Benchmark on Adaptive Regulation
Rejection of unknown/time-varying multiple narrow band disturbances
The results

Direct and Indirect Adaptive Regulation Strategies for Rejection of Time Varying Narrow Band Disturbances Applied to a Benchmark Problem

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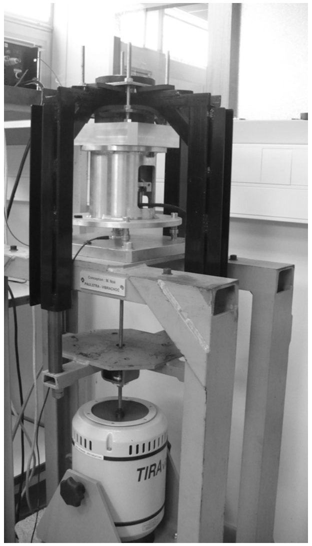

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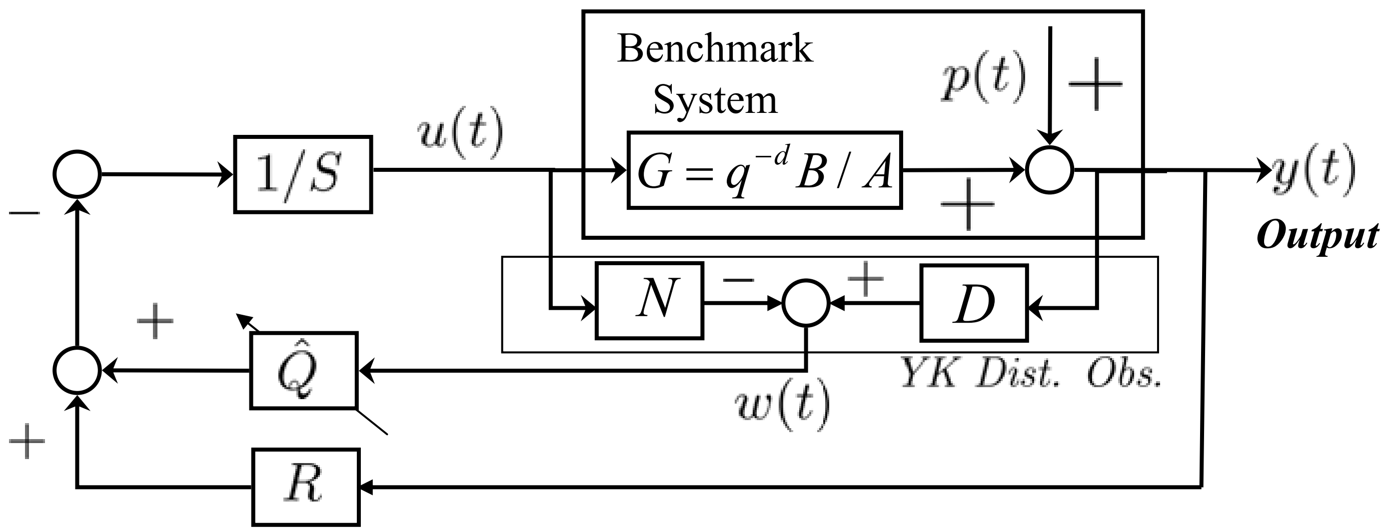
Methodological comparison

