Innovation Week on Renewable Energy Systems

MONITORING ,FAULT DETECTION & CONTROL IN R.E.S
THE WIND TURBINE CASE
AN APPROACH

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ELECTRICAL & COMPUTER ENGINEER

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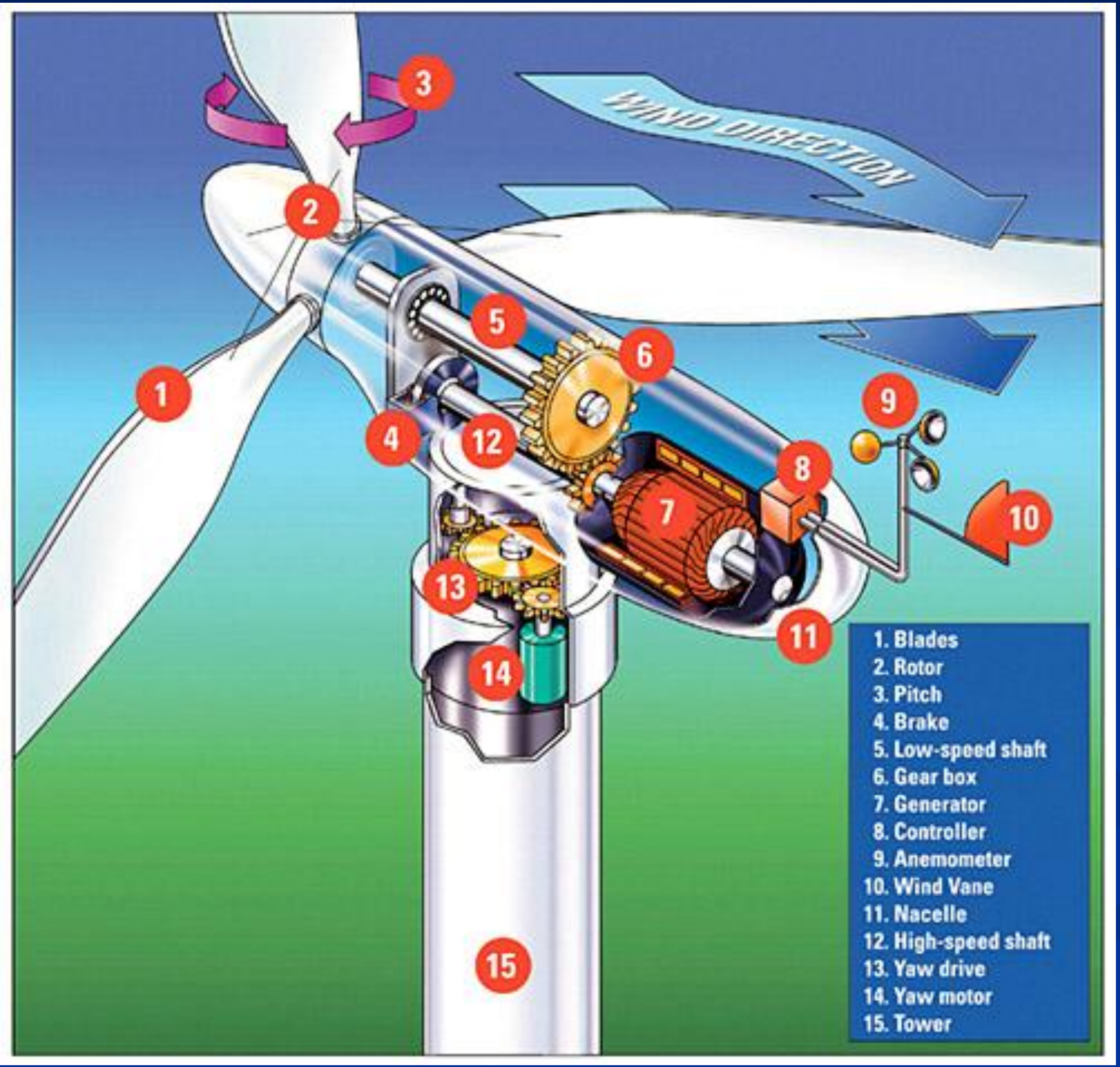
Contents

Goals

- The study of characteristic
- Electrical Signal reception
- Sampling
- DSP
- ADuC7026 Microcontroller Programming with C
- Compination of the above so as to determine:
- **The condition of a system**
- Use of Keil Uvision development enviroment
- System simulation

Wind Turbine Construction(1)



Wind Turbine Construction(2)

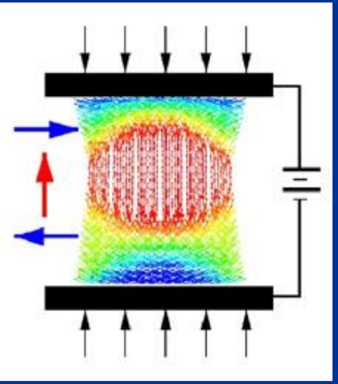
- Moving Parts
- DC Generator - Gearbox
- Vibration Generation
- Vibration Patterns
- Proper Operation
- Data
- Prediction Capability

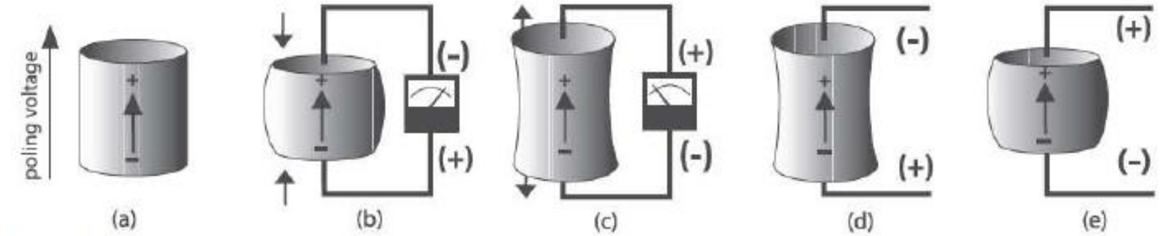
<u>Goal</u>

Collecting, Storing Processing Vibration Data

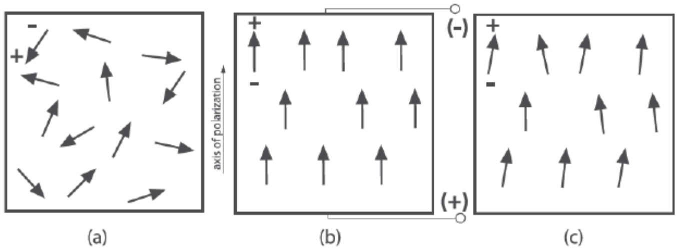
Piezoelectric Transducers

- Turning Pressure to Electrical Signal
- Use as sensors
- Structure – Function

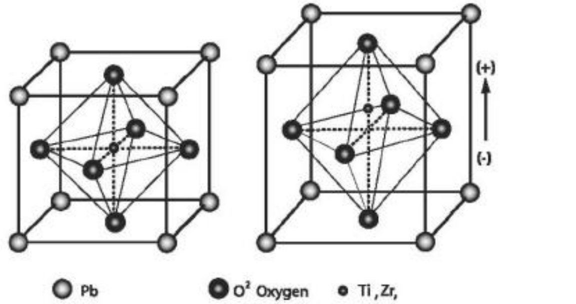




Σχήμα 2.3
Αντίδραση πολωμένου πιεζοηλεκτρικού στοιχείου σε εφαρμοζόμενη διέγερση

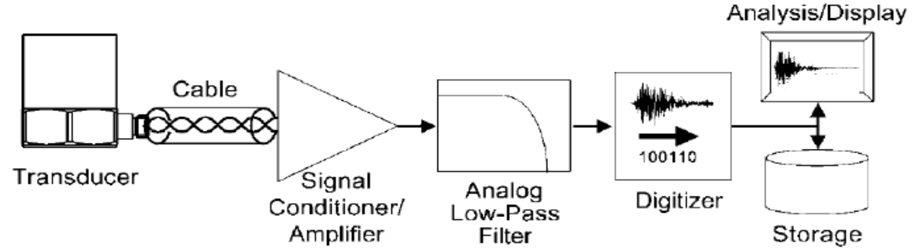


Σχήμα 2.2
Διαδικασία πόλωσης:
(a) Πριν την πόλωση οι περιοχές έχουν τυχαίο προσανατολισμό.
(b) Ένα ηλεκτρικό πεδίο συνεχούς ρεύματος πολύ μεγάλης έντασης χρησιμοποιείται για την πόλωση .
(c) Μετά την απομάκρυνση του πεδίου παραμένει εναπομείνουσα πόλωση

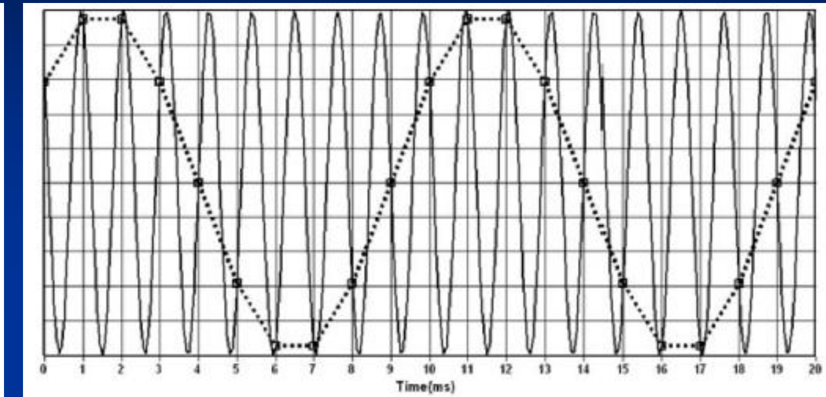


Σχήμα 2.1 Κρυσταλλική δομή πιεζοηλεκτρικού κεραμικού πριν και μετά την διαδικασία πόλωσης

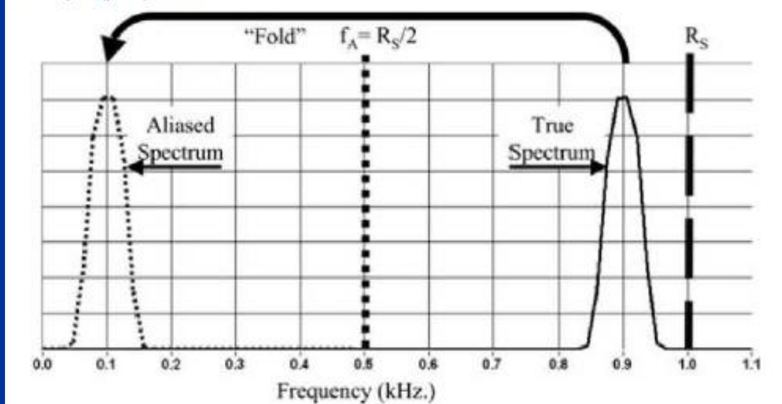
Data Collection



Σχήμα 3.1
Μονοπάτι σήματος του σηστήματος.
- Αισθητήρας
- Καλώδιο
- conditioner/ενισχυτής σήματος
- Αναλογικό βαθυπερατό φίλτρο
- A/D μετατροπέας - ψηφιοποιητής
- Run-time ανάλυση και απεικόνιση
- Αποθήκευση δεδομένων



Σχήμα 3.5
Σφάλματα Aliasing παρατηρούμενα στο πεδίο του χρόνου .
Ρυθμός δειγματοληψίας =1 kS/s,
Συχνότητα σήματος=900 Hz.

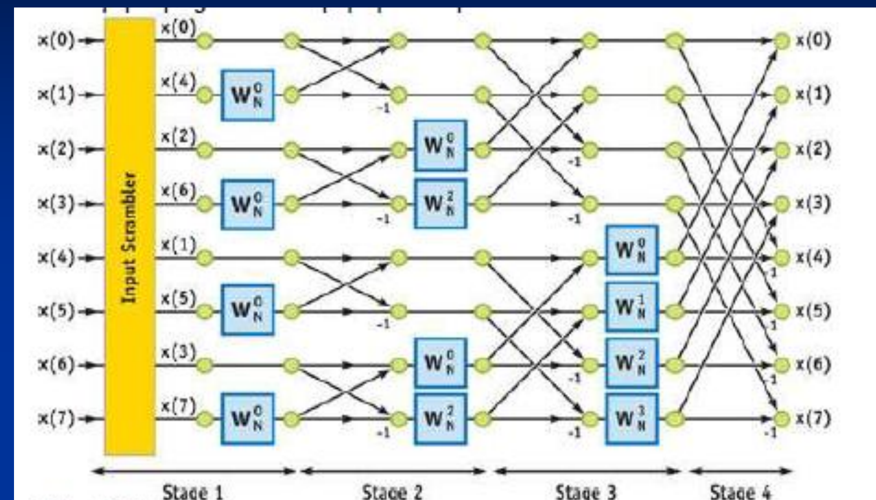


Σχήμα 3.6
Λάθη Aliasing όπως φαίνονται στο πεδίο της συχνότητας
sample rate =1 kS/S
signal frequency =900 Hz.

- Sampling
- Shannon Theorem
- Aliasing
- Filters
- Oversampling

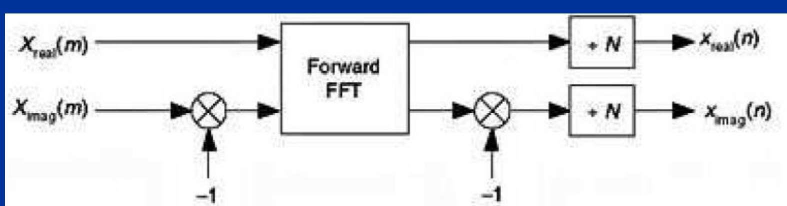
Fourier Transforms

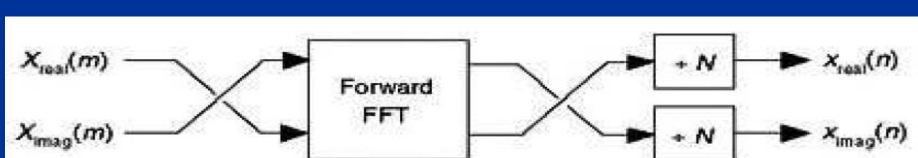
- Frequency Analysis
- DFT
- Fast Fourier Transform (FFT)
- FFT Algorithm
- Reversre FFT



Σχήμα 3.15A
Decimation-in-Time Butterfly Algorithm

- $$F(k) = \sum_{n=0}^{N-1} f(n) W_N^Q$$
- $$W_N^Q = e^{-j\frac{2\pi Q}{N}}$$
- $$Q = \left\{ \left\lfloor \frac{k \cdot 2^{Stage}}{N} \right\rfloor \right\}_{bit-reversed}$$ (twindle factor)
- $$0 \leq k \leq \frac{N-1}{2}$$
- $$1 \leq Stage \leq \log_2(N)$$





$e^{ix} = \cos x + i \sin x$

Fourier Transforms(2)

$$X(m\Delta f) = \Delta t \sum_{n=0}^{N-1} x(n\Delta t) e^{-j2\pi \cdot m \cdot \Delta f \cdot n \cdot \Delta t}$$

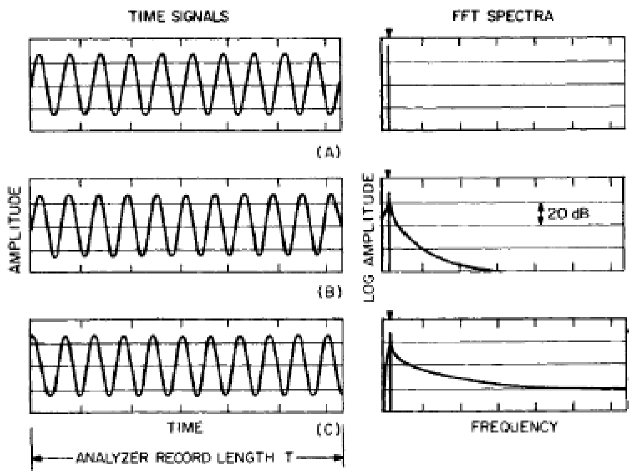
$$m = 0,1,2,3,\ldots,(N-1)$$

DFT

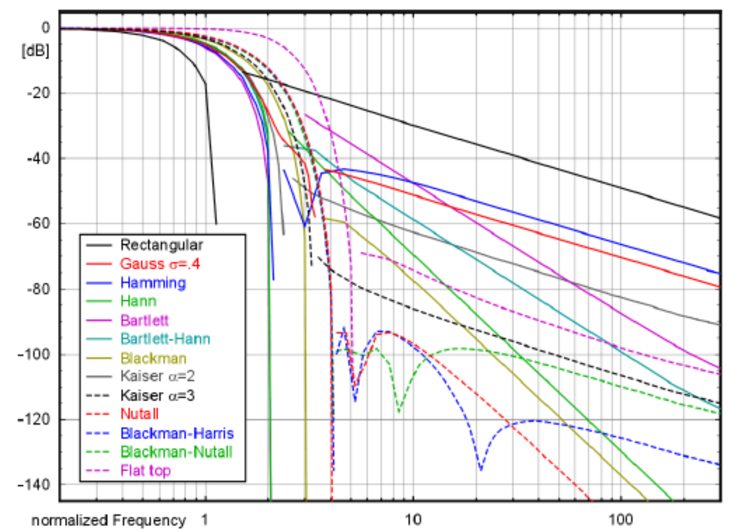
$$\Delta f = \frac{1}{N\Delta t}$$

Nyquist frequency refers to m=(N/2).
[(N/2)+1] frequency elements are useful data
[(N/2)−1] frequency components are non-useful data and represent negative frequency components (Euler's formula)

Leakage – Windowing

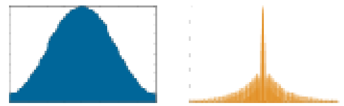


Σχήμα 3.16
Αποτελέσματα time-window κατα την ανάλυση ημιτονοειδούς σήματος με διάταξη ανάλυσης FFT χρησιμοποιοώντας rectangular παράθυρο
(A) Ακέραιος αριθμός περιόδων , καμία ασυνέχεια.
(B) και (C) Όχι ακέραιος αριθμός περιόδων με διαφορετικές σχέσεις φάσης παράγοντας διαφορετική ασυνέχεια όταν τα άκρα ενώνονται σε βρόγχο.



Στο παρακάτω διάγραμμα παρουσιάζονται κάποια **σημαντικά παράθυρα:**

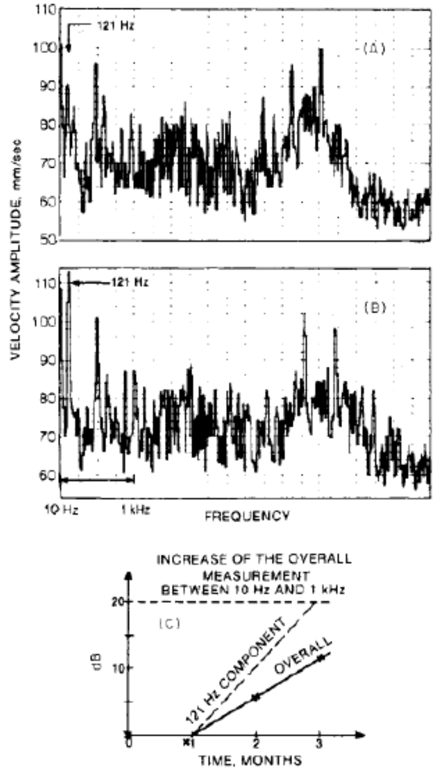
Rectangular window	$w(n)=1$		
Hann window	$w(n)=0.5\left(1-\cos\left(\frac{2\pi n}{N-1}\right)\right)$	$w_0(n)=0.5\left(1+\cos\left(\frac{2\pi n}{N-1}\right)\right)$	
Hamming window	$w(n)=0.54-0.46\cos\left(\frac{2\pi n}{N-1}\right)$	$w_0(n)\overset{def}{=}w\left(n+\frac{N-1}{2}\right)$ $=0.54+0.46\cos\left(\frac{2\pi n}{N-1}\right)$	The window is optimized to minimize the maximum (nearest) side lobe, giving it a height of about one-fifth that of the Hann window, a raised cosine with simpler coefficients.



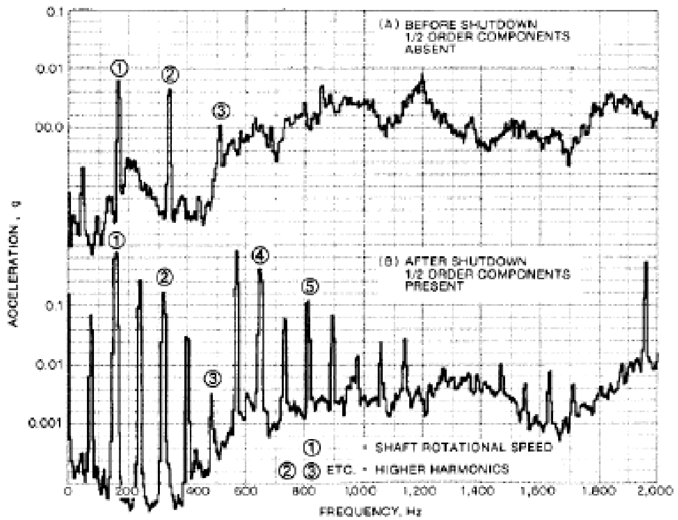
Hamming window; B=1.37

Vibration Analysis

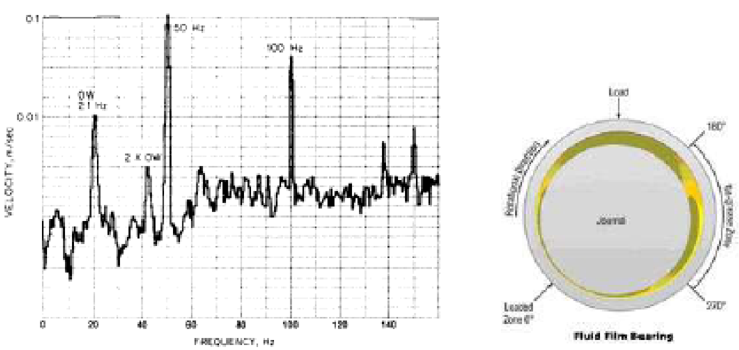
- Condition Monitoring
- Changes in Frequency Spectrum
- Spectrum Interpretation & diagnosis



Σχήμα 3.21
Ανάλυση τάσης εξέλιξης (trend analysis) σε μία συνολική μέτρηση και σε ένα μόνο εύρος
(A) Φάσμα συχνότητας δόνησης μετρούμενο βάση της ταχύτητας για ένα κιβώτιο ταχυτήτων μετά την εγκατάσταση .Να σημειωθεί το μεγάλο πλάτος του συχνοτικού στοιχείου των 480 Hz που κυριαρχεί στο φάσμα αναφοράς
(B)Το φάσμα συχνότητας δόνησης μετρούμενο βάση της ταχύτητας τρεις μήνες μετά. Να σημειωθεί η αύξηση στο συχνοτικό στοιχείο των 121 Hz το οποίο αντιστοιχεί στην ταχύτητα του άξονα στην έξοδο του κιβωτίου
(C)Καμπύλες που συγκρίνουν την αύξηση στο συχνοτικό στοιχείο των 121 Hz. Η αύξηση στη συνολική ταχύτητα στο εύρος από 10 μέχρι 1000 Hz δείχνει ένα αναπτυσσόμενο σφάλμα.



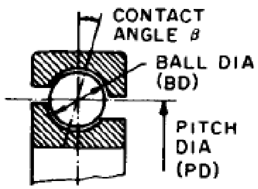
Σχήμα 3.22
Φάσμα επιτάχυνσης ρουλεμάν τύπου journal σε φυγοκεντρικό συμπιεστή.
(A) Συμπιεστής σε καλή κατάσταση .Πριν την παύση λειτουργίας του το μοτίβο της δόνησης είναι φυσιολογικό με μερικές αρμονικές της περιστροφικής ταχύτητας του συμπιεστή και θόρυβο στις υψηλές συχνότητες λόγω έμφυτων αναταράξεων
(B) Συμπιεστής με χαλαρότητα στα ρουλεμάν (journal bearings).



Σχήμα 3.23
Ανάλυση φάσματος δόνησης μετρούμενης στα ρουλεμάν τύπου journal μιας αντλίας ,που απεικονίζει συχνοτικά στοιχεία λόγω στροβιλισμού λαδιού στο 42% της περιστροφικής ταχύτητας.

Spectrum Interpretation & diagnosis(1)

- Subharmonic Elements
- Low harmonics of the rotating speed
- Harmonics of the transmission Line
- Higher Harmonics of the rotating speed

Nature of fault	Frequency of dominant vibration, Hz = rpm/60	Direction	Remarks
Rotating members out of balance	$1 \times$ rpm	Radial	A common cause of excess vibration in machinery
Misalignment and bent shaft	Usually $1 \times$ rpm Often $2 \times$ rpm Sometimes 3 and $4 \times$ rpm	Radial and axial	A common fault
Damaged rolling element bearings (ball, roller, etc.)	Impact rates for the individual bearing component Also vibrations at high frequencies (2 to 60 kHz) often related to radial resonances in bearings	Radial and axial	Uneven vibration levels, often with shocks Impact Rates f (Hz): For Outer Race Defect $f(\text{Hz}) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right)$  For Inner Race Defect $f(\text{Hz}) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD}\cos\beta\right)$ For Ball Defect $f(\text{Hz}) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD}\cos\beta\right)^2\right]$ n = number of balls or rollers f_r = relative rps between inner and outer races
Journal bearings loose in housing	Subharmonics of shaft rpm, exactly $\frac{1}{2}$ or $\frac{1}{3} \times$ rpm	Primarily radial	Looseness may only develop at operating speed and temperature (e.g., turbomachines)

Παλινδρωμίζουσες Μηχανές

Spectrum Interpretation & diagnosis(2)

Oil-film whirl or whip in journal bearings	Slightly less than half shaft speed (42 to 48 percent)	Primarily radial	Applicable to high-speed (e.g., turbo) machines
Hysteresis whirl	Shaft critical speed	Primarily radial	Vibrations excited when passing through critical shaft speed are maintained at higher shaft speeds. Can sometimes be cured by tightening the rotor components.
Damaged or worn gears	Tooth-meshing frequencies (shaft rpm × number of teeth) and harmonics	Radial and axial	Sidebands around tooth-meshing frequencies indicate modulation (e.g., eccentricity) at frequency corresponding to sideband spacings. Normally only detectable with very narrow-band analysis and cepstrum analysis.
Mechanical looseness	2 × rpm		Also sub- and interharmonics, as for loose journal bearings
Faulty belt drive	1, 2, 3, and 4 × rpm of belt	Radial	The precise problem can usually be identified visually with the help of a stroboscope
Unbalanced reciprocating forces and couples	1 × rpm and/or multiples for higher-order unbalance	Primarily radial	
Increased turbulence	Blade & vane passing frequencies and harmonics	Radial and axial	An increased level indicates increased turbulence
Electrically induced vibrations	1 × rpm or 2 times line frequency	Radial and axial	Should disappear when power is turned off

Reprocating Engines

Static eccentricity	2 × line frequency and components at $\omega \times [nR_s(1-s)/p \pm k_1]$	Radial	Can result from poor internal alignment, bearing wear, or from local stator heating (vibration worsens as motor heats up).
Weakness/looseness of stator support, unbalanced phase resistance or coil sides Shorted stator laminations/turns	2 × line frequency	Radial	Referred to as "loose iron." Difficult to differentiate between this group using only vibration analysis, but they will also be apparent at no load as well as on load.
Loose stator laminations	2 × line frequency and components spaced by 2 × line frequency at around 1 kHz	Radial	Can have high amplitude but not usually destructive. The high-frequency components may be similar to static eccentricity.
Dynamic eccentricity	1 × rpm with 2 × slip-frequency sidebands and components at $\omega \times [((nR_s \pm k_e) \times (1-s)/p) \pm k_1]$	Radial	Can result from rotor bow, rotor runout, or from local rotor heating (vibration worsens as motor heats up).
Broken or cracked rotor bar Loose rotor bar Shorted rotor laminations Poor end-ring joints	1 × rpm with 2 × slip-frequency sidebands and components similar to those given above for dynamic eccentricity with addition of 2 × slip-frequency sidebands around slot harmonics	Radial	The slip sidebands may be low level, requiring a large dynamic range as well as frequency selectivity in measuring instrumentation. Typical spectra show that these components in the region of the principal vibration slot harmonics also have slip-frequency sidebands.

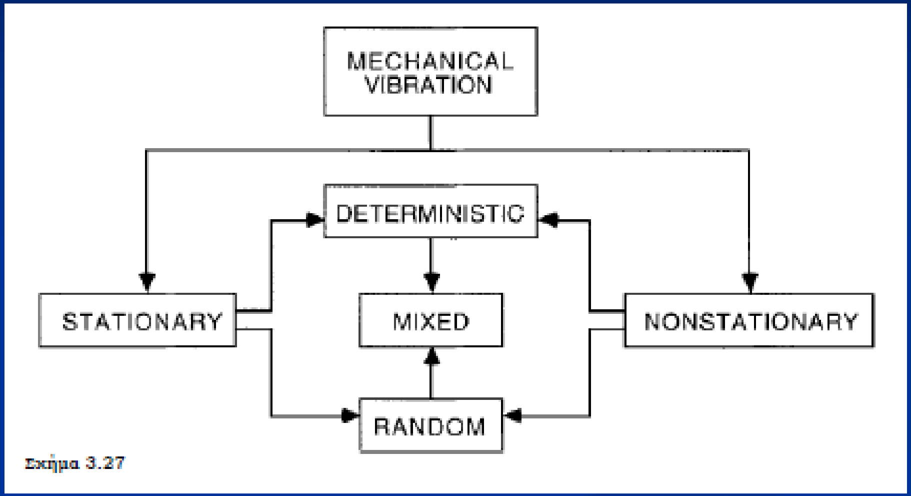
Inductive engines

Vibration Cause	Symptomatic Frequency	Dominant Plane	Comment
Unbalanced Rotor Shaft	1 × *RPM*	Radial	Type of unbalance can be determined from phase relationships (see Table 2)
Bent Shaft or Angular Misalignment	1 ×, 2 × *RPM*	Axial	See Table 2 for more information
Parallel Misalignment	1 ×, 2 × *RPM*	Radial	See Table 2 for more information
Mechanical Looseness	1 ×, 2 ×, 3 ×, 4 × *RPM* etc. also 0,5 ×, 1,5 × *RPM* etc.	Radial	High number of harmonics and possible interharmonics characterizes truncation
Damaged Rolling Element Bearings	Induced resonance in the bearing housing and machine casing in the range 1 to 20 kHz typically	—	Resonance is excited by impacts of local faults in the bearing. Also frequencies due to fundamental impact repetition rates (see Fig.6), which are generally lost among other signals + noise at lower frequency however
Oil Whirl and Whip in Sleeve Bearings	0,43 to 0,48 × *RPM*	Radial	Sleeve Bearings are common in larger motors
Static Eccentricity	2 × line frequency and components at $\omega \times [nR_s(1-s)/p \pm k_1]$	Radial	Can result from poor internal alignment, bearing wear, or from local stator heating[1)] (Vibration worsens as motor heats up)
Weakness/Looseness of Stator Support, **Unbalanced Phase Resistance or Coil Sides,** **Shorted Stator Laminations/Turns**	2 × line frequency	Radial	Referred to as "loose iron" Difficult to differentiate between this group using only vibration analysis, but they will also be apparent at no load as well as on load
Loose Stator Laminations	2 × line frequency and components spaced by 2 × line frequency at around 1 kHz[†]	Radial	Can have high amplitude but not usually destructive. The high frequency components may be similar to static eccentricity[†]
Dynamic Eccentricity	1 × *RPM* with 2 × slip frequency sidebands and components at $\omega \times [((nR_s \pm k_e) \times (1-s)/p) \pm k_1]$	Radial	Can result from rotor bow, rotor runout, or from local rotor heating[2)] (Vibration worsens as motor heats up)
Broken or Cracked Rotor Bar, **Loose Rotor Bar,** **Shorted Rotor Laminations,** **Poor End-Ring Joints**	1 × *RPM* with 2 × slip frequency sidebands and components similar to those given above for dynamic eccentricity[†]	Radial	The slip sidebands may be low level, requiring a large dynamic range as well as frequency selectivity in measuring instrumentation. Typical spectra are shown in the appendix showing that these components in the region of the principal vibration slot harmonics also have slip frequency sidebands

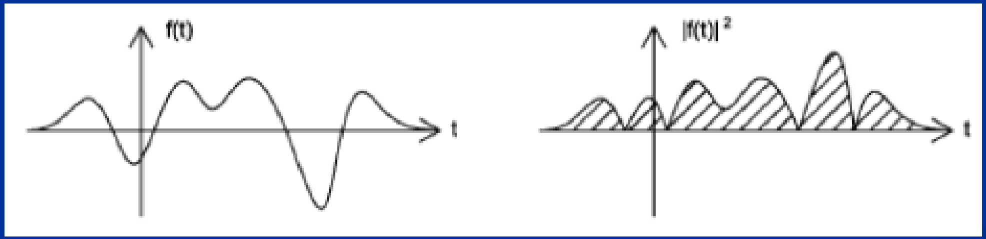
DC Generators

Categorizing Vibrations

- Stationary Vibration
- Non-Stationary Vibration
- Deterministic Vibration
- Random
- Mixed



Energy & Power



Microcontroller ADuC7026

- Embedded Systems
- ARM7TDMI
- Olimex Development Platform
- Keil-Uvision Develoment Enviroment

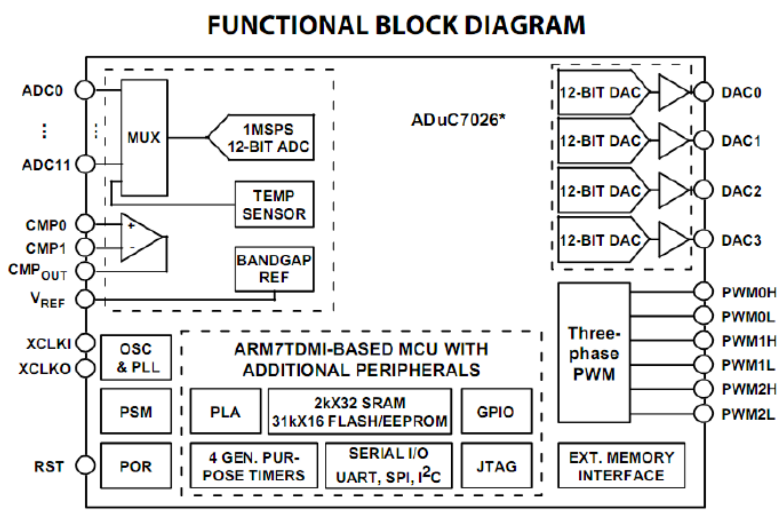
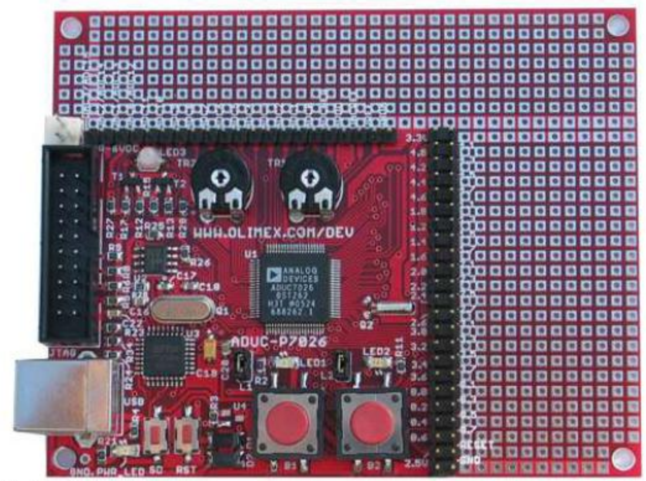


Figure 1

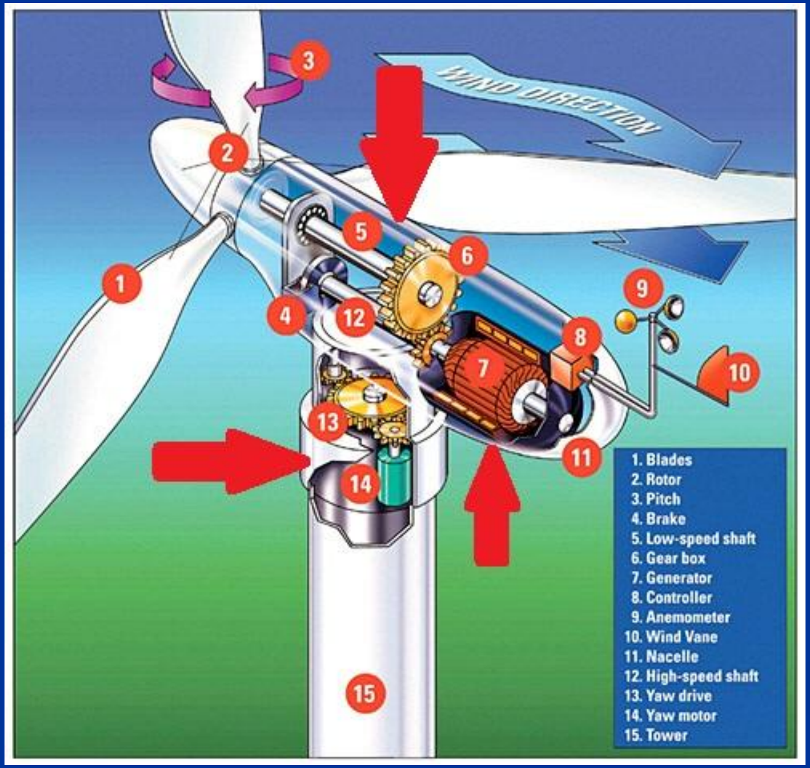
Σχήμα 4.1



Σχήμα 4.5

Fault Detection using the microcontroller(1)

- Ordinance
- Sampling rate
- Variable Number of channels with variable depth of analysis
- Data flow



Possibility of locating sensors on gearbox

Fault Detection using the microcontroller(2)

- Code Structure
- Variables
- Data storage
- Functions & Processing
- Sampling Functions

Συνάρτηση δειγματοληψίας:

```
__irq void IRQ_Handler(void)
{
Buffers[NA].Buffer[ADCCP][pos]=(ADCDAT >> 16);          /*αποστολή 1 δείγματος*/
ADCCP=(ADCCP+1)%channels;
if(ADCCP==0)pos=(pos+1)%COL;
if((ADCCP==0)&&(pos==0))NA=(NA+1)%NOB;
return;
}
```

Fault Detection using the microcontroller(3)

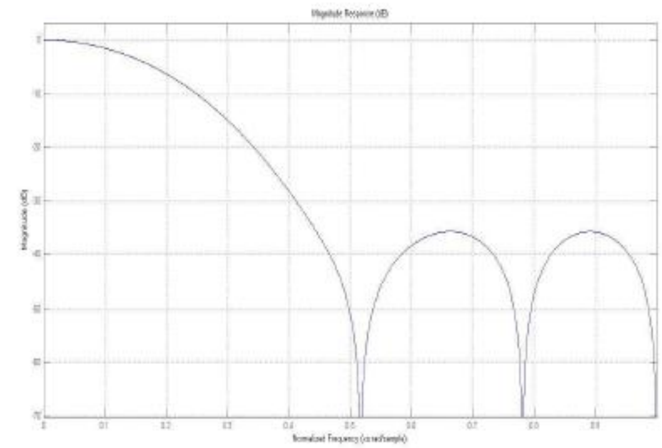
- Filter Design - Initialization - High frequency cut-off
- Window
- System startup
  - CPU
  - Timers
  - Ports
  - Interrupts
  - ADC
- Processing
  - FFT
  - Scrambler
  - Twindle Factors
  - Butterfly
  - Reverse FFT
  - Cepstrum
  - Histogram
  - Power & rms
  - Continuous production of average value of a large number of consecutively added numbers
- Control Function

Filter & cutting off high frequency elements

- Matlab
  - Filter1=fir1(9,0.001);

```
void sortFIR(void)
{
int i,j,k,m,n;
i=0;j=0;k=0;m=0;n=0;addup=0;
if (NA!=0)j=(NA-1);        //Επιλογή buffer
if (NA==0)j=(NOB-1);
for(m=0;m<COL;m++)
{
for(i=0;i<channels;i++)
{
for(k=(bufferlength-1);k>0;k--){Array[i].data[k]=Array[i].data[k-1];}        //Ολίσθηση
Array[i].data[0]=Buffers[j].Buffer[i][m];                //Τοποθέτησηση στη δομή δεδομένων
από τον buffer
for(n=0;n<bufferlength;n++){addup+=Array[i].data[n]*FIR[n];}             //πέρασμα τιμών
από το φίλτρο
Array[i].G[m]=addup;
addup=0;
}
}
}
```

fvtool(Filter1);



```
>> lowpass
lowpass =
   0.0161    0.0379    0.0931    0.1559    0.1969    0.1969    0.1559    0.0931
0.0379    0.0161
```

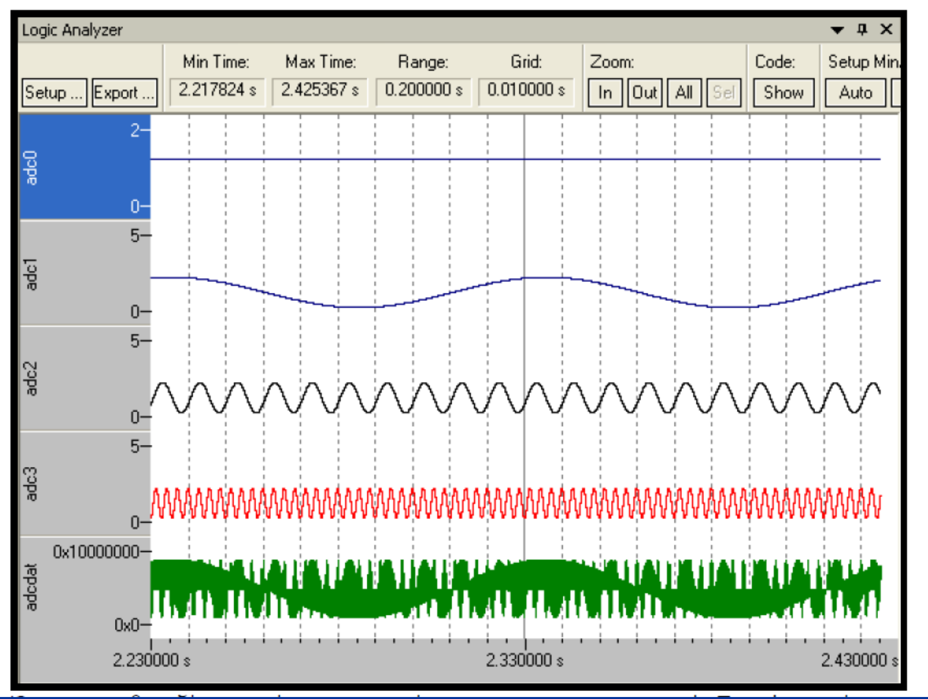
Scrambler

Bit-reversal

				# Bits			
Initial	Binary	Mirrored Binary	Scrambled	3	4	5	6
0	00	00	0	0	0	0	0
1	01	10	2	4	8	16	32
2	10	01	1	2	4	8	16
3	11	11	3	6	12	24	48
orange	*2	4	0	1	2	4	8
violet	(*2)+1	5	2	5	10	20	40
		6	1	3	6	12	24
		7	3	7	14	28	56
		8	0	0	1	2	4
		9	2	4	9	18	36
		10	1	2	5	10	20
		11	3	6	13	26	52
		12	0	1	3	6	12
		13	2	5	11	22	44
		14	1	3	7	14	28
		15	3	7	15	30	60
		16	0	0	0	1	2
		17	2	4	8	17	34
		18	1	2	4	9	18
		19	3	6	12	25	50
		20	0	1	2	5	10
		21	2	5	10	21	42
		22	1	3	6	13	26
		23	3	7	14	29	58
		24	0	0	1	3	6
		25	2	4	9	19	38
		26	1	2	5	11	22
		27	3	6	13	27	54
		28	0	1	3	7	14
		29	2	5	11	23	46
		30	1	3	7	15	30
		32	0	0	0	0	1
		33	2	4	8	16	33
		34	1	2	4	8	17
		35	3	6	12	24	49
		36	0	1	2	4	9
		37	2	5	10	20	41
		38	1	3	6	12	25
		39	3	7	14	28	57
		40	0	0	1	2	5
		41	2	4	9	18	37
		42	1	2	5	10	21
		43	3	6	13	26	53
		44	0	1	3	6	13
		45	2	5	11	22	45
		46	1	3	7	14	29
		47	3	7	15	30	61
		48	0	0	0	1	3
		49	2	4	8	17	35
		50	1	2	4	9	19
		51	3	6	12	25	51
		52	0	1	2	5	11
		53	2	5	10	21	43
		54	1	3	6	13	27
		55	3	7	14	29	59
		56	0	0	1	3	7
		57	2	4	9	19	39
		58	1	2	5	11	23
		59	3	6	13	27	55
		60	0	1	3	7	15
		61	2	5	11	23	47
		62	1	3	7	15	31
		63	3	7	15	31	63

Simulation(1)

- Simulation capability with keil uvision
- Simulating inputs
- Capability of verification of variable values and data flow
- Proper FFT operation

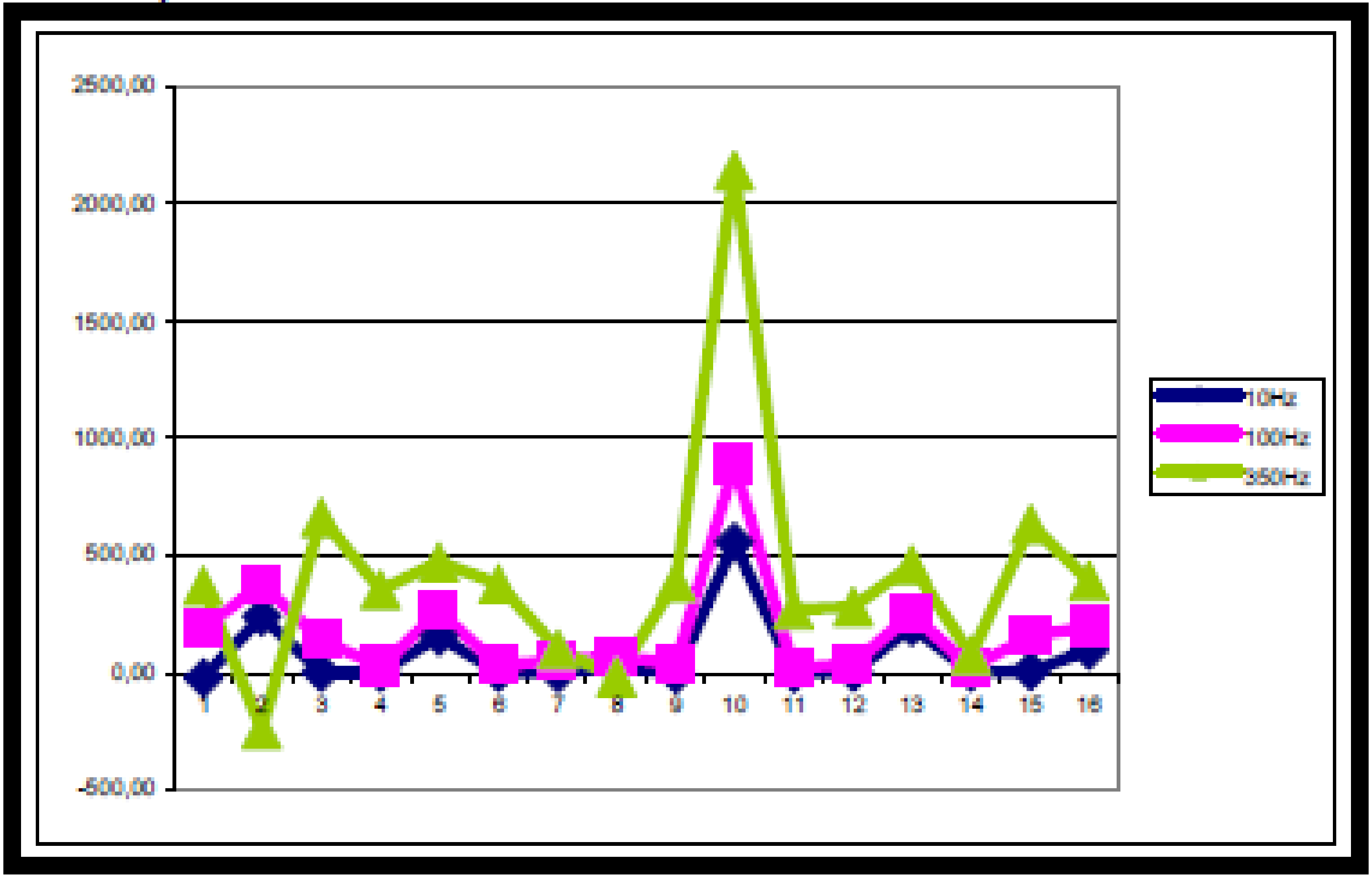


Συνοψίζοντας σε ενιαίο πίνακα:

Channel	0	1	2	3
0	15418	15396,88	15608	15787
1	4066,8	4308,172	4444,3	3826,5
2	2196,4	2197,82	2335,4	2858,3
3	2455,5	2458,822	2485,7	2810,8
4	0,481	153,4095	262,87	471,83
5	2575,9	2579,041	2609,6	2954,6
6	3418,7	3415,734	3472,7	3517,9
7	1862,9	1893,09	1931,5	1843,8
8	4062,8	4057,608	4103,8	4450,4
9	479,37	1037,408	1370,9	2621
10	2195,4	2192,311	2215,9	2462,6
11	5260,5	5262,413	5302,7	5541,9
12	0,6152	196,8524	253,55	459,75
13	2400,7	2404,721	2426,7	2474,4
14	3417,8	3425,244	3571,1	4049,8
15	6161,3	6257,119	6359,7	6554,8
	0 Hz	10 Hz	100Hz	350Hz
0		-21,48	190,09	368,99
1		241,36	377,54	-240,29
2		1,39	138,97	661,84
3		3,36	30,26	355,38
4		152,93	262,39	471,35
5		3,10	33,65	378,61
6		-2,93	54,04	99,28
7		30,18	68,59	-19,10
8		-5,23	41,00	387,58
9		558,04	891,55	2141,68
10		-3,09	20,45	267,23
11		1,95	42,24	281,45
12		196,24	252,94	459,13
13		4,04	26,05	73,67
14		7,46	153,31	632,03
15		95,85	198,39	393,52

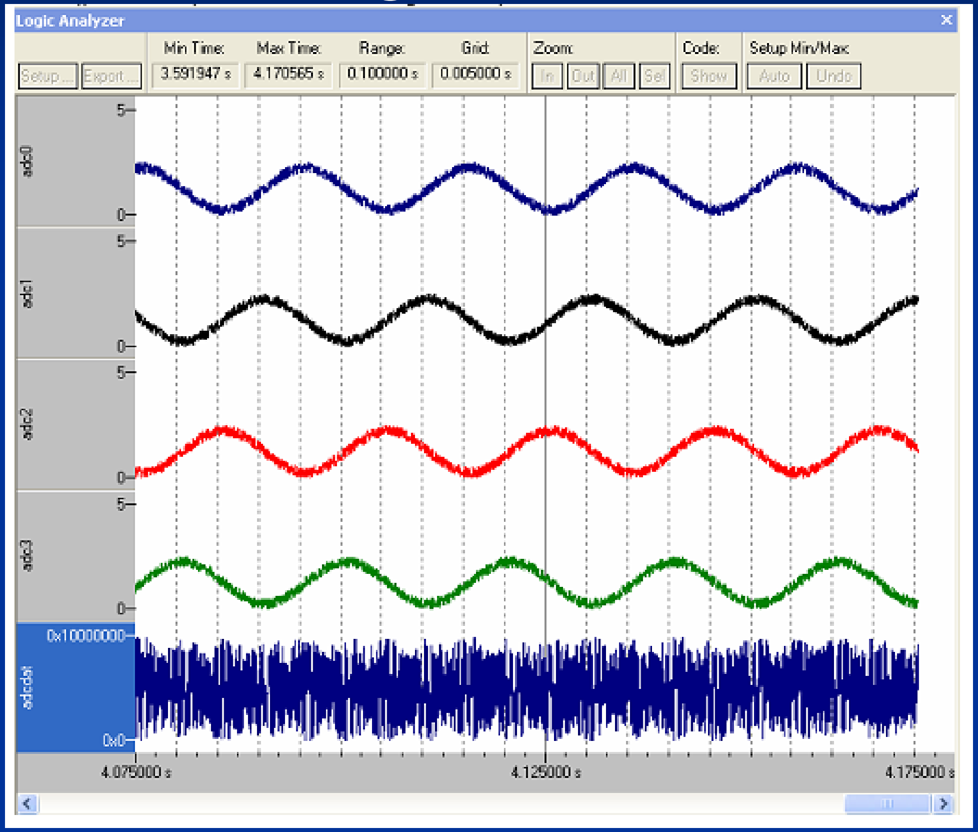
Simulation(2)

Έτσι προκύπτει:



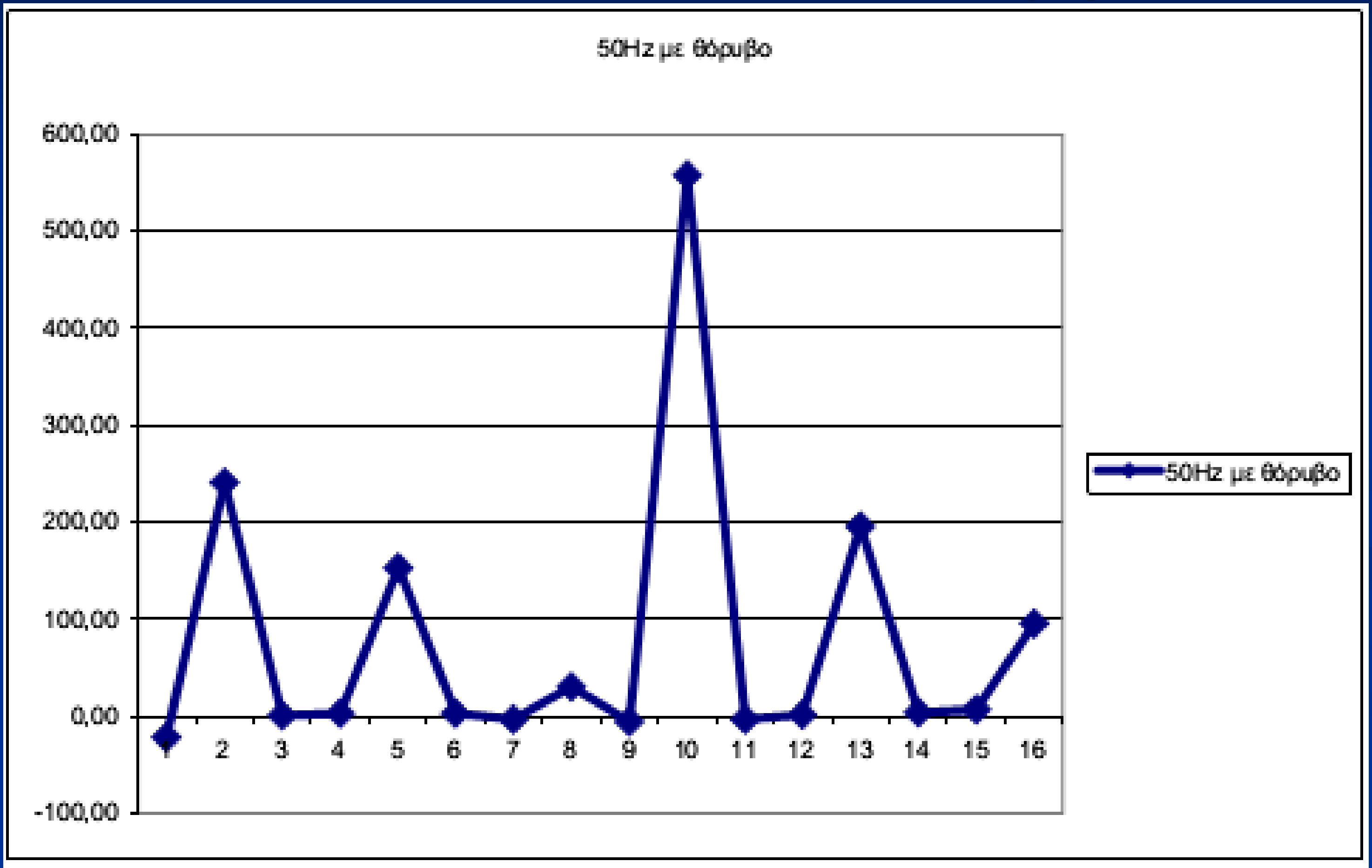
Simulation(3)

- Sinusoidal signal with noise:



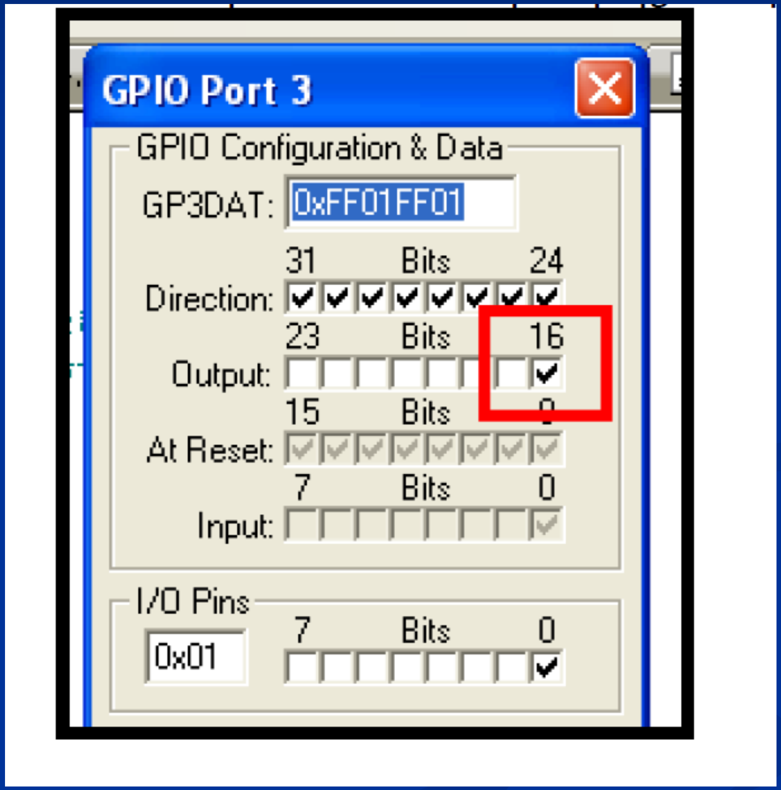
Channel	0	1
0	15418	15442,9
1	4066,8	4150,825
2	2196,4	2226,635
3	2455,5	2464,847
4	0,481	144,1399
5	2575,9	2585,461
6	3418,7	3428,348
7	1862,9	1880,781
8	4062,8	4069,918
9	479,37	813,0291
10	2195,4	2199,528
11	5260,5	5270,973
12	0,6152	138,2589
13	2400,7	2406,118
14	3417,8	3460,375
15	6161,3	6212,131
	0 Hz	50 Hz noised
0		24,54
1		84,02
2		30,20
3		9,39
4		143,66
5		9,52
6		9,68
7		17,87
8		7,08
9		333,66
10		4,13
11		10,51
12		137,64
13		5,43
14		42,59
15		50,86

Simulation(4)



Simulation(5)

- Monitoring & Control
  - Standard values
  - Using the power variable
  - Led activation



Conclusions

- Piezoelectric transducers
  - Suitable to be used as sensors
- System Monitoring
  - Condition diagnosis
  - Timely repair
  - Fault detection
  - System type recognition
- Keil-Uvision
  - Capability of developing and simlating application
  - Inputs Simulation
  - Peripherals Simulation

Thank you for your attention.