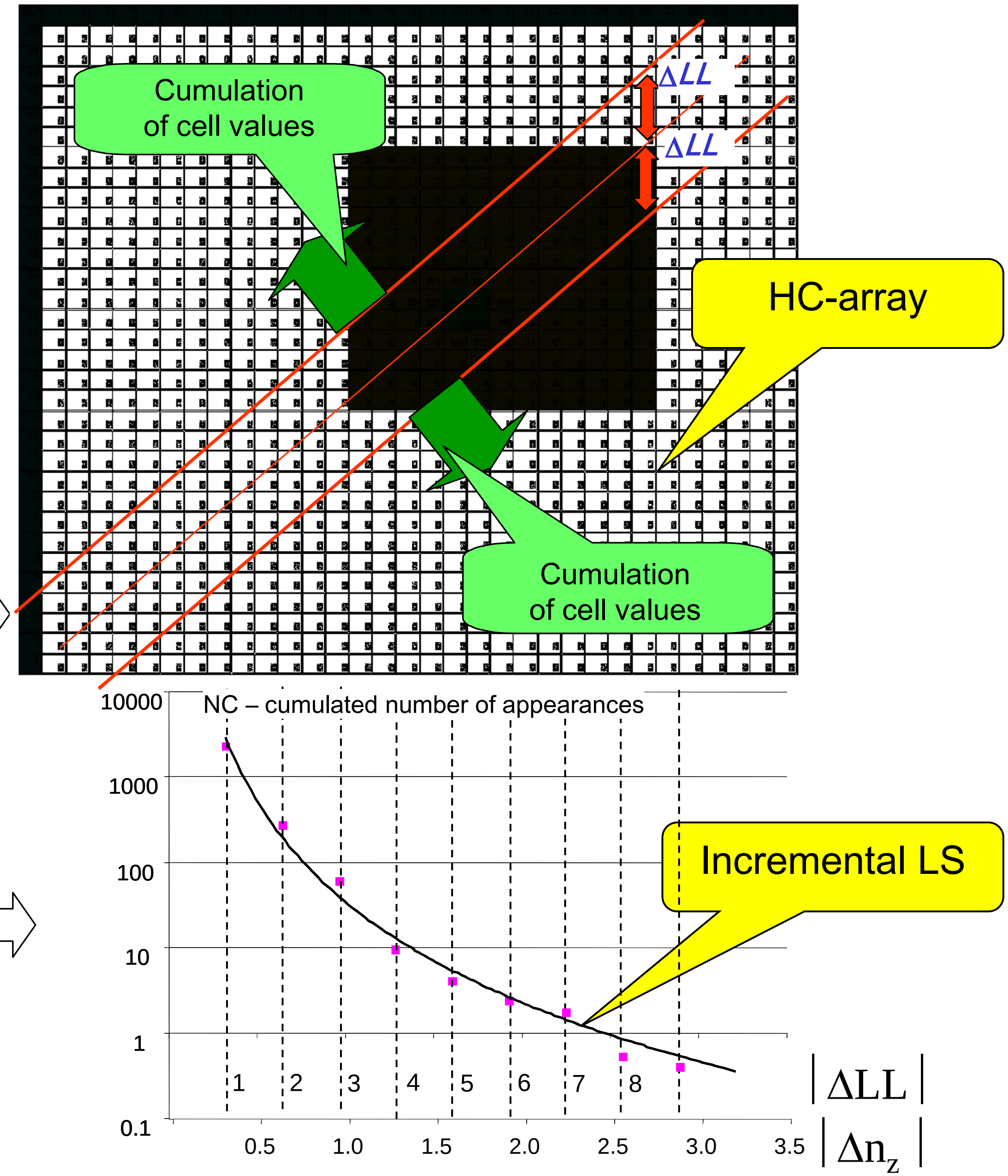
Summarized HC-array

↓

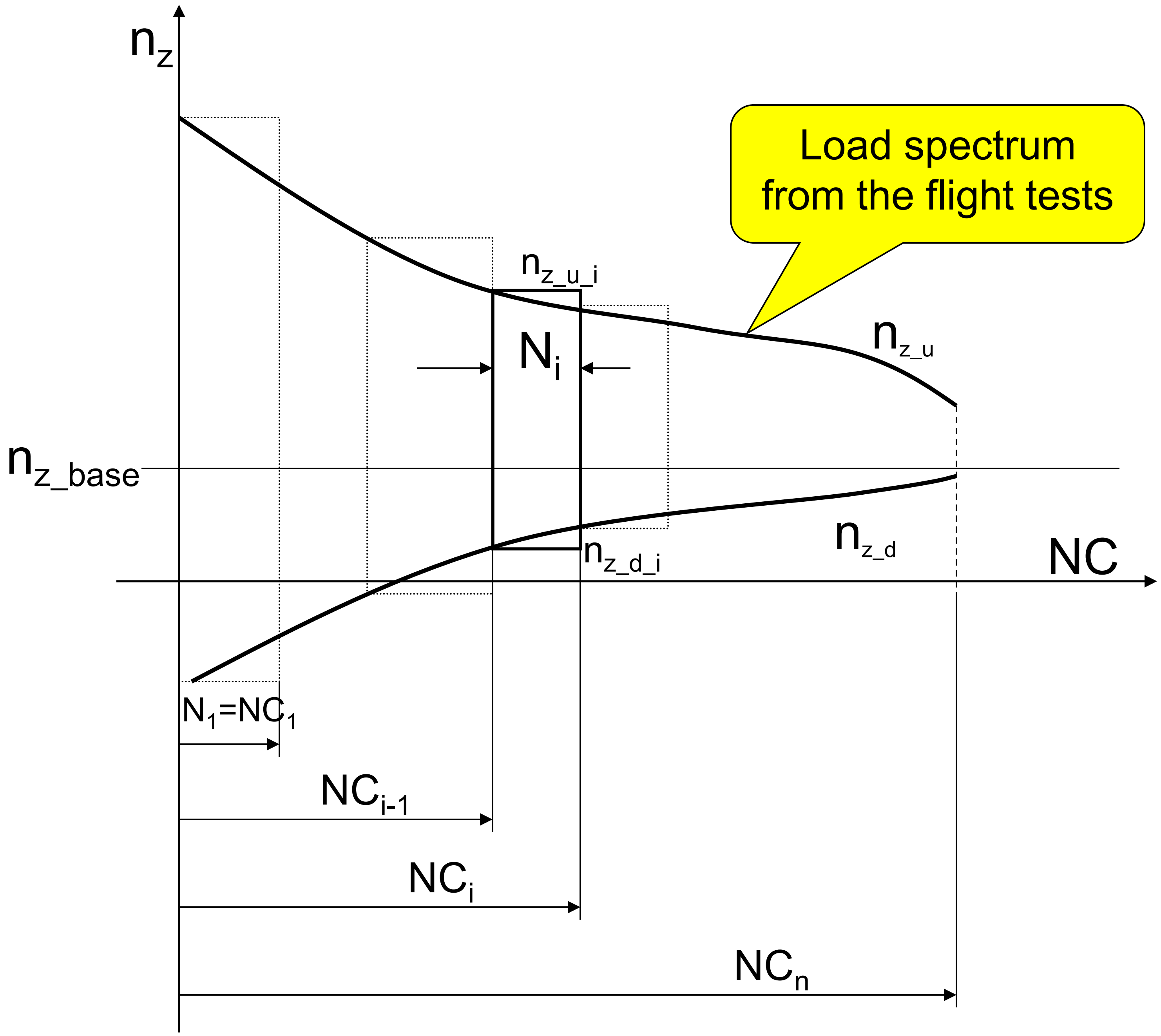
Analysis of apperances of particular load increments

↓

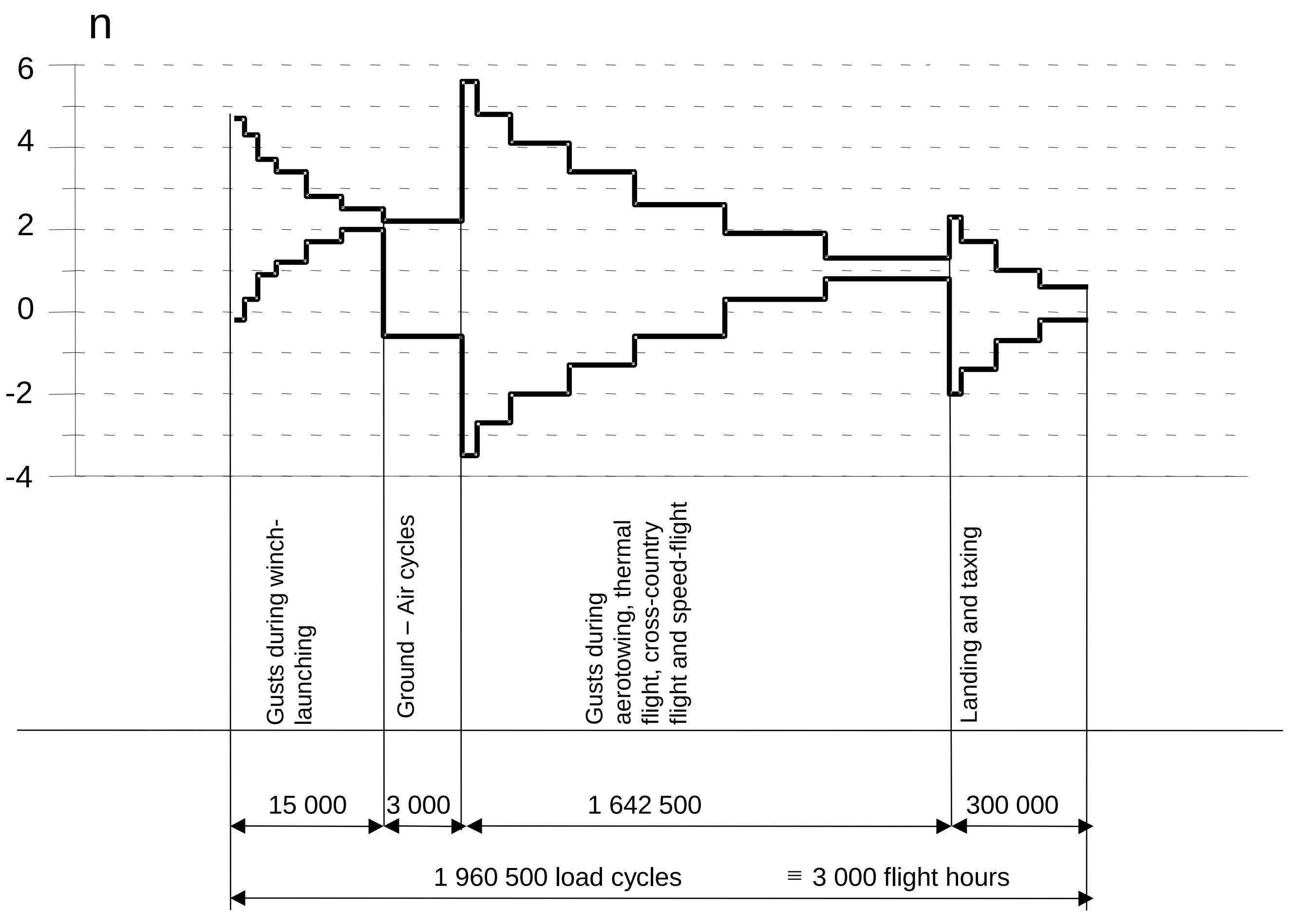
Incremental LS



Transition from incremental LS to the block form of a



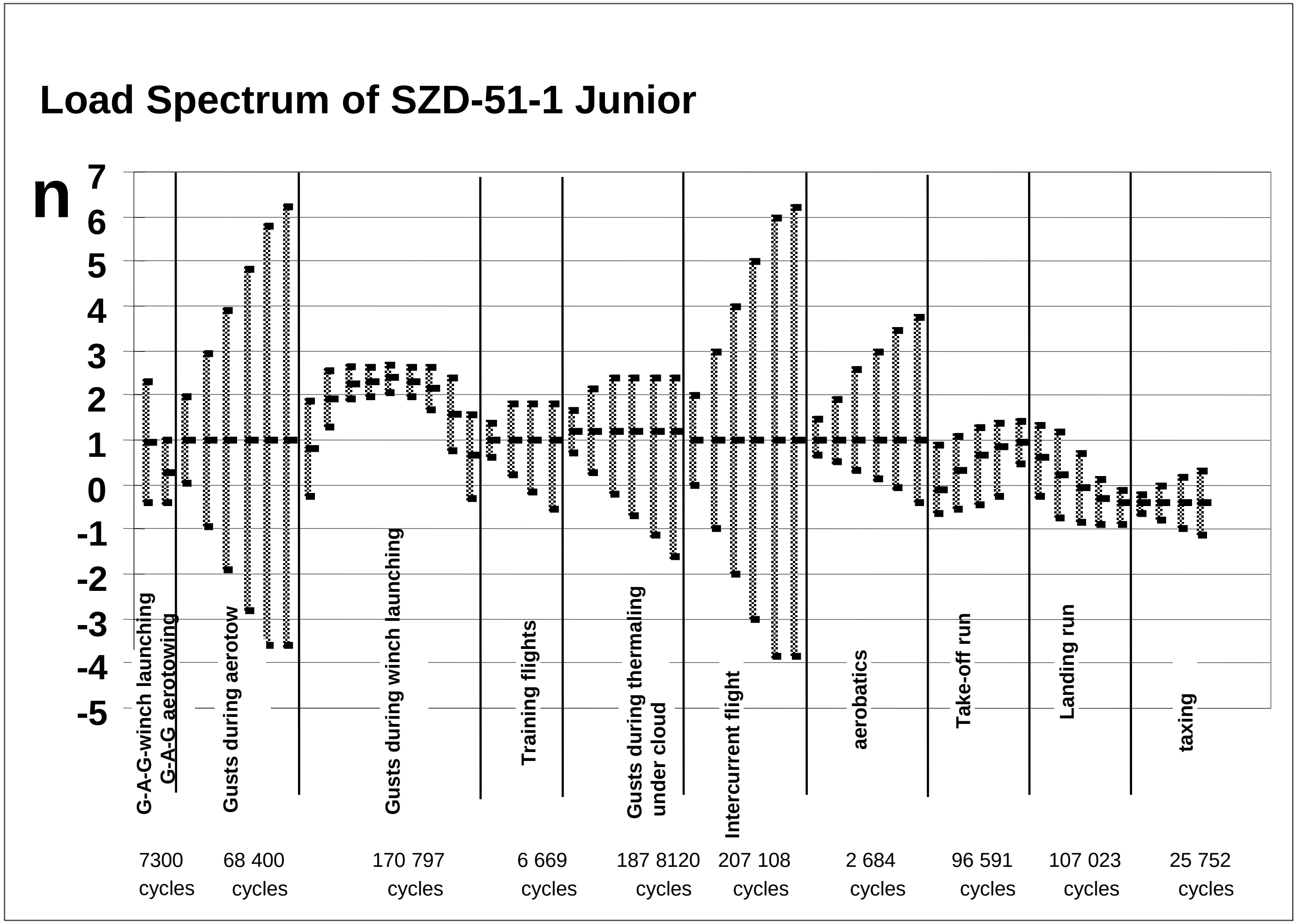
LS as a set of blocks of load cycles



Glider Load Spectrum elaborated by Thielemann –Franzmeyer

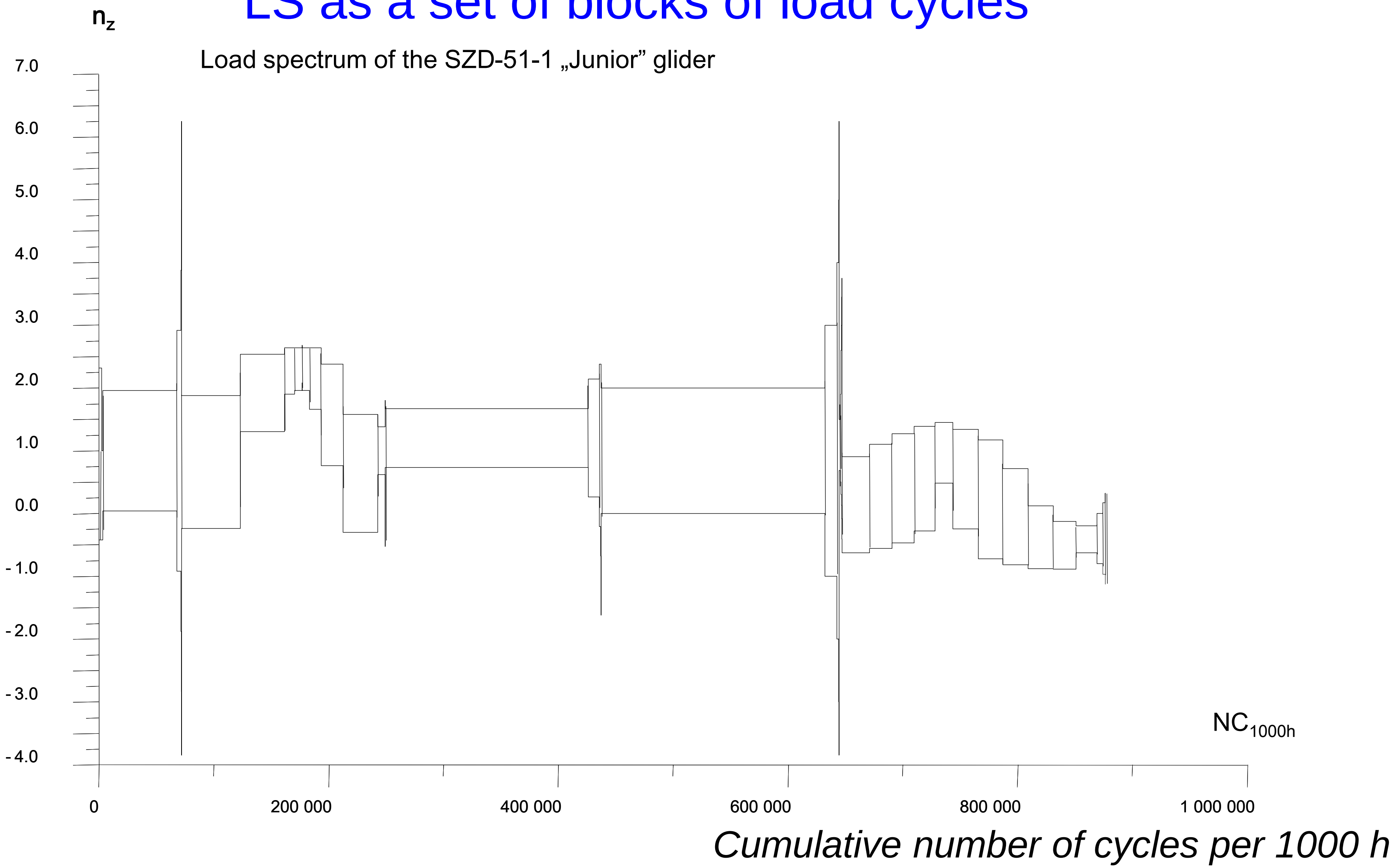
(applied in Germany in 60's of the XX century for testing GFRP gliders)

LS as a set of blocks of load cycles



Load spectrum of SZD-51-1glider - elaboration based on Stafiej method

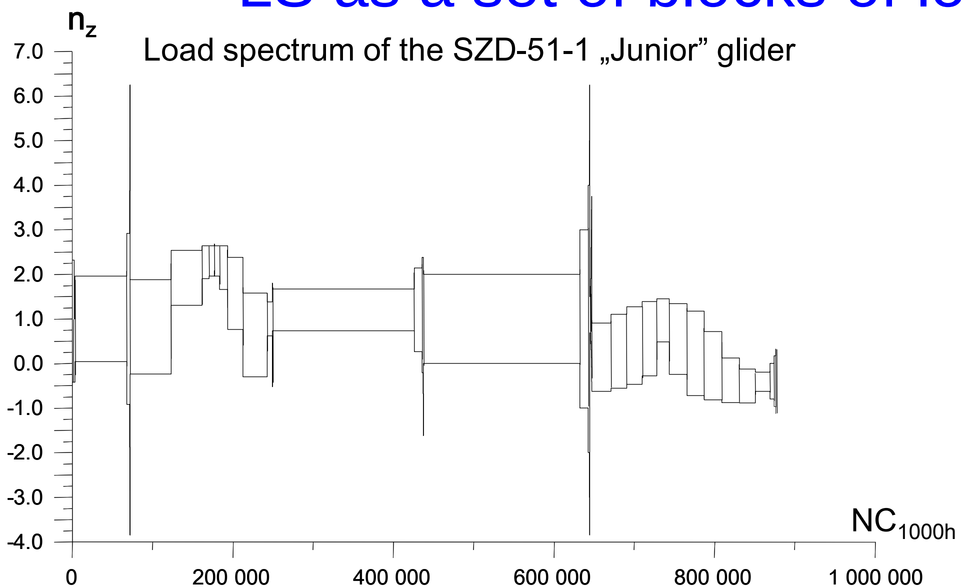
LS as a set of blocks of load cycles

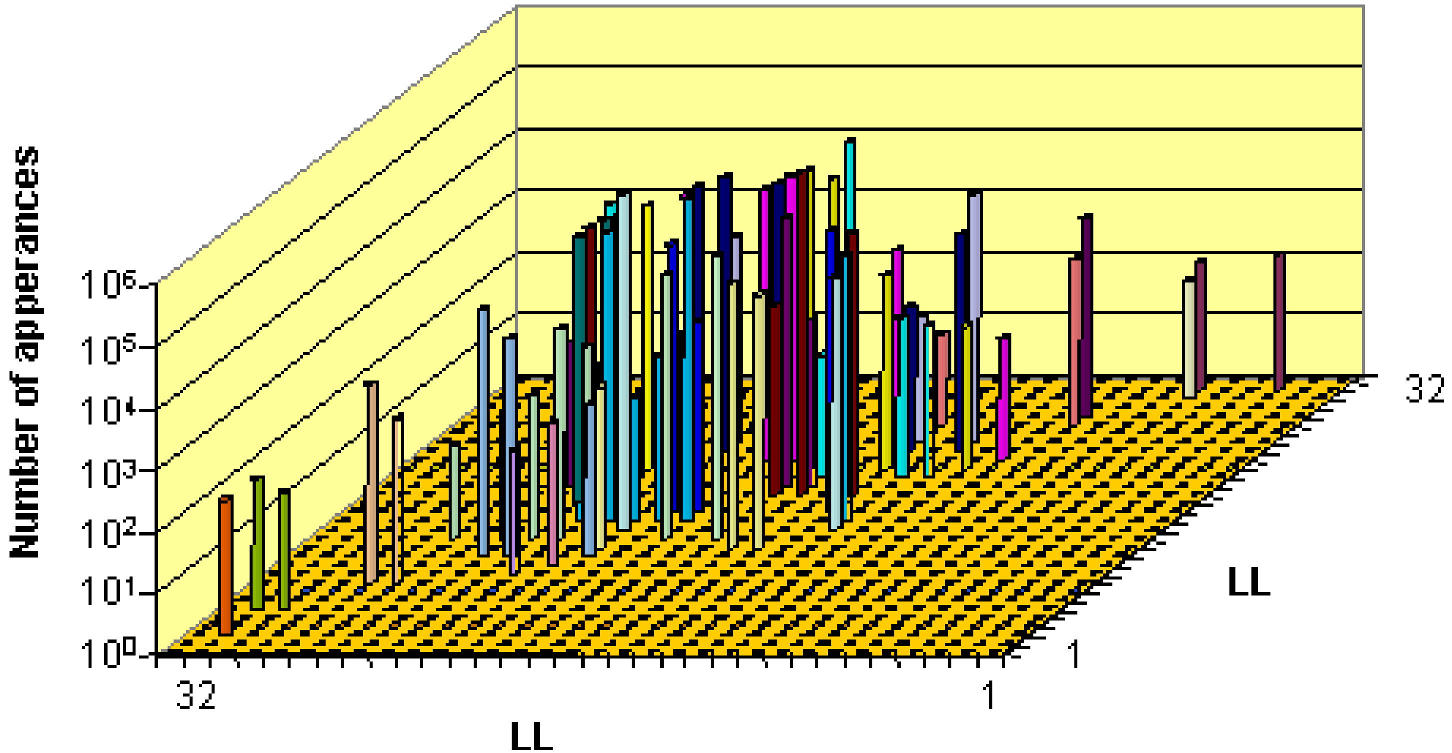


Load spectrum of SZD-51-1glider – elaboration based on Stafiej method

another form of the LS presentation

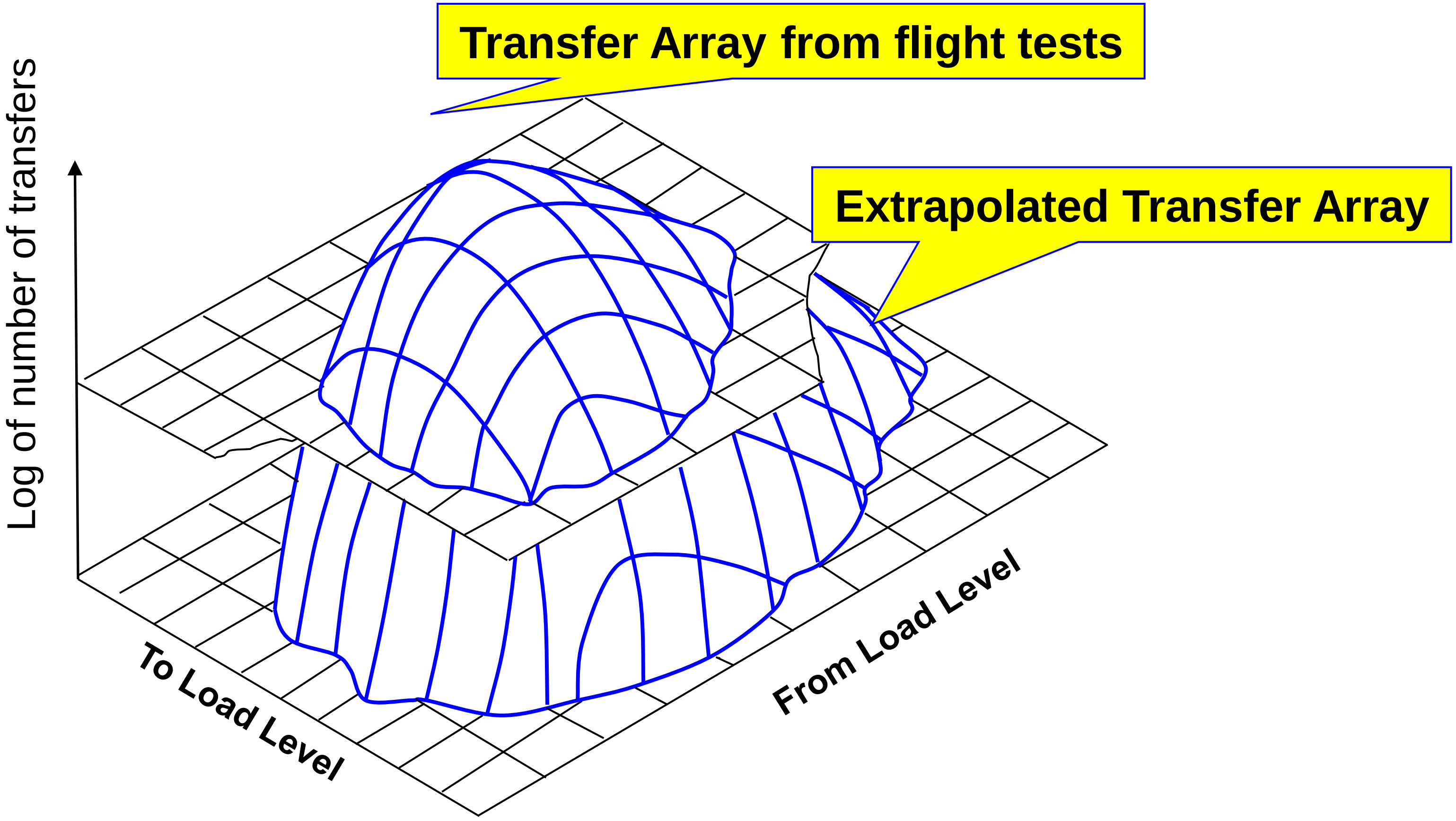
LS as a set of blocks of load cycles versus a Transfer A



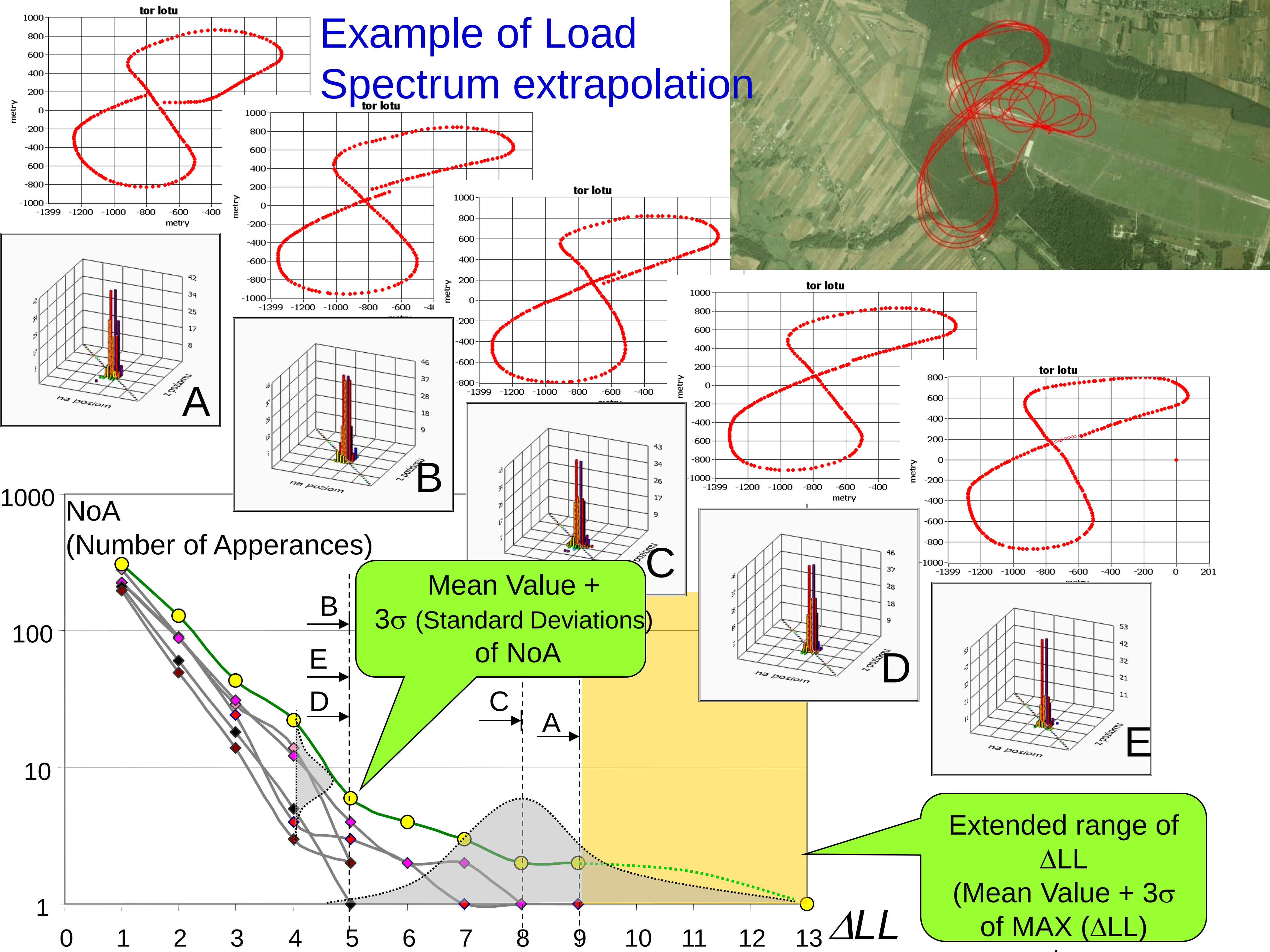


Extrapolation of Load Spectra

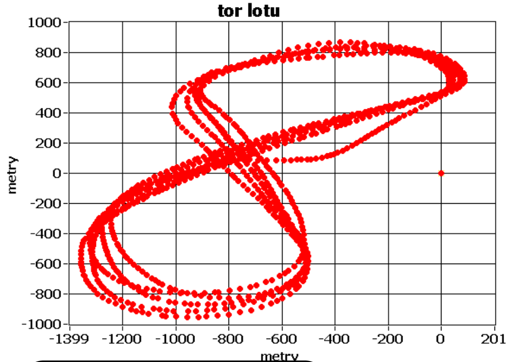
Idea of Load spectrum extrapolation

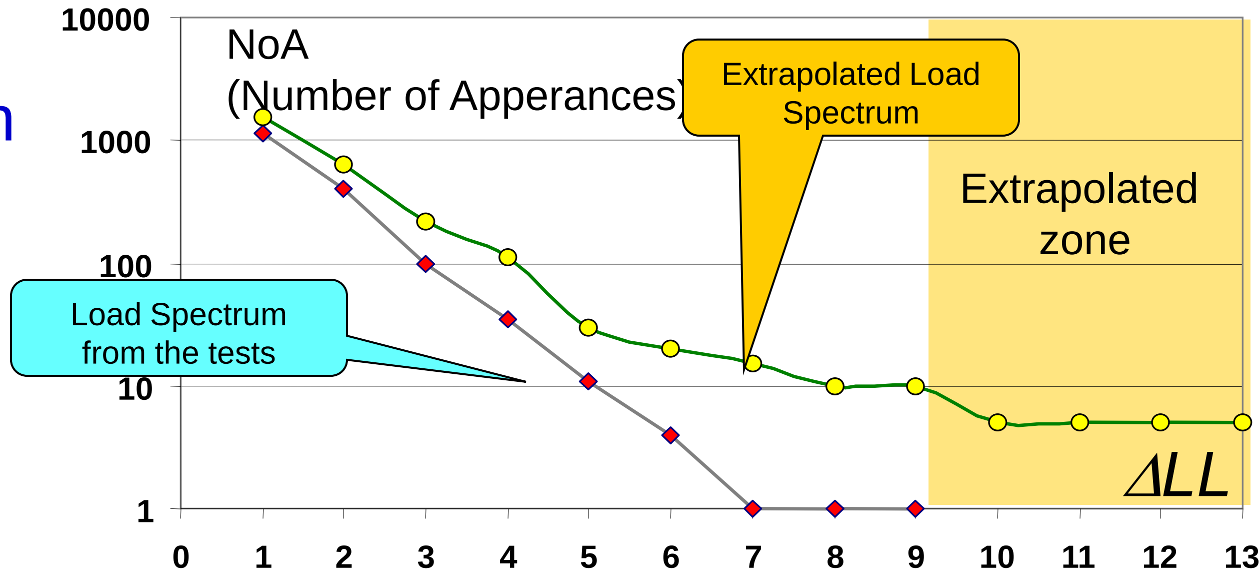


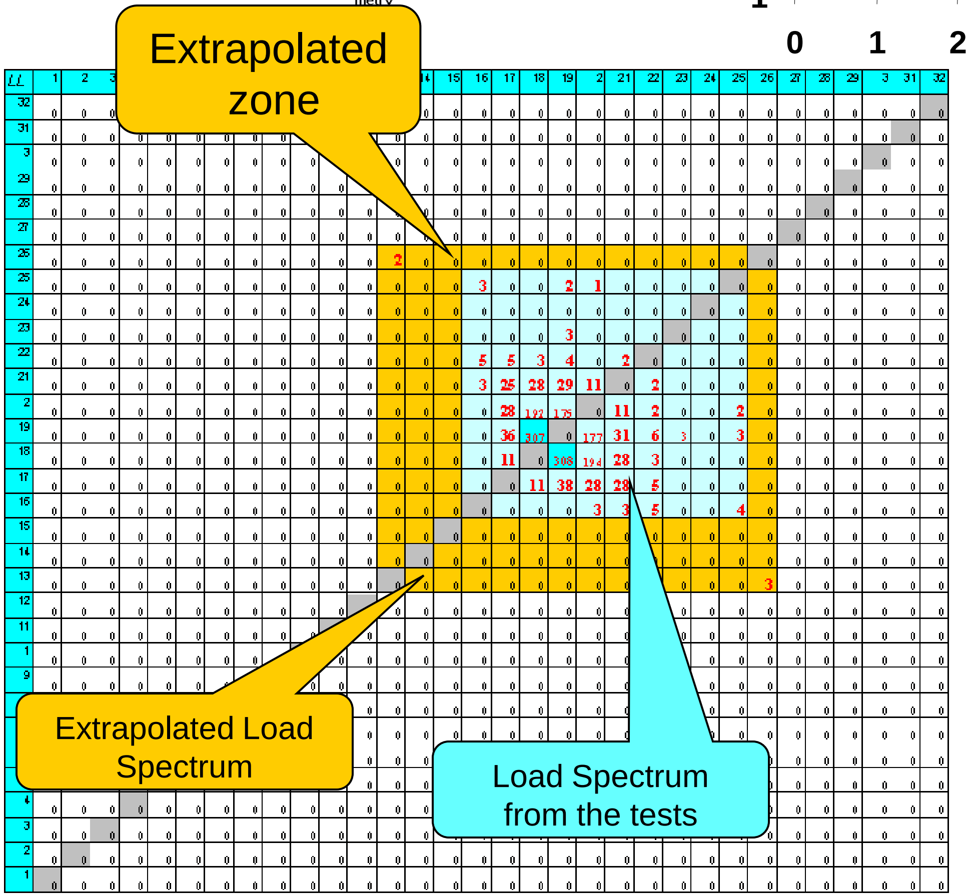
Example of Load Spectrum extrapolation

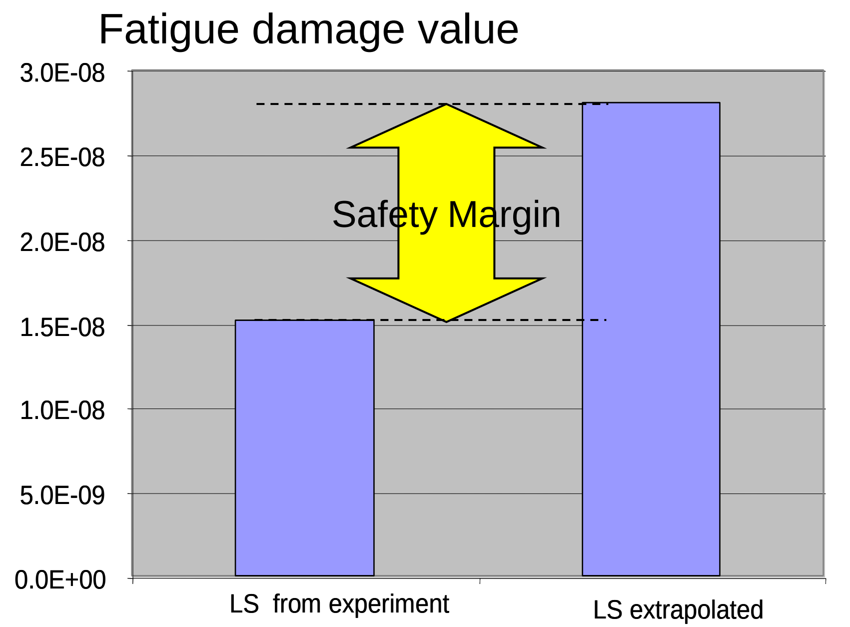


Example of Load Spectrum extrapolation







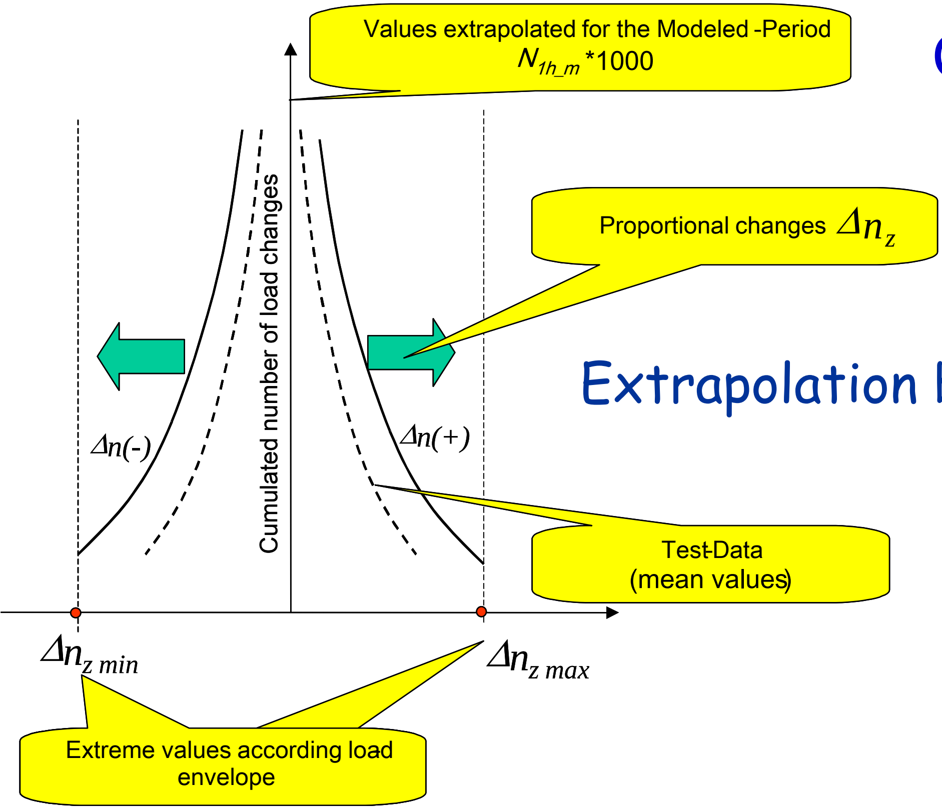


Calculated on the basis of the High diagram presented already in previos slid

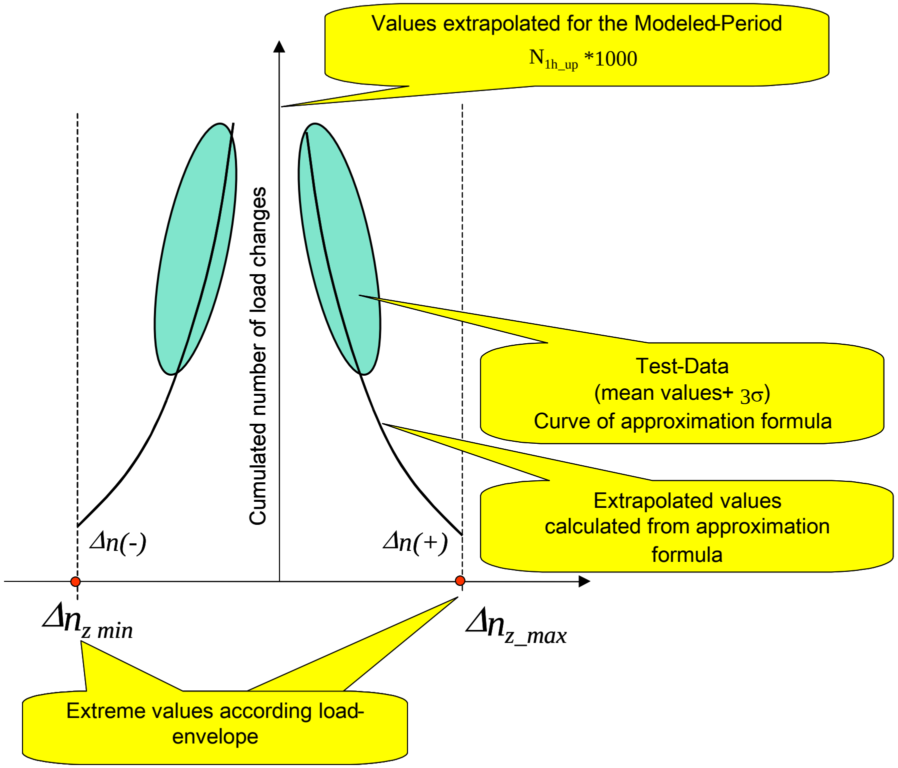
Other methods of LS extrapolation

Trivial methods of LS extrapolation
(without phisical basis)

Extrapolation by the test-data range rescaling



+3σ load number concept



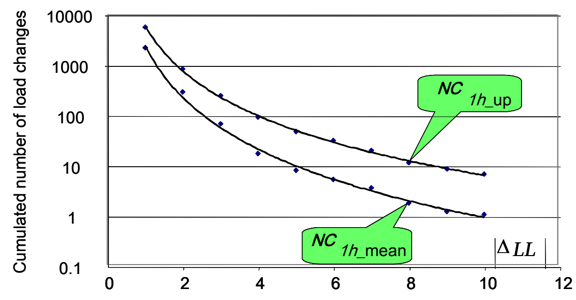
Stochastic method of LS extrapolation 1/4

T-array
Flight No1

Cumulation

Cumulated (summarized) T-array from experiment

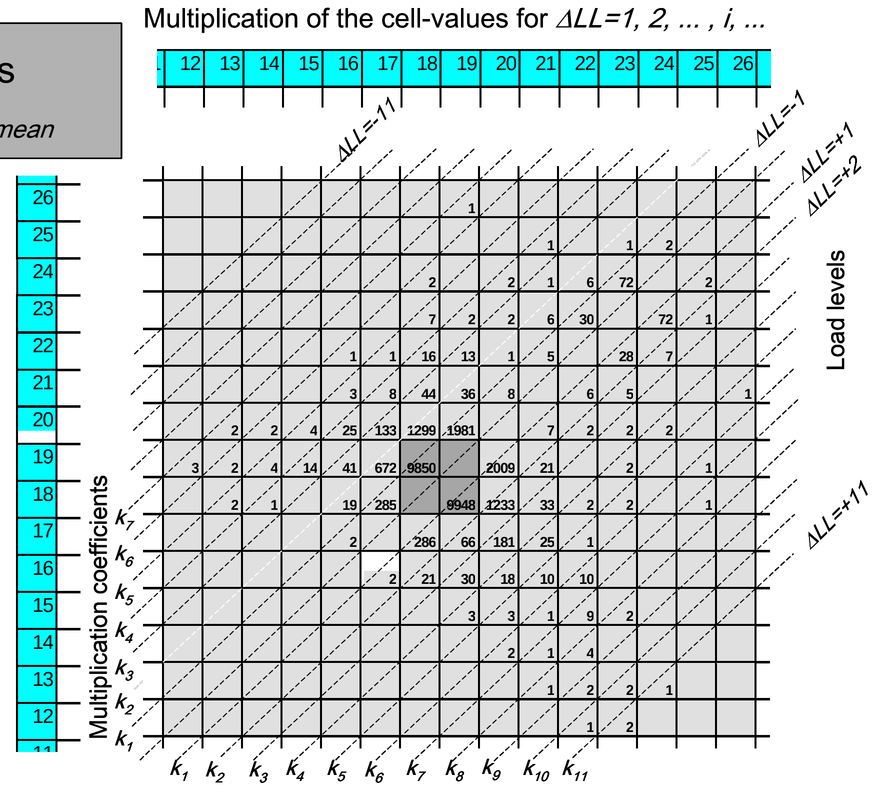
Statistical analysis of ΔLL apperances



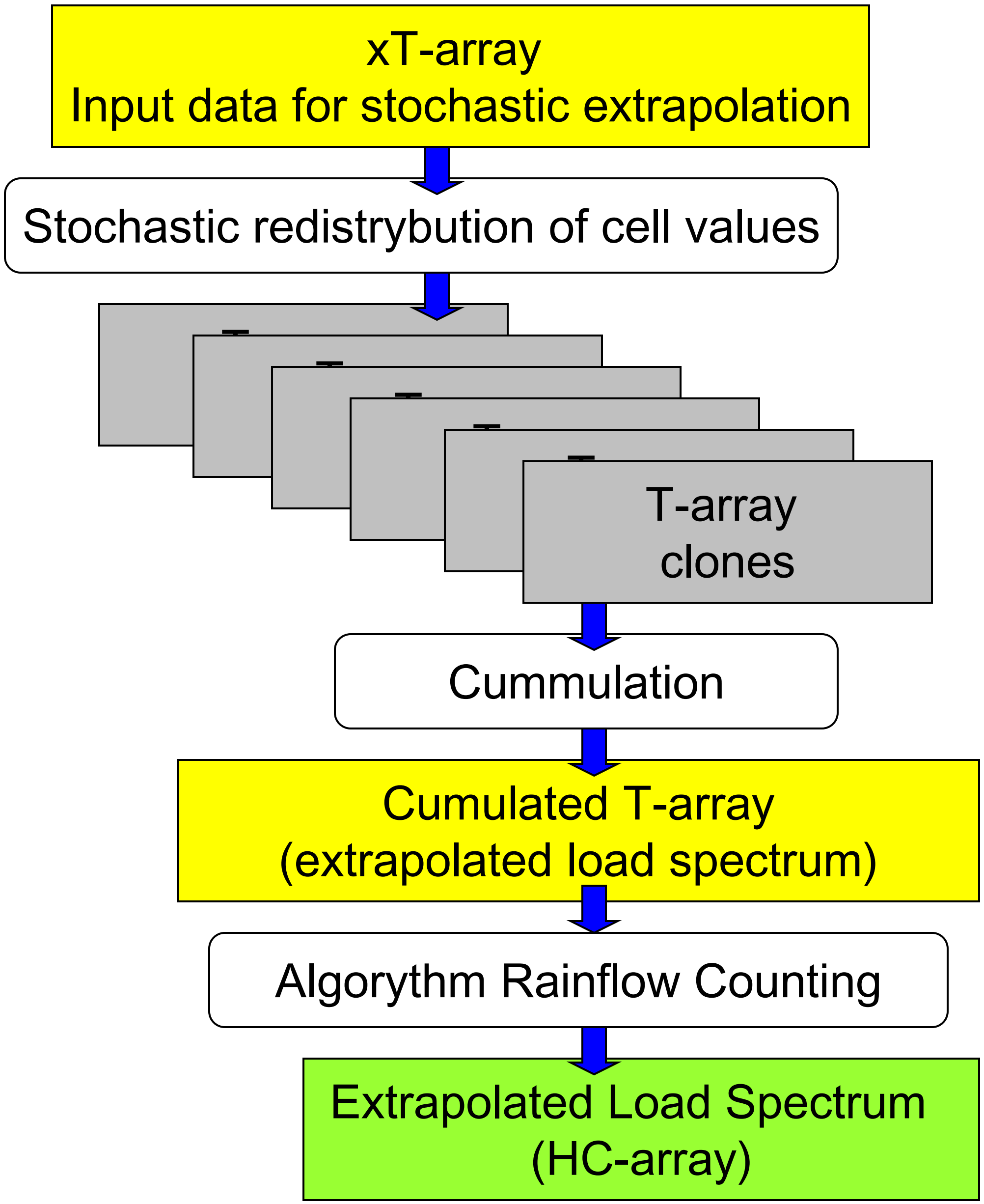
Array of ratios
$k_i = NC_{i\_up} / NC_{i\_mean}$

Multiplication of the cell-values for $\Delta LL = 1, 2, \ldots, i, \ldots$

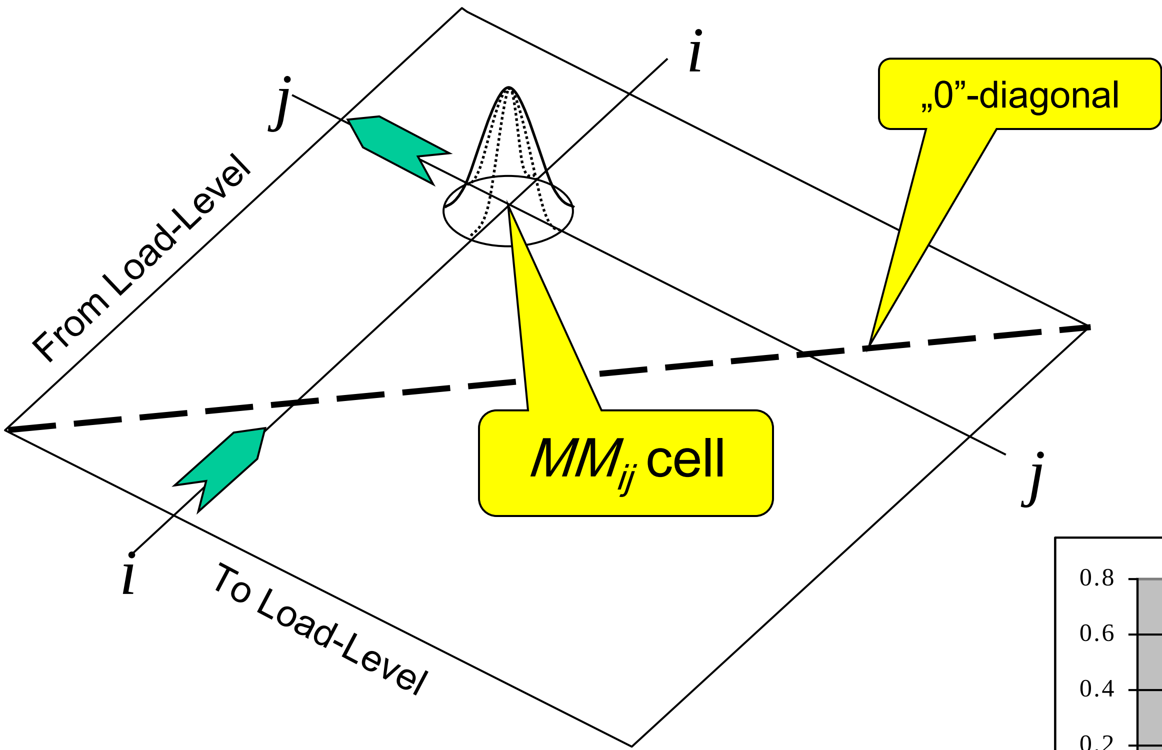
xT-array
Input data for stochastic extrapolation

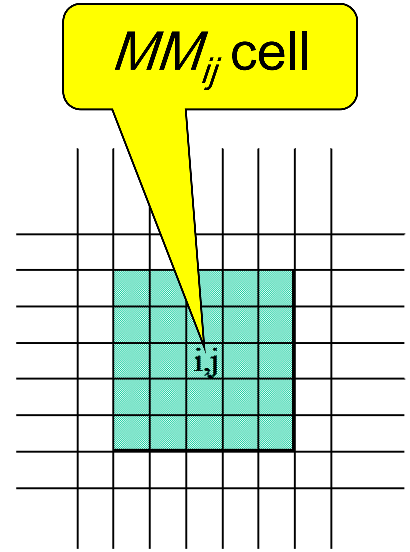


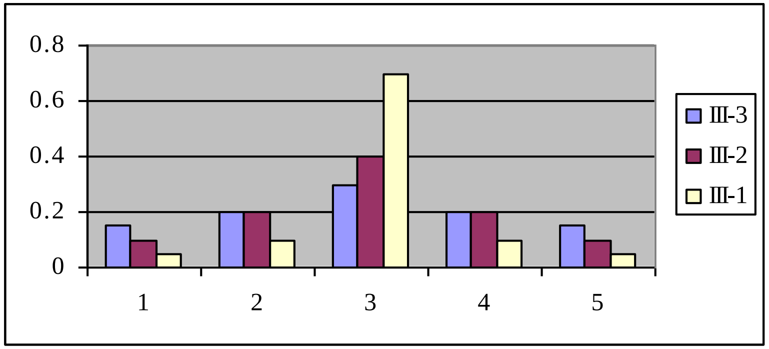
Stochastic method of LS extrapolation 2/4



Stochastic method of LS extrapolation 3/4





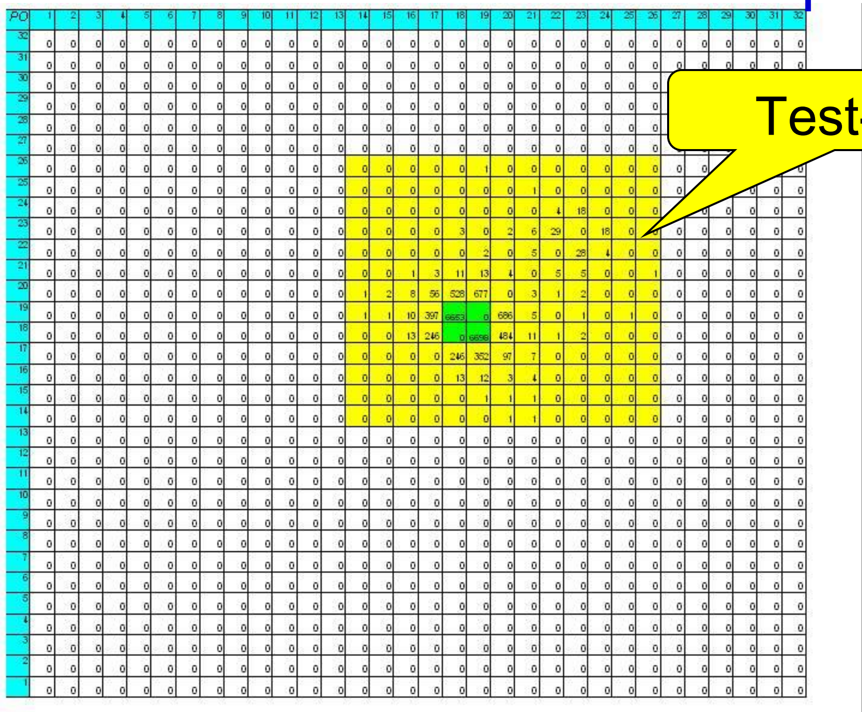


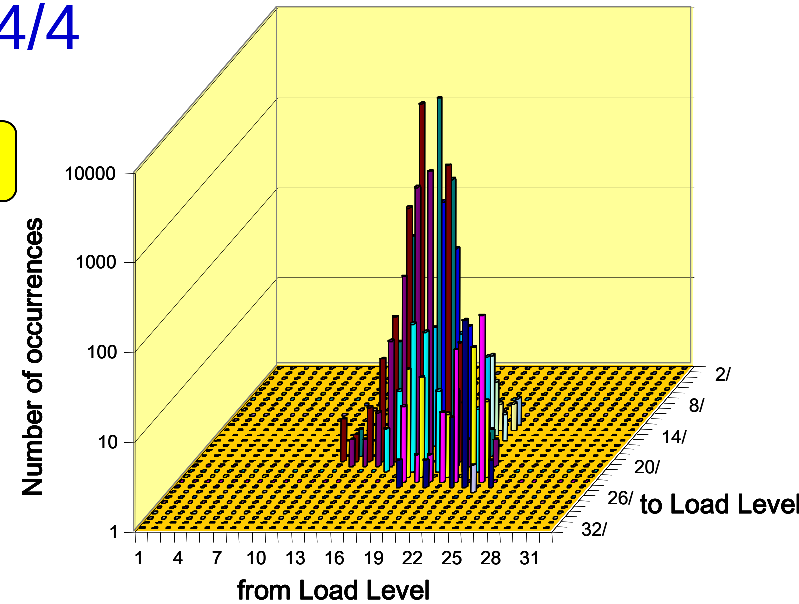
Reproduction clons of the xT- array

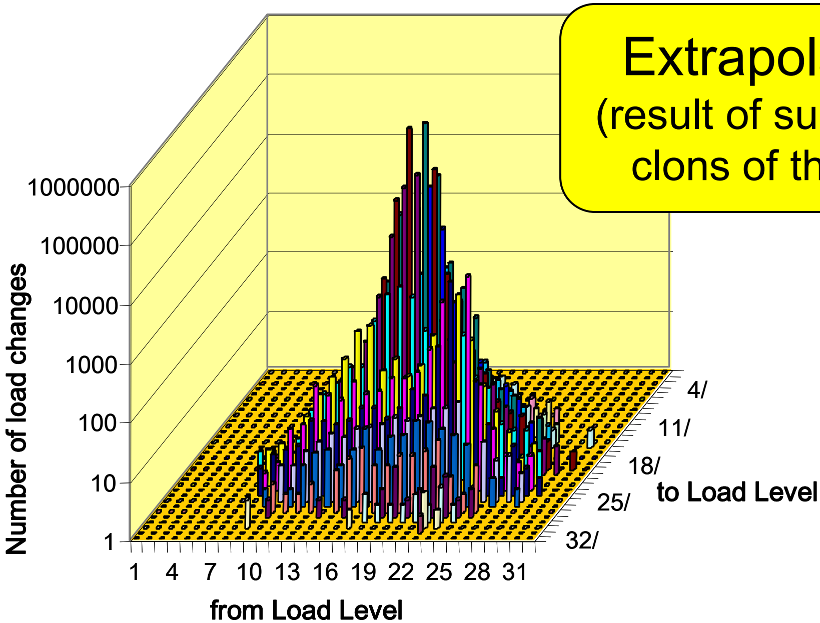
The number of xT-clons depends on the ratio between modeled period of operation and the time of all flights included to the xT-array

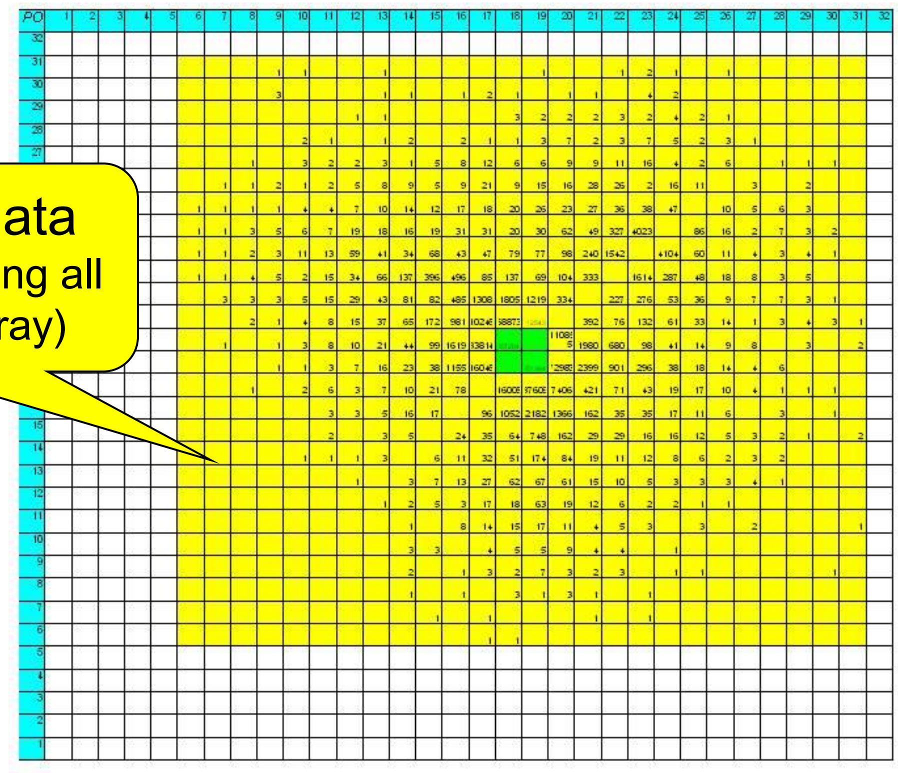
Probability distributions used for numerical simulations

Stochastic method of LS extrapolation 4/4

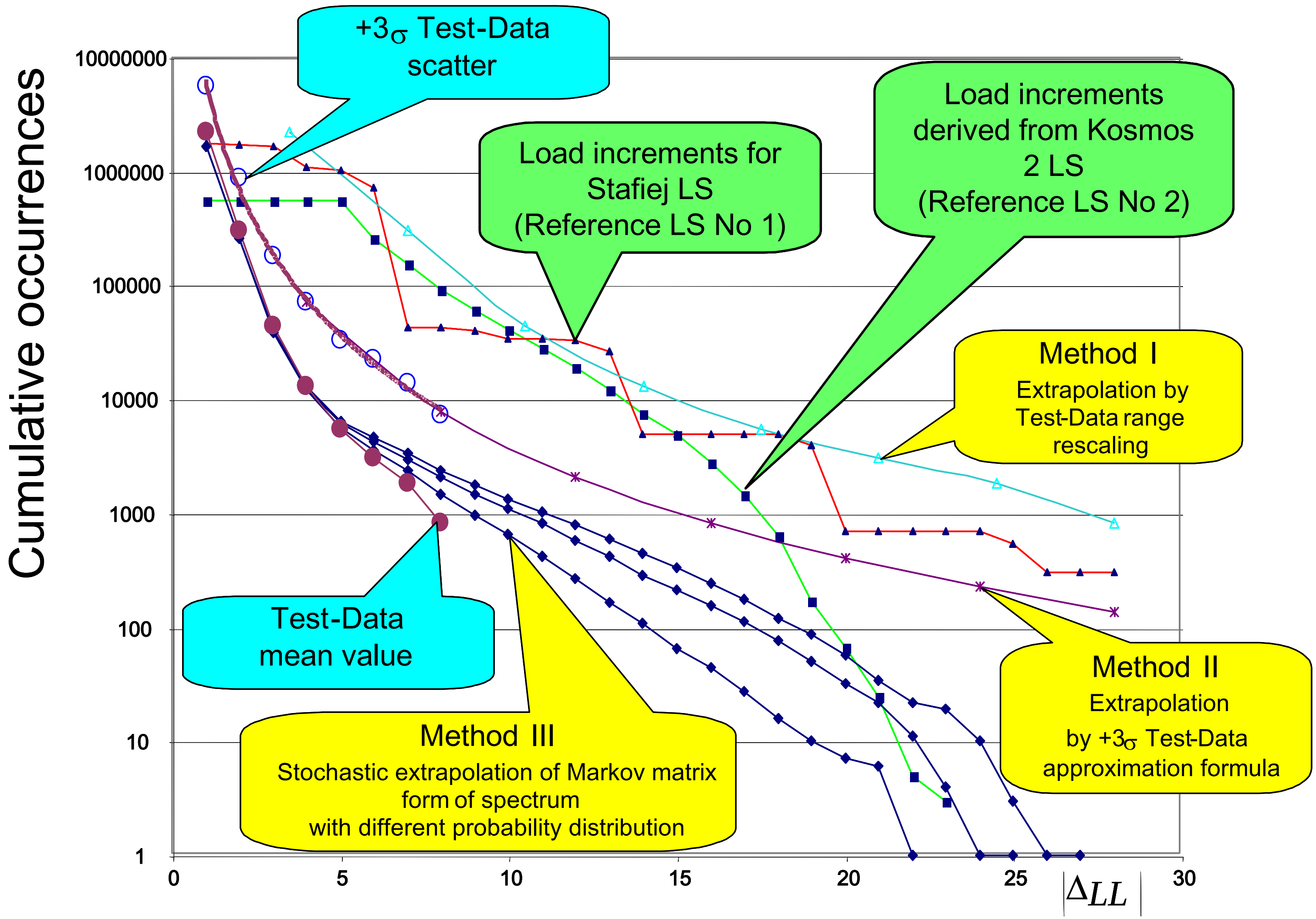






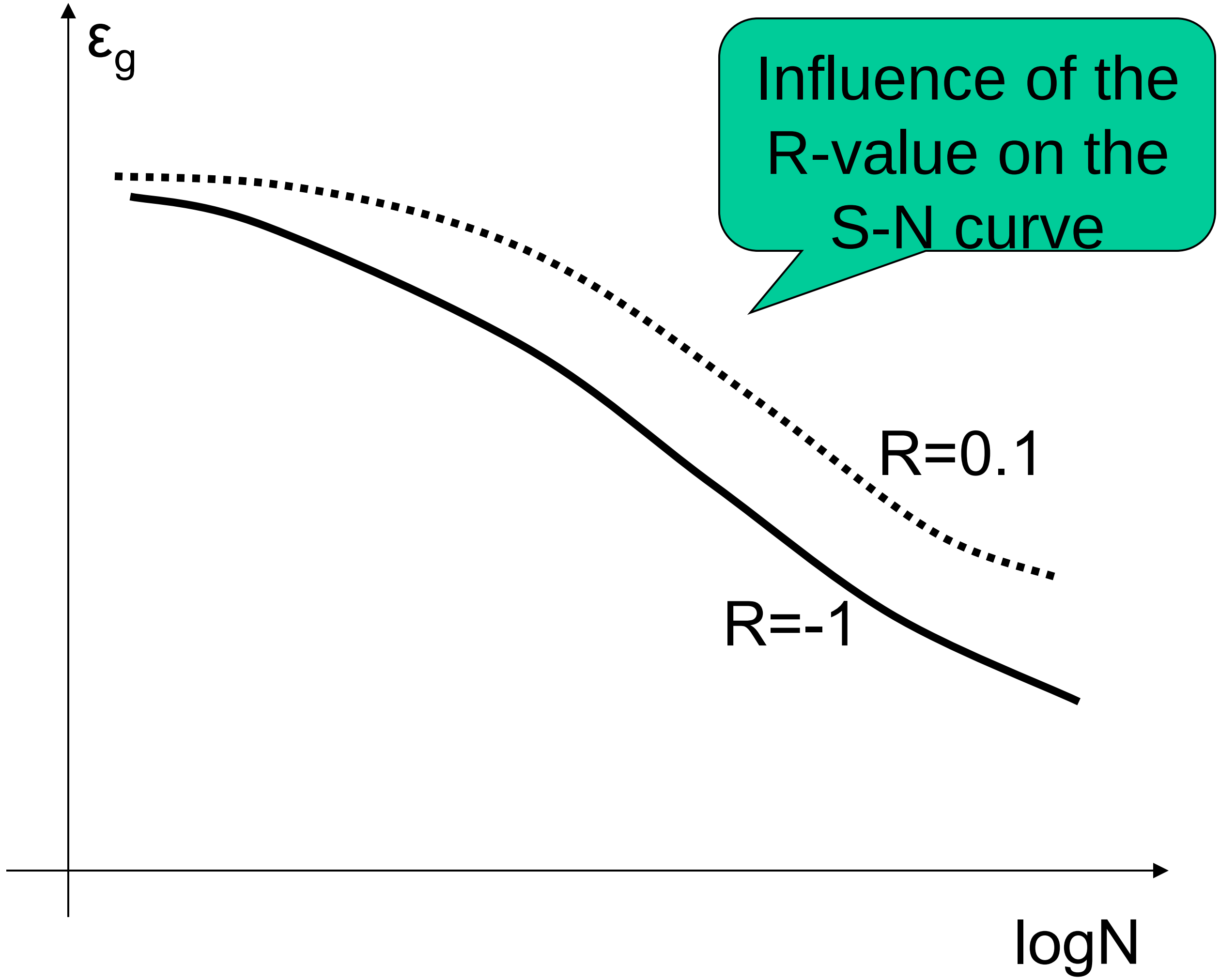


Comparision of the methods of LS extrapolation

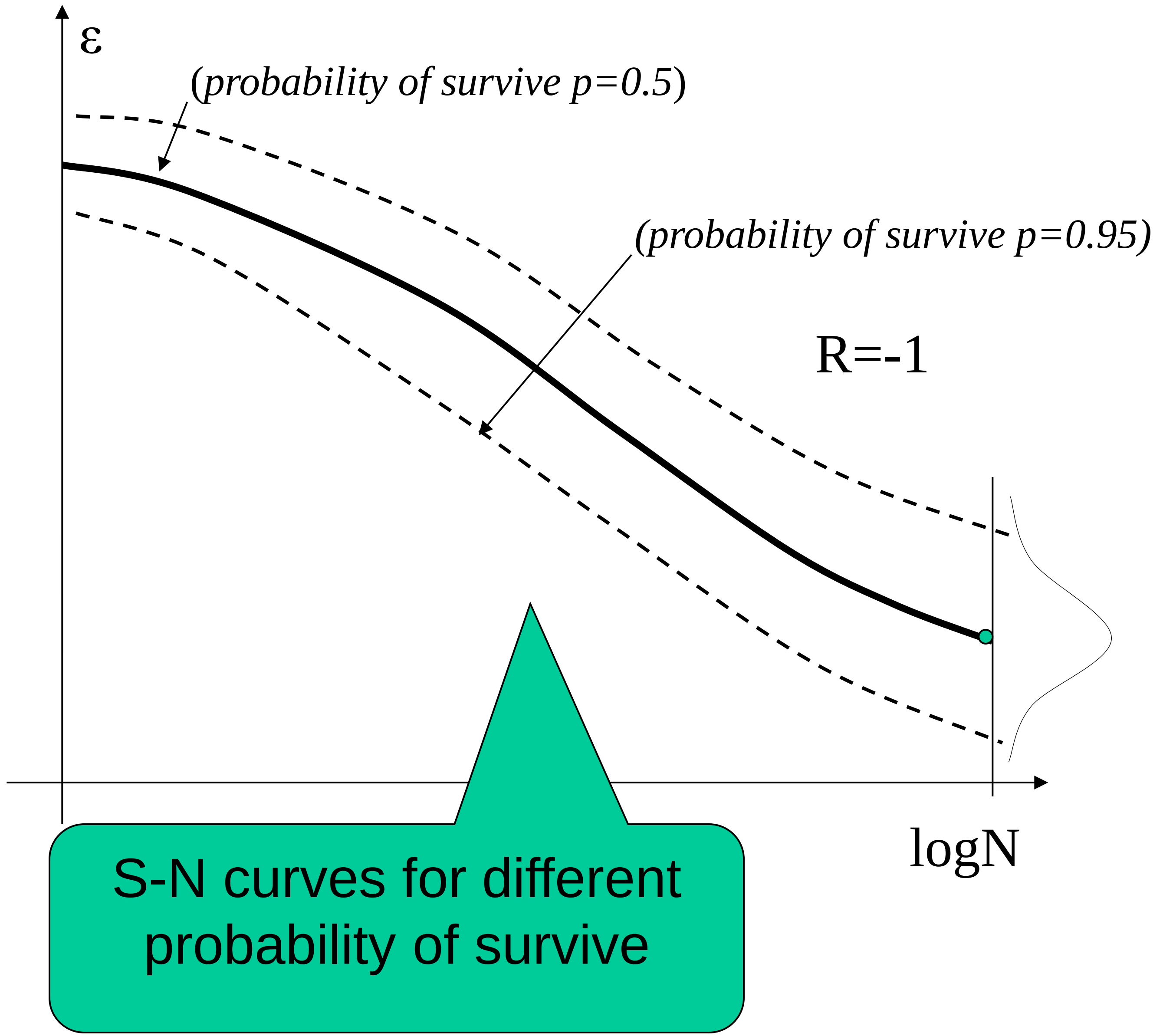


Fatigue properties of the materials & Fatigue charts

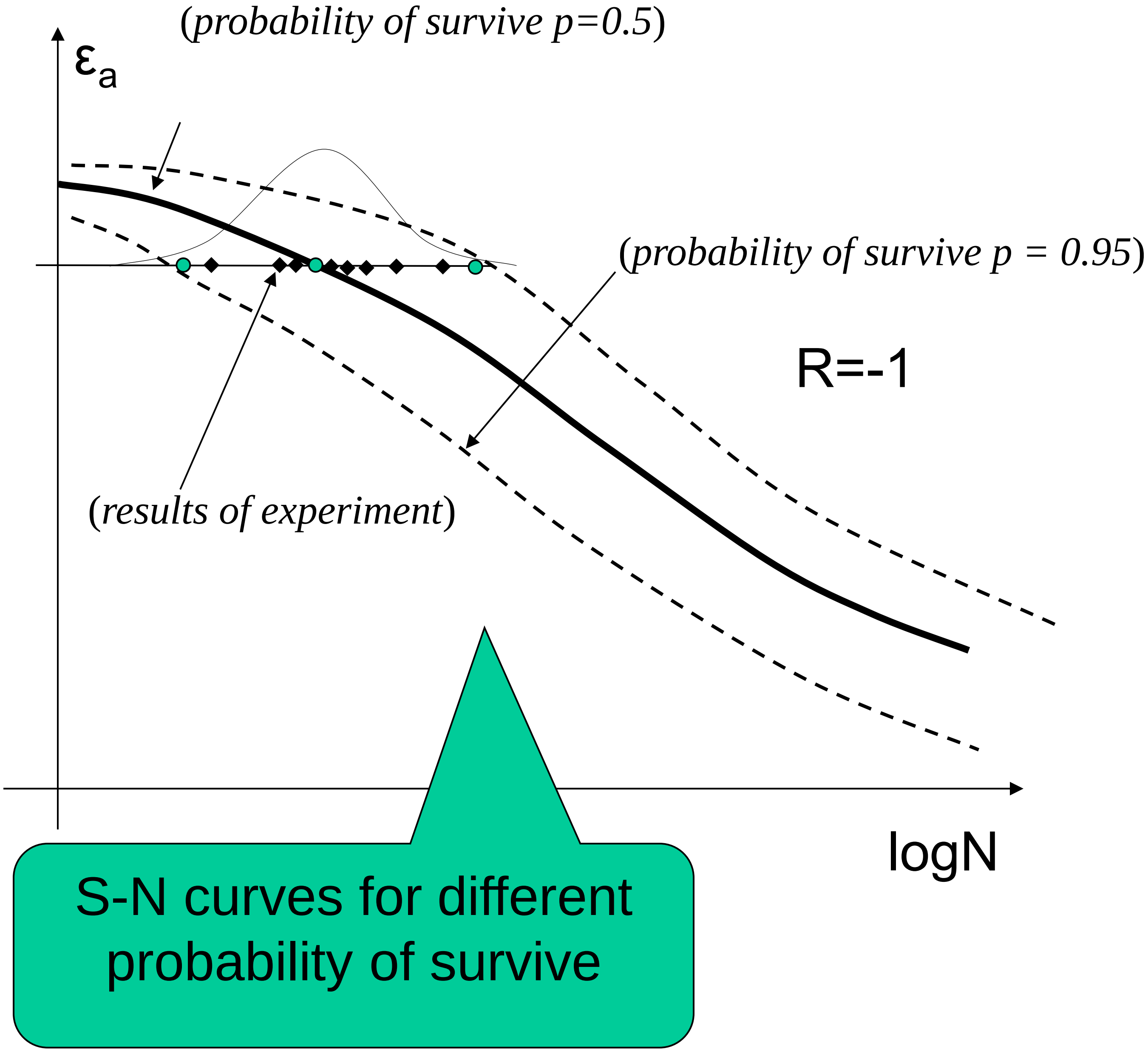
S-N curves



S-N curves


ε
(probability of survive p=0.5)
(probability of survive p=0.95)
R=-1
logN
S-N curves for different probability of survive

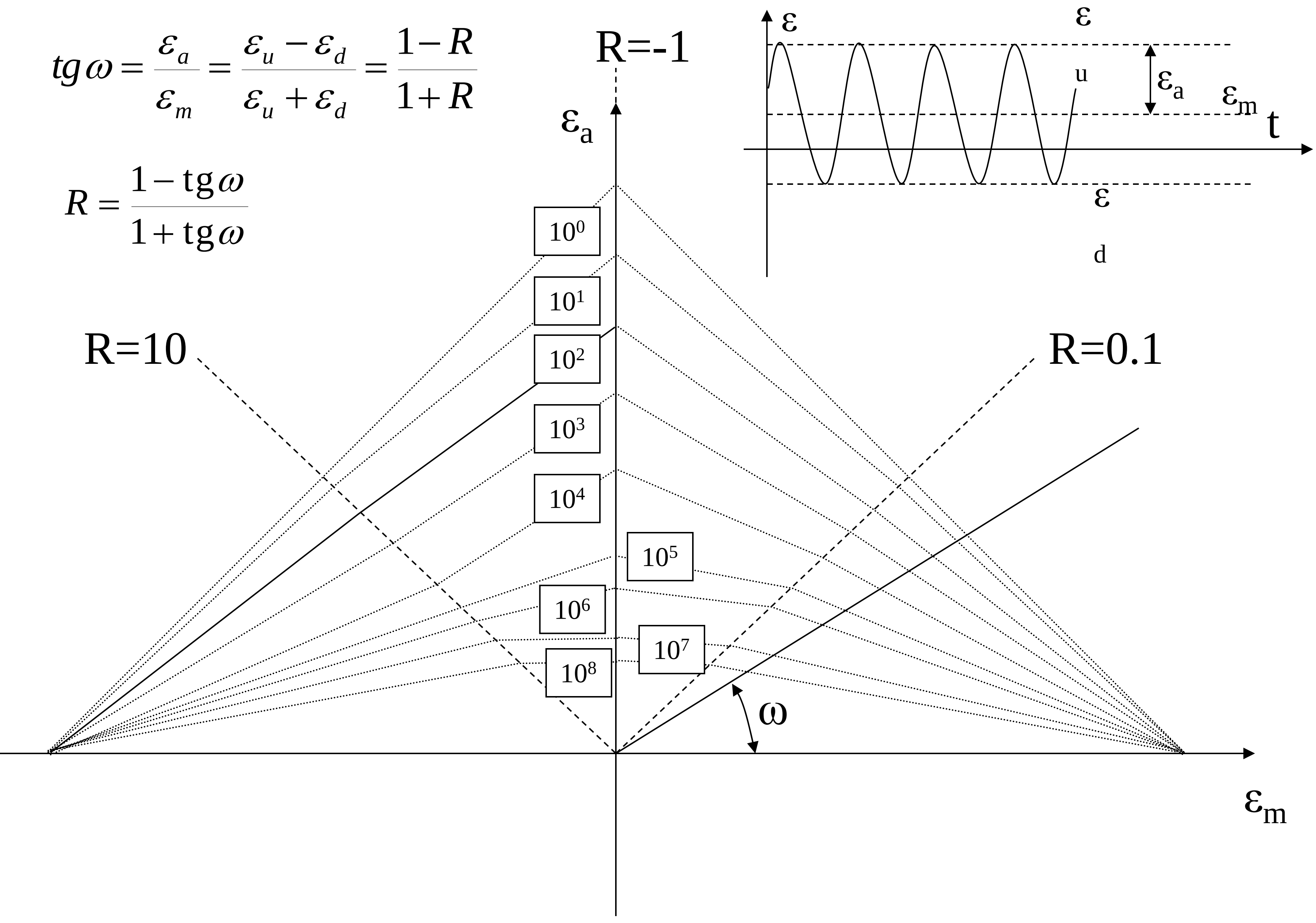
S-N curves


(probability of survive p=0.5)
εa
(probability of survive p = 0.95)
R=-1
(results of experiment)
logN
S-N curves for different probability of survive

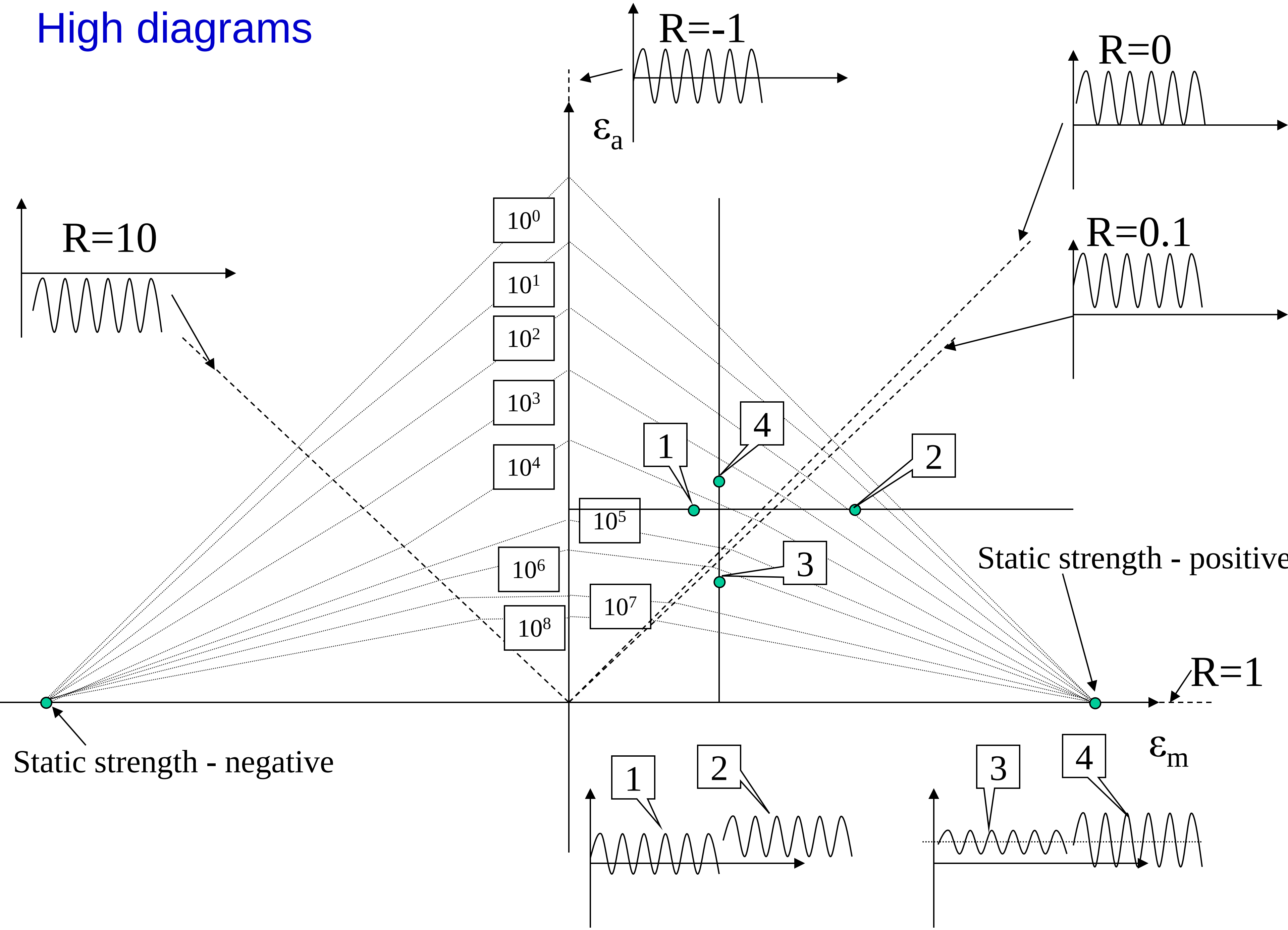
High diagrams

$$tg\,\omega = \frac{\varepsilon_a}{\varepsilon_m} = \frac{\varepsilon_u - \varepsilon_d}{\varepsilon_u + \varepsilon_d} = \frac{1-R}{1+R}$$

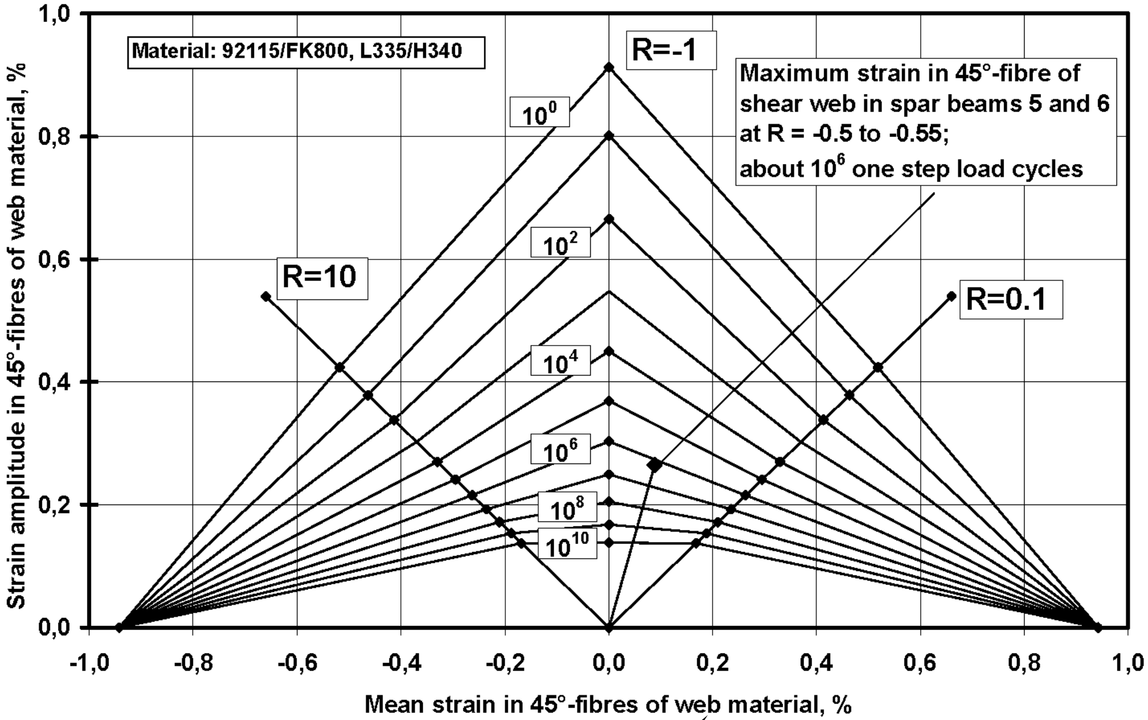
$$R = \frac{1-\mathrm{tg}\,\omega}{1+\mathrm{tg}\,\omega}$$



High diagrams



High diagrams



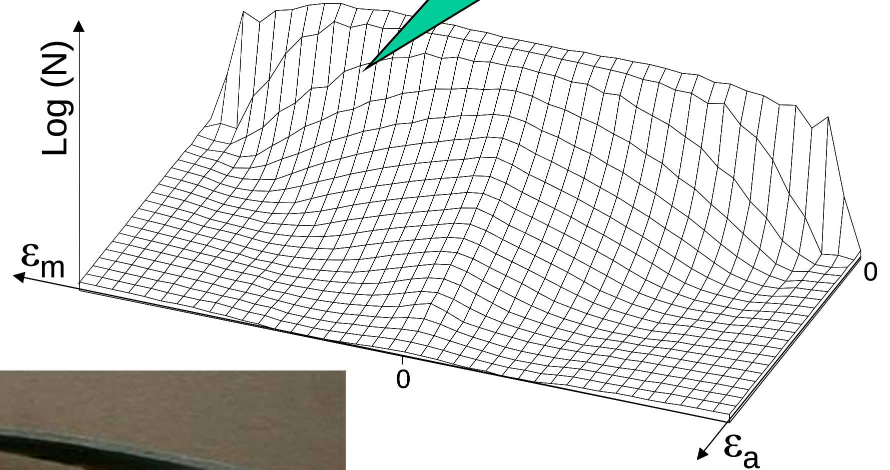
Source: PROPOSAL FOR A CERTIFICATION PROCEDURE OF EXTENDED SAILPLANE LIFETIME

Christoph W. Kensche

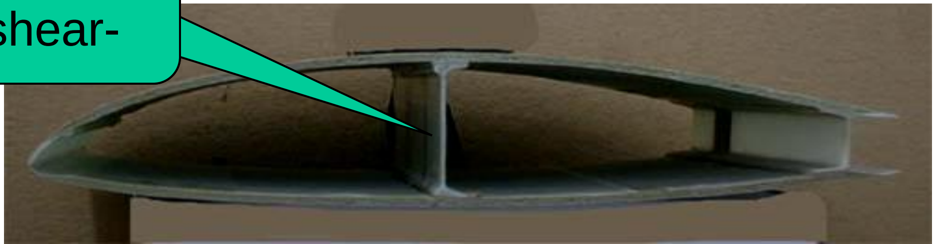
Institute of Structures and Design

German Aerospace Center (DLR)

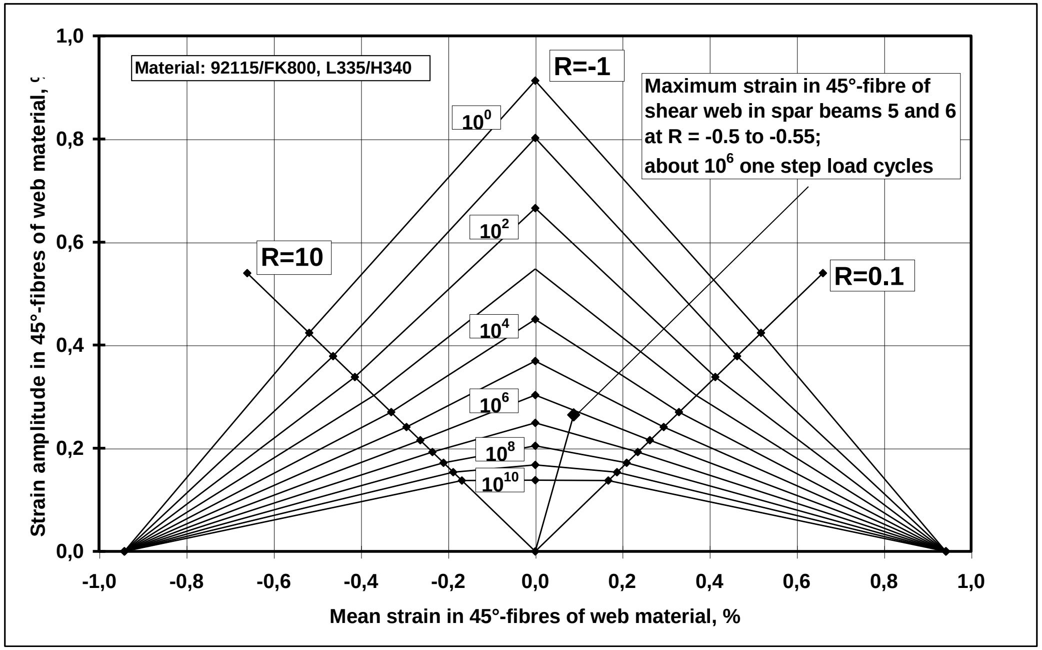
3D visualisation of Number of Cycles to Failure



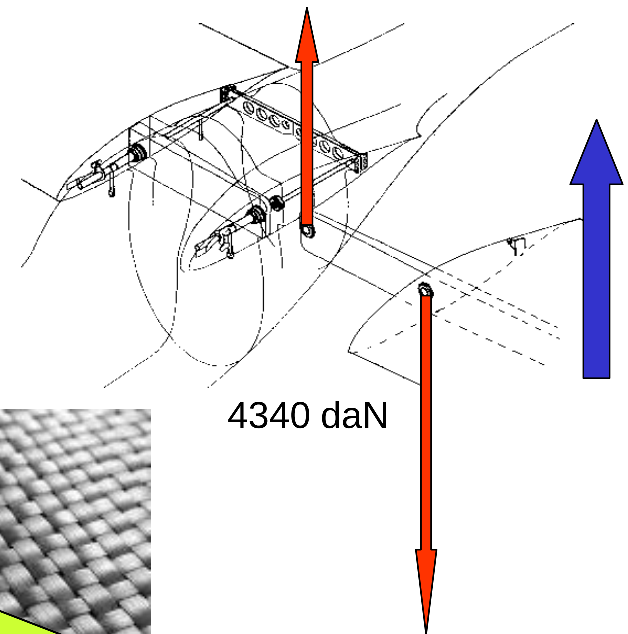
Example of High diagram for the wing spar shear-web

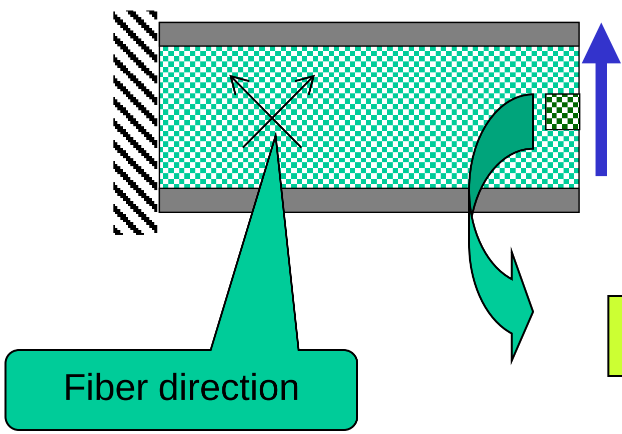


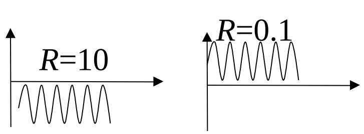
Why this High diagram is symetrical ?



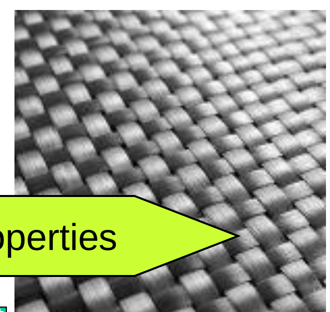
High diagram for the shear-web of the wing spar

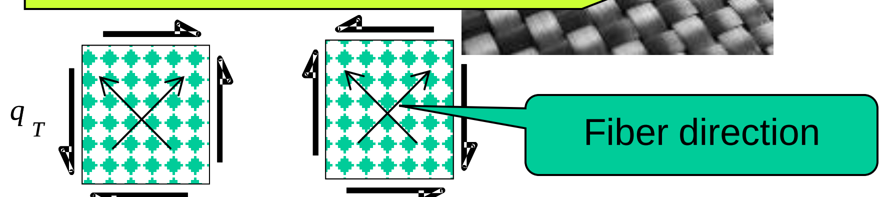




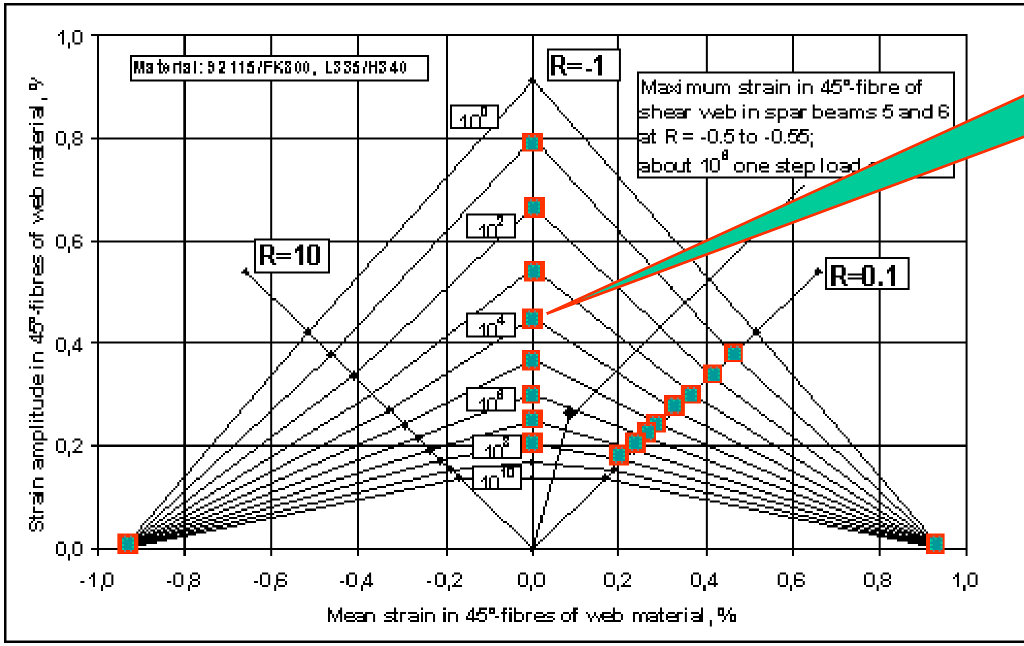


Similarity of cyclic properties





Work consumption for the High diagram



At least seven specimens in each marked point

Even in simplest case it is necessary to test at least 126 specimens !!!

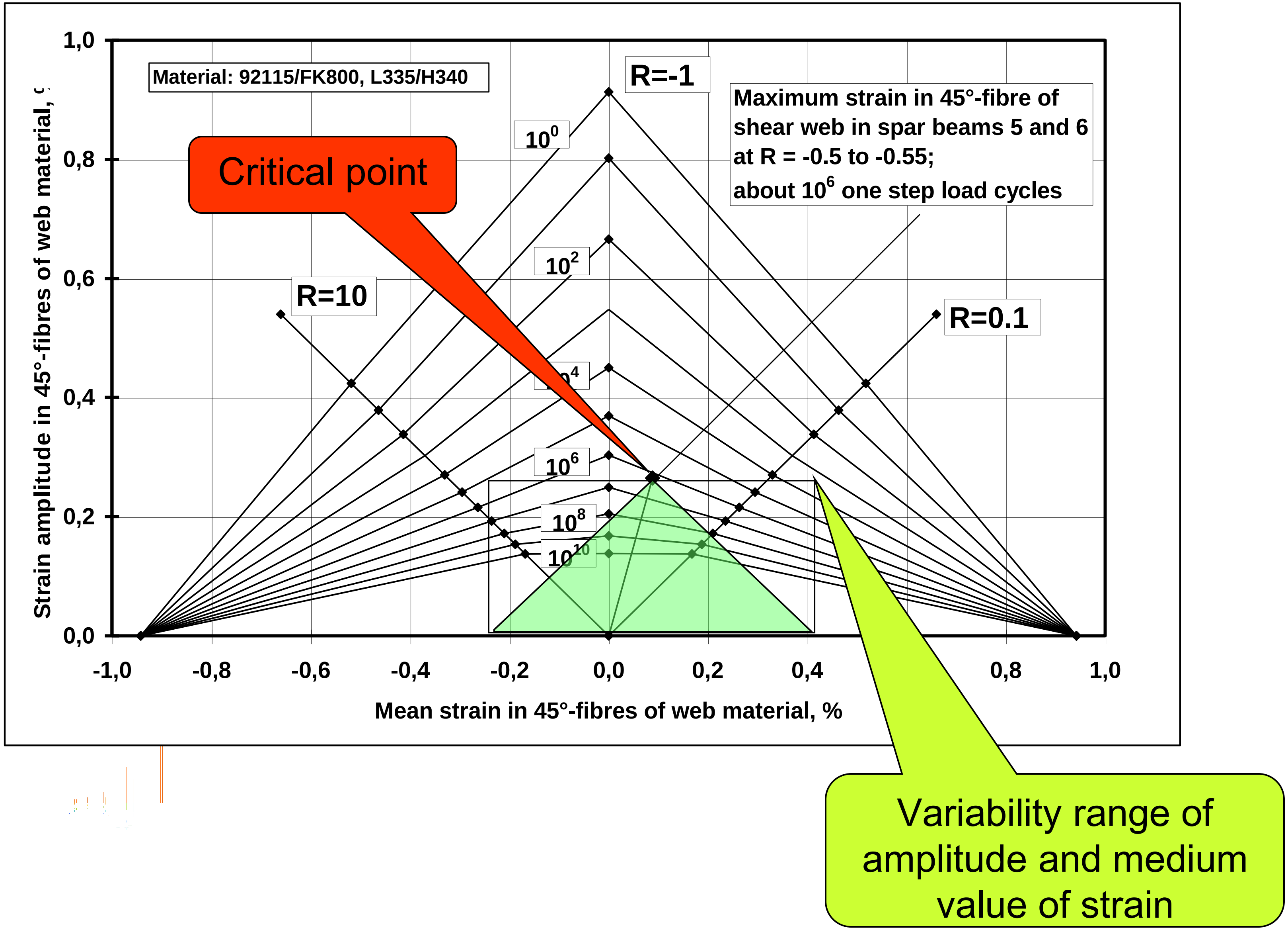
Sources of information about fatigue properties of the composites:

O. Krause, Ch. Kensche „Summary Fatigue Test Report OB_TG1_R026 rev. 0", 2006 - raport z programu OPTIMAT BLADES („Confidential").

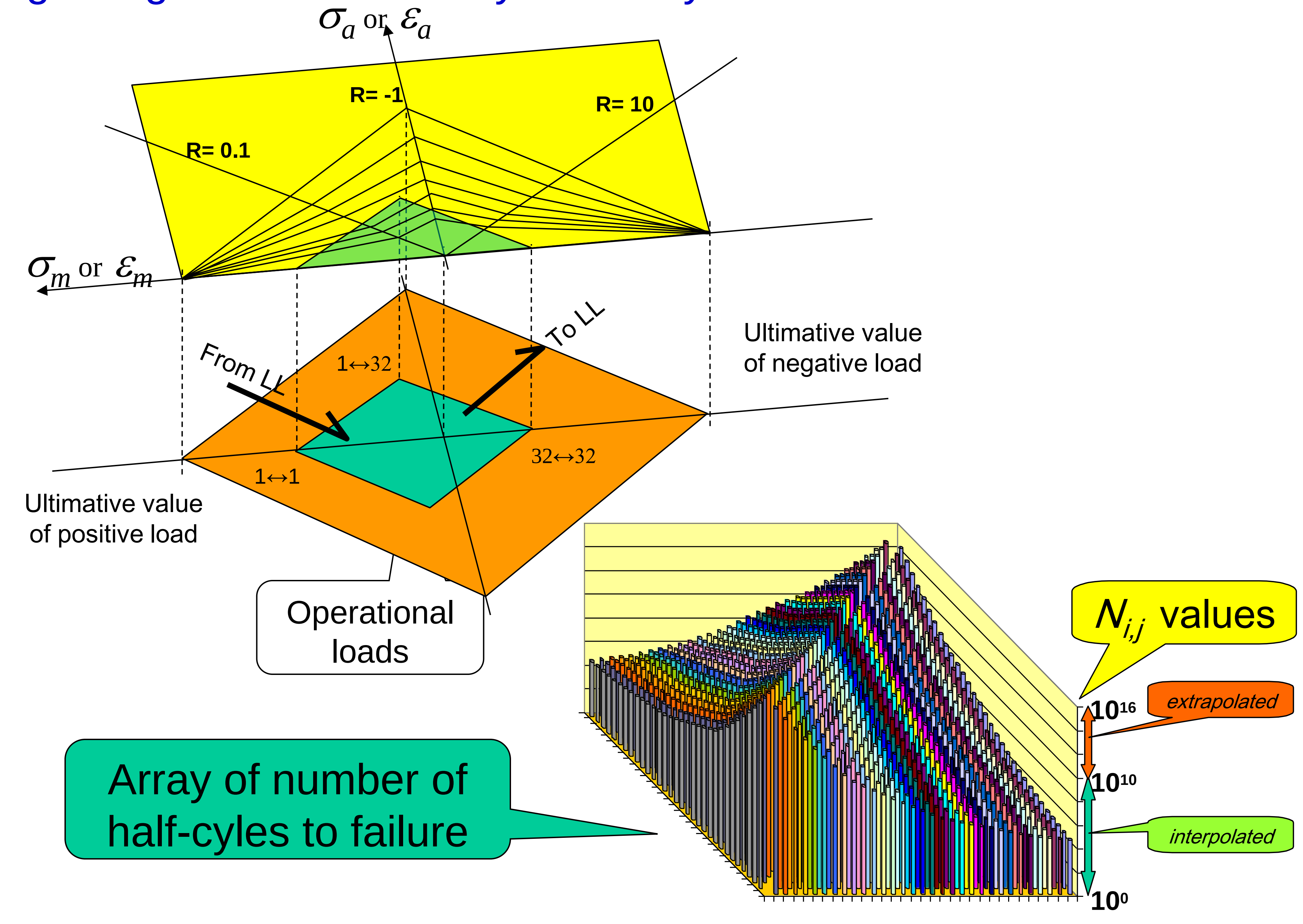
J. F.Mandell, D. D. Samborsky „DOE/MSU Composite Material Fatigue Database: Test Methods, Materials, and Analysis" - CONTRACTOR REPORT SAND97-3002, UC-121O, 1997, - raport z podobnych badań

Raports from wind turbine developement programs

High diagrams – operational zones



High diagrams versus array of half-cycles to failure



Orginal Palmgren – Miner formula

Load spectrum & fatigue damage

$$D = \sum_{i=1}^{l} \frac{n_i}{N_i} = 1$$

For majority of materials D≠1

$$D = \sum_{i=1}^{32} \sum_{j=1}^{32} D_{i,j} = \sum_{i=1}^{32} \sum_{j=1}^{32} \frac{n_{i,j}}{N_{i,j}}$$

Number of half-cyles in the LS

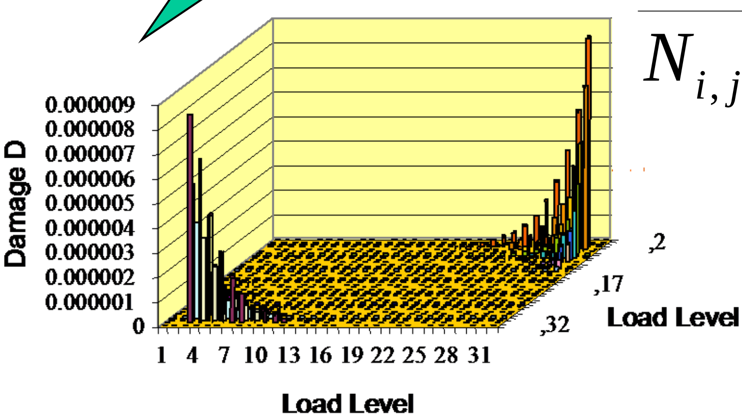
Number of half-cyles to failure

Palmgren – Miner formula modyfied for array calculacions

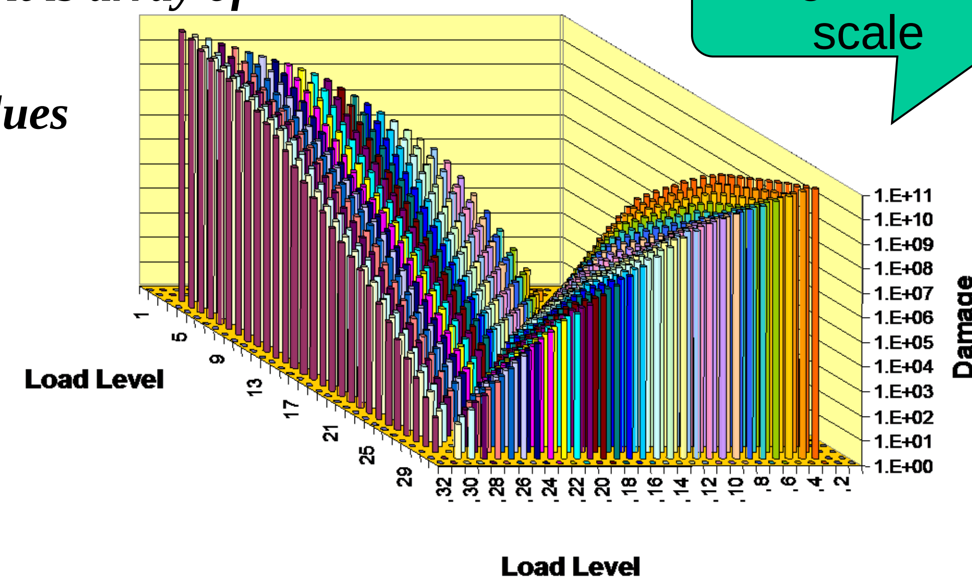
Unitary Damage Array (UDA - array of damage-values for the Unitary Transfer-Array, i.e. array having all values equal to 1)

In other words it is array of $\frac{1}{N_{i,j}}$ ***values***

Linnear scale

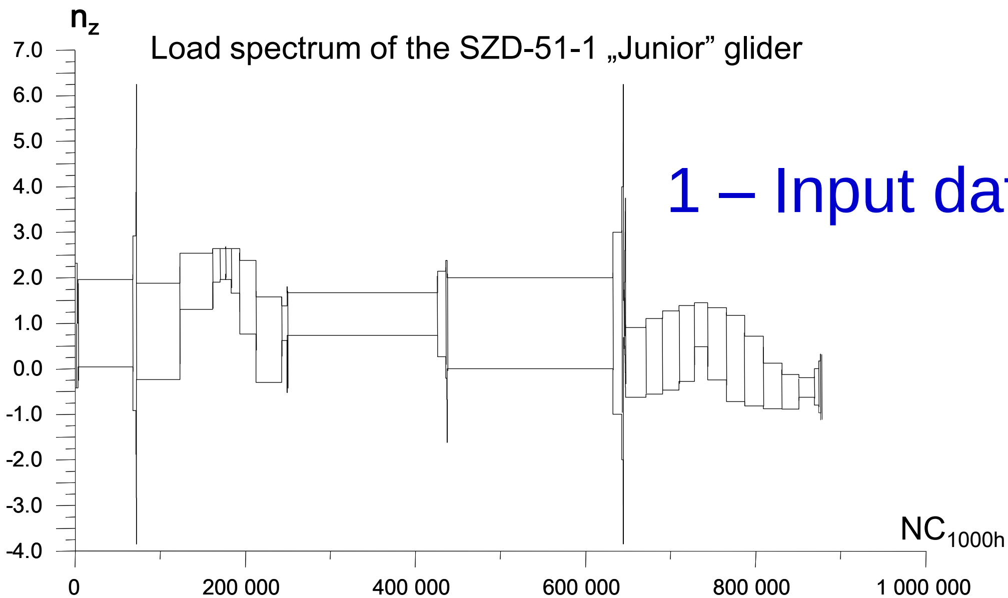


Logarithmic scale



Example of fatigue calculations 1/2:

$$D = \sum_{i=1}^{32} \sum_{j=1}^{32} D_{i,j} = \sum_{i=1}^{32} \sum_{j=1}^{32} \frac{n_{i,j}}{N_{i,j}}$$

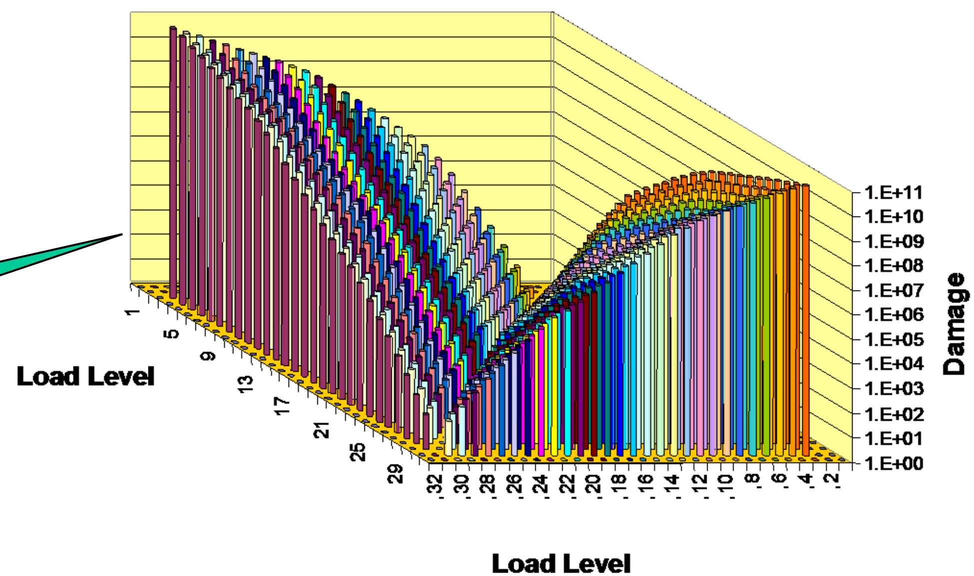


1 – Input data: the Load Spectrum of the PW-5 glider

Cumulated number of load cycles for 1000h of PW-5 operation = 1 753 072

2 – Input data: fatigue properties of the material

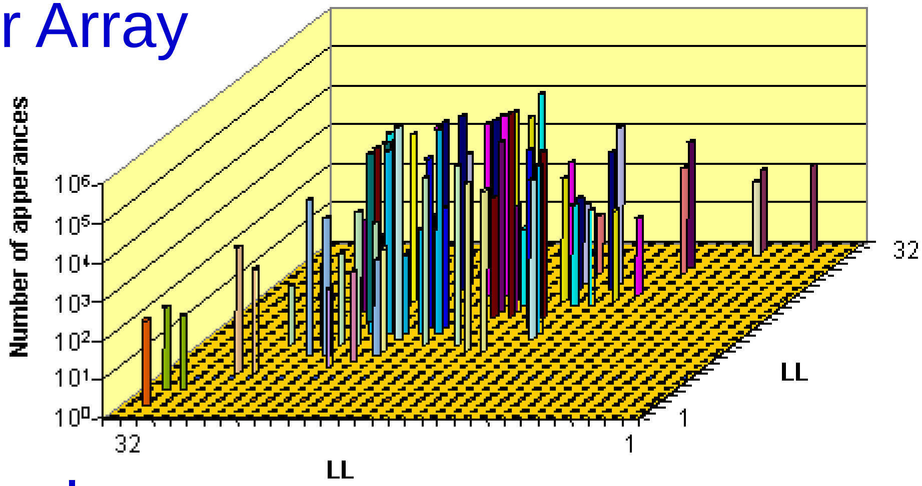
$1/N_{i,j}$ values



Example of fatigue calculations 2/2:

3 – Transition of LS to Transfer Array

$n_{i,j}$ values for 1000 h of glider operation



4 – Calculation of the damage value:

$$D = \sum_{i=1}^{32} \sum_{j=1}^{32} D_{i,j} = \sum_{i=1}^{32} \sum_{j=1}^{32} \frac{n_{i,j}}{N_{i,j}}$$

In the case of PW-5 glider wing spar shear web

$D_{1000h} = 0.00389$

5 – Calculation the life-time:

(Assumption that critical D value is equal to 1)

Life Time = (1/0.00389) * 1000h =257 069h

Improvement of the fatigue testing - Equivalent Load Spectra

Problem description:

Can we substitute a full Load Spectrum by another Load Spectrum, which allows simplification of the fatigue test arrangement and decreasing the workload?

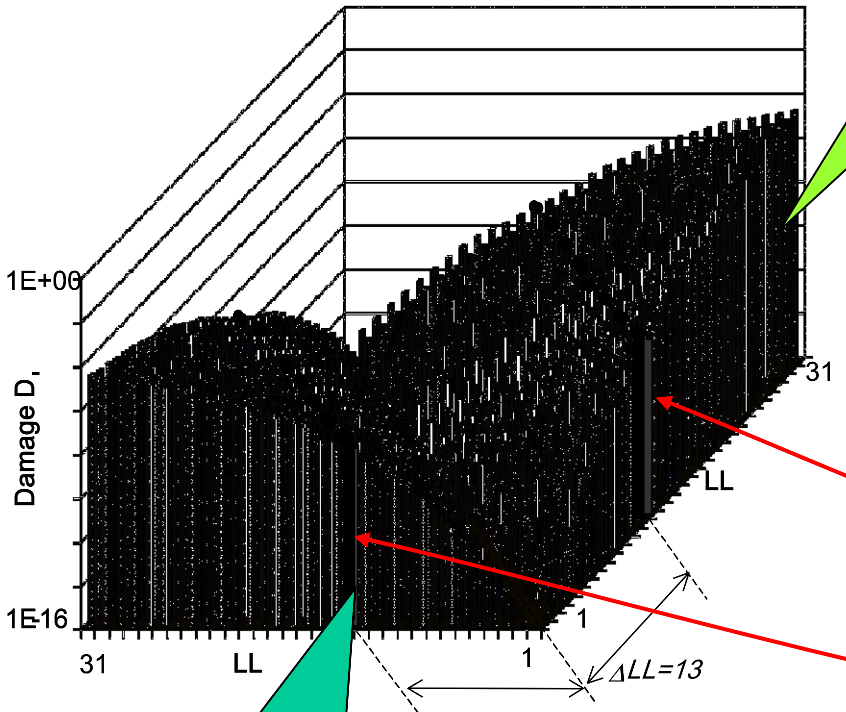
The main requirement:

In both cases of the LS the D value should be the same

Equivalent Load Spectra

A – simplification by substituting the full LS by the blocks of constant-amplitude load cycles

$1/N_{i,j}$ values



Medium value of unitary damage

$$D1_m = \frac{D}{NC_{1000h}} = \frac{0.00389}{1753072} = \mathbf{2.21896E-09}$$

These are the lines of $1/N_{i,,j}$ = 2.218E-09

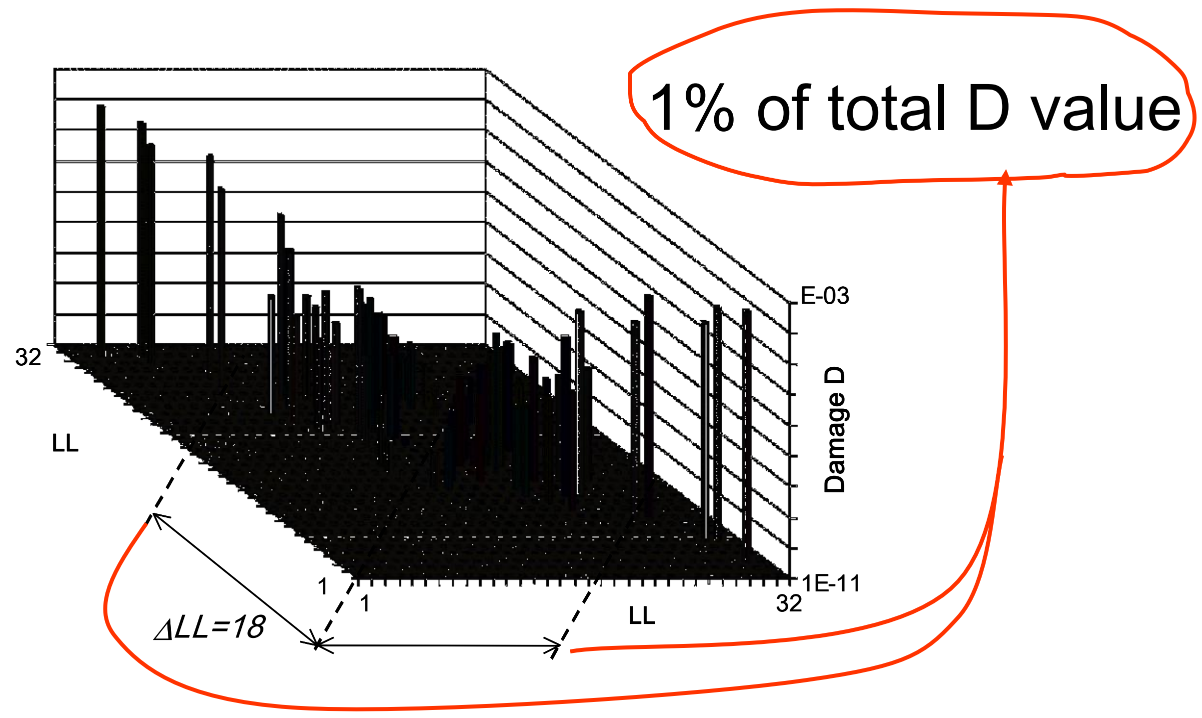
This is the value of damage produced by the whole LS divided by the number of load cycles

Conclusion: Instead of the full LS one can apply 1 753 072 load cyles having constant Load Level increments equal to 13

Equivalent Load Spectra

Problem: are all cells in the Half-Cycle Array equally important ?

Damage-values for the Unitary Transfer-Array



Note: In the case of PW-5 glider LS – the half –cycles placed within ΔLL= 18 zone are producing only 1% of total D value

Conclusion: We can neglect the load cycles within ΔLL= 18 zone

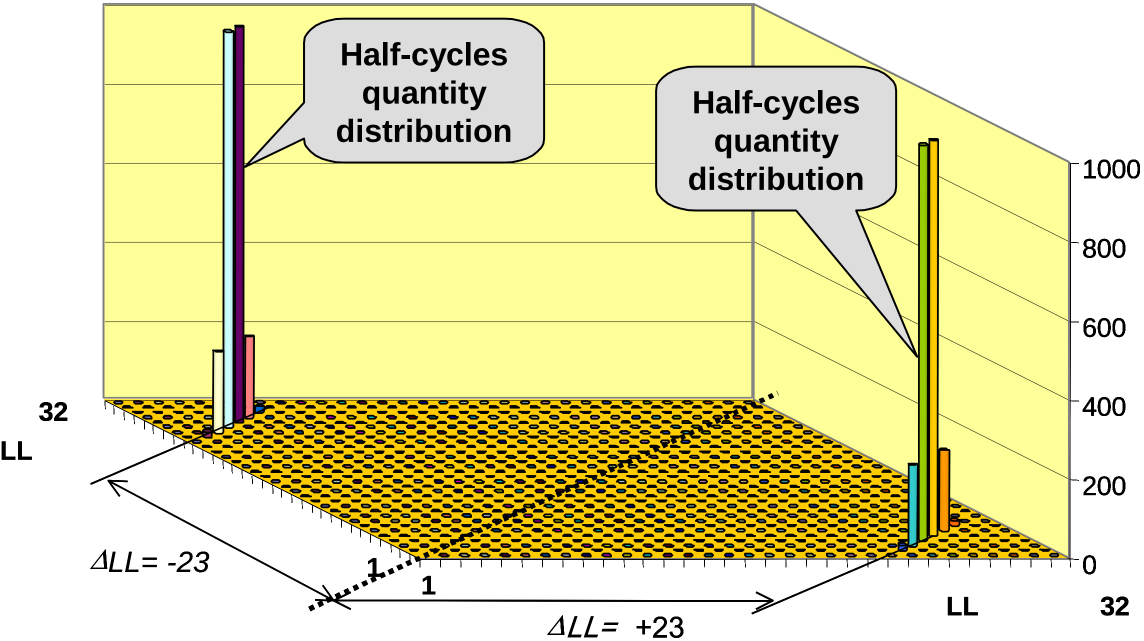
Result: The LS is reduced from 1 753 072 load cycles to only 4882 load cycles without significant change of the D value

Equivalent Load Spectra

The new value of D_{1m} after this reduction:

$$D1_m = \frac{D}{NC_{1000h}} = \frac{0.00389}{4882} = \mathbf{7.96E-07}$$

This value corresponds with the values of Unitary Damage Array for DLL = 23



	Load Spectrum - full	Load Spectrum reduced
Number of half-cycles LP	1 753 072	4882
Equivalent load increment $\lvert \Delta LL \rvert$	13	23
Value of Damage coefficient D for 1000h of operation	0.00389	0.003866

Conlusion: This is significant simplification of the fatigue test!!!

Equivalent Load Spectra

Another method of fatigue test simplification – „One- step" fatigue test:

„One-step" fatigue test, i.e. 10 000 cycles of loads within design limit as a prove of 12 000 hours of operation

The biggest load increment is between LL=31 and LL=3

PROPOSAL FOR A CERTIFICATION PROCEDURE FOR SAILPLANES
Christoph W. Kensche
Institute of Structures and Design
German Aerospace Center (DLR)

$$\frac{D}{UDA_{3,31}\textbf{(medium value)}} = \frac{0.00389}{8.52E\text{-}06} = 457$$

load changes
(i.e. ~229 load cycles for 1000h of operation)

What is the safety margin if we apply such a test?

(comparison of the number of cyles for 12 000h of glider operation)

$$\frac{10\ 000\ \ cycles}{12 \cdot 229\ \ cycles} \cdot 100\% = 365\%$$

Equivalent to scatter factor of 3.65

The end of the part regarding the Load Spectra