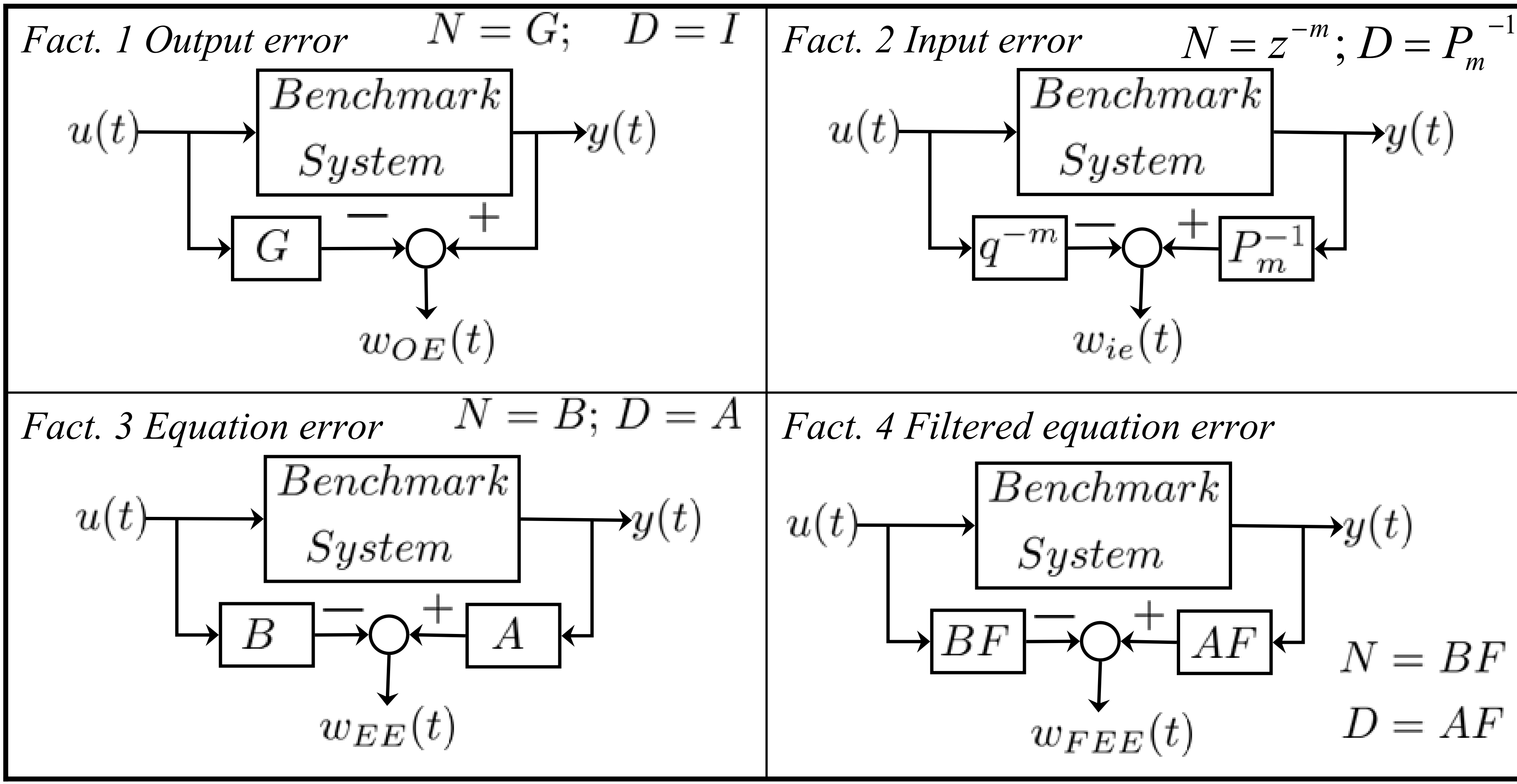
- 7 contributions
- 6 contributions use Youla-Kucera parametrization of various kinds
- 1 contribution use L.P.V. + spike frequency estimation
- 5 contributions use "direct" adaptation and 2 contributions use "indirect" adaptation
- *Different techniques for the design of the "central controller"*



General scheme for adaptive regulation using
YK controller parametrization

Youla Kucera Controller Parametrization

- Based on the *right coprime factorization:* $G = ND^{-1}$
- Provide observers for the (non measurable) disturbance.
- **Various choices for N and D**



Comparison of Methodologies

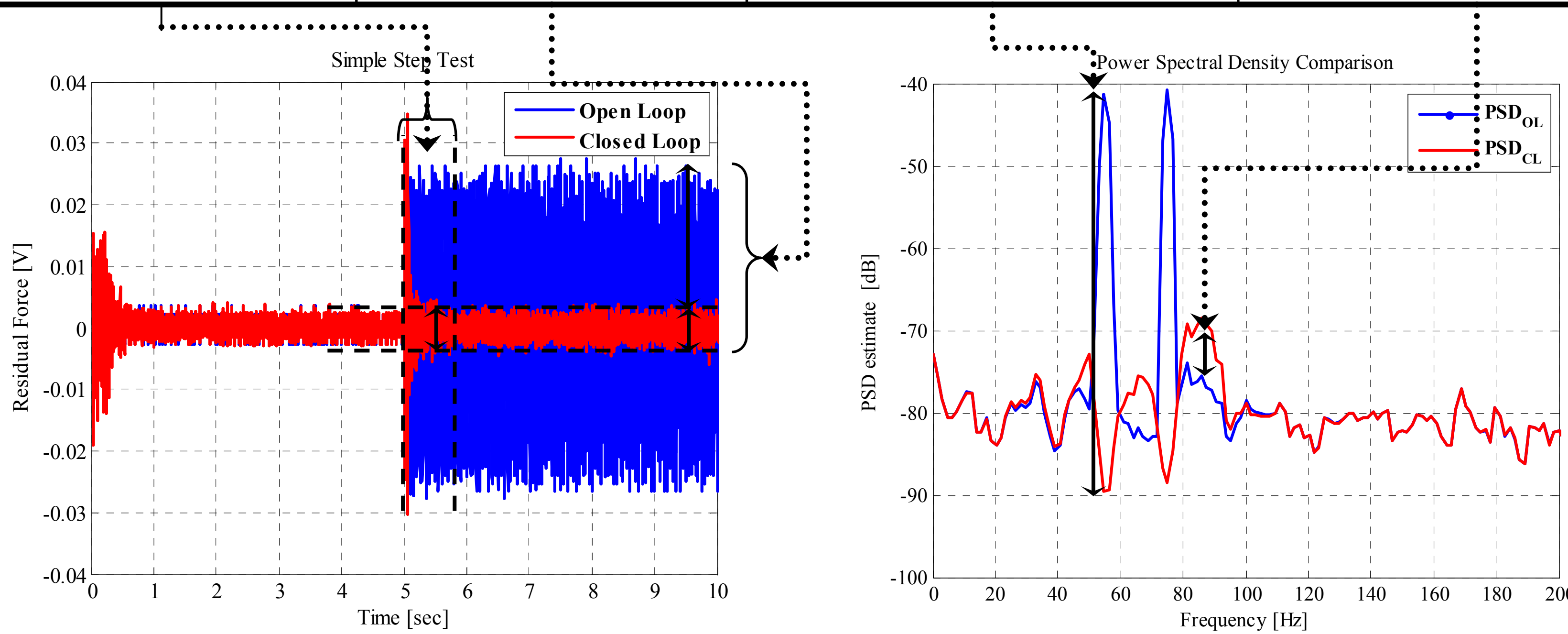
Participant	Type of YK parametrization	Type of Q-filter	Central contr. Design	Dist. Rejec. method	Type of adaptation	Number of parameters to adapt
Aranovskiy et al.	**Output error**	FIR cascaded w/fixed filter	No central controller	IMP	**Direct**	$2n$
Callafon et al.	**Filtered equation error**	FIR	H_2	H_2	**Direct**	All levels 29
Karimi et al.	**No**	No	No	H_∞ +IMP	**Indirect (LPV w/interpol.)**	n
Wu et al.	**Equation error (filtered)**	FIR cascaded w/fixed BP filter	LQR	IMP	**Direct**	$2n$
Xu et al.	**Input error**	IIR (notch structure)	Pole Placement	Plant Model Inversion	**Direct**	n
Airimitoaie et al.	**Equation error**	IIR cascaded w/fixed filter	Pole Placement	Output sens. shaping	**Indirect**	n
Castellanos et al.	**Equation error**	FIR cascaded w/fixed filter	Pole Placement	IMP	**Direct**	$2n$

FIR = Finite Impulse Response　　IIR = Infinite Impulse Response　　IMP = Internal Model Principle

n = Number of narrow band disturbances

Performances to be measured on the residual force

Transient Duration	Global Attenuation	Disturbance Attenuation	Maximum Amplification
TD(s)	*GA(dB)*	*DA(dB)*	*MA(dB)*



Time response (left) and PSD comparison (right) for rejection of a double narrow band disturbance at [55,75] Hz.

The tuning capabilities (steady state performance) are the most important!

Time domain measurements on the residual force

Square of the truncated-two norm $N^2Y = \sum_{i=1}^{m} y(i)^2$	***Maximum value*** $MV = \max_m \lvert y(i) \rvert$	***Mean Square*** $MSE = \frac{1}{m}\sum_{i=1}^{m} y(i)^2$

Measurements for simple step and step frequency changes test

Measurements for chirp test

Global attenuation

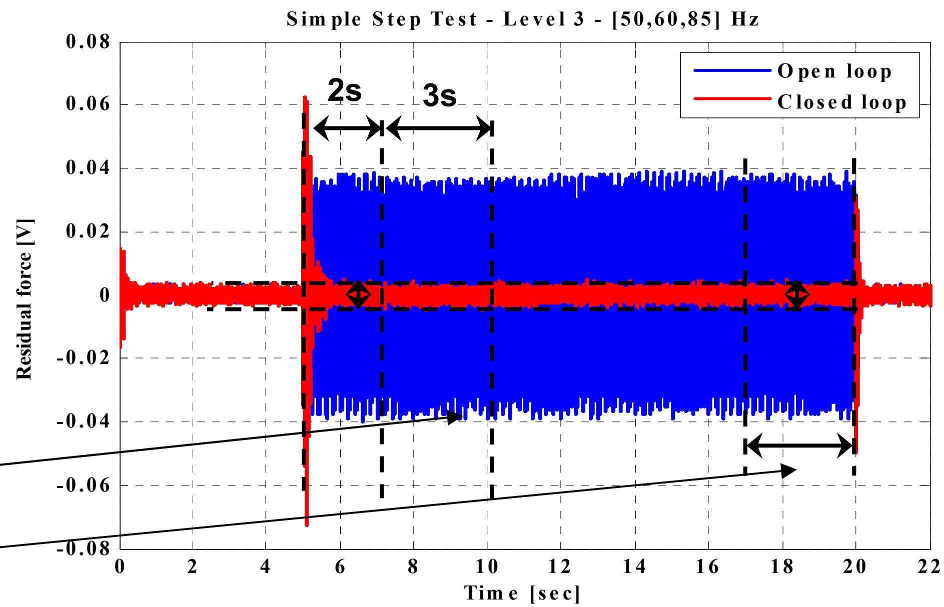
$$GA = 20\log_{10}\left(\frac{N^2Y_{ol}(\text{s.s.})}{N^2Y_{cl}(\text{s.s.})}\right)$$

Transient duration

Step applied at T=5s

$$\alpha_i = \frac{N^2Y_{cl}(7:10)}{N^2Y_{cl}(17:20)}$$

$\alpha_i \leq 1.21 \Rightarrow$ *transient duration* $\leq 2s$



Transient and steady state behavior for the Simple Step protocol

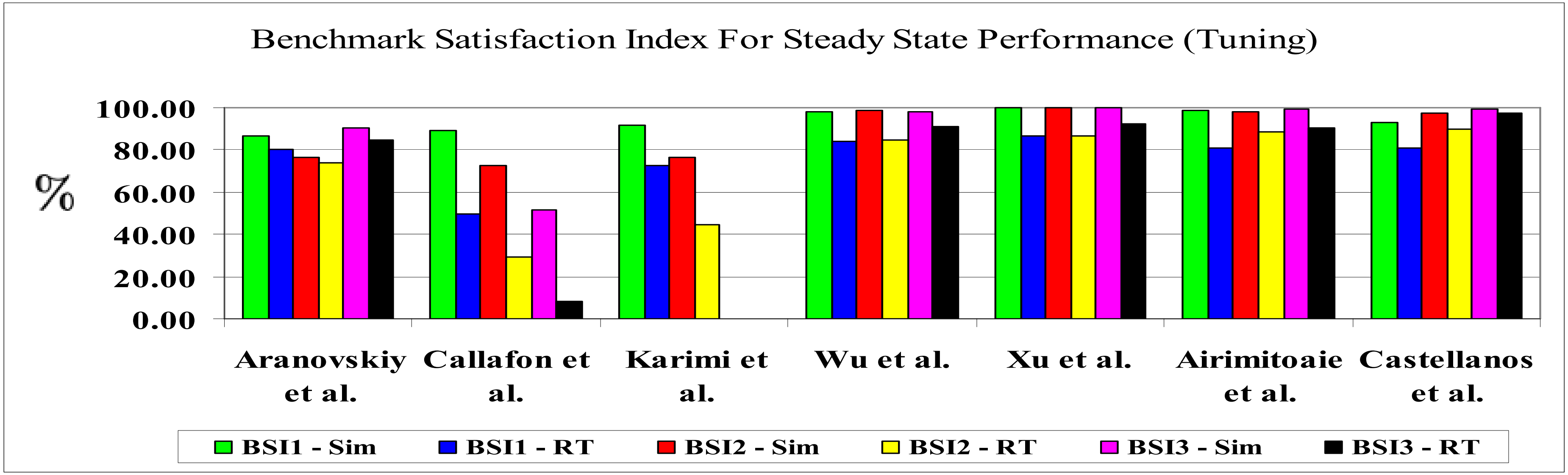
Benchmark Satisfaction Index (BSI)

- Benchmark specification define a **min** value to be achieved (GA, DA) and a **max** value not to be over passed (MA, TD)
- Full satisfaction of the benchmark specs. : BSI=100%
- Less than half of the specifications for GA, DA are achieved: BSI= 0%
- If the achieved MA,TD are twice the specification: BSI=0%
- Average over the various experimental protocols are considered
- A global BSI averaging the BSI for the various protocols is considered
- The global BSI_{SS} for ***steady state*** (tuning) is an average over all achieved MA,GA,DA
- **Simulation and real time experiments are considered.**

GA= Global Attenuation, DA= Disturbance Attenuation, MA = Maximum Amplification
TD= Transient Duration

Benchmark satisfaction index(BSI) (simulation and real – time)

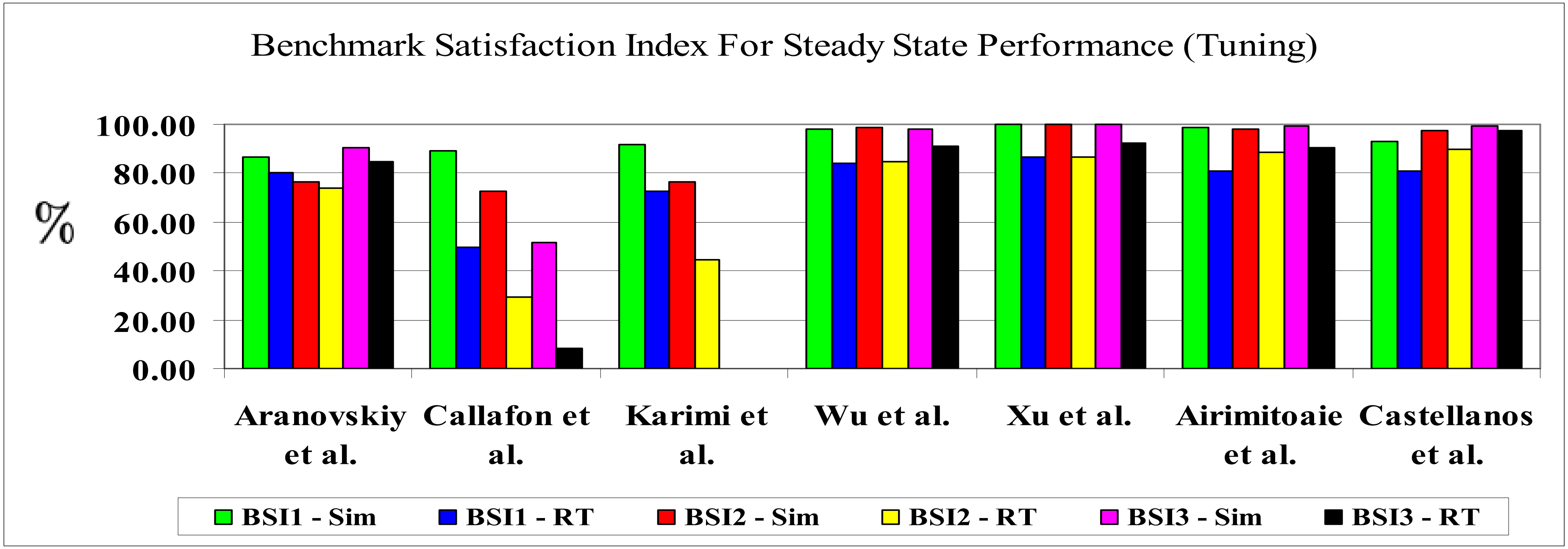
(steady state)	Level 1		Level 2		Level 3	
	BSI1 - Sim	**BSI1 - RT**	**BSI2 - Sim**	**BSI2 - RT**	**BSI3 - Sim**	**BSI3 - RT**
Aranovskiy et al.	86.94%	80.22%	76.33%	73.58%	90.65%	84.89%
Callafon et al.	89.21%	49.37%	72.89%	29.08%	51.74%	8.40%
Karimi et al.	91.92%	72.89%	76.13%	44.33%	-	-
Wu et al.	98.31%	**83.83%**	98.48%	84.69%	98.01%	91.00%
Xu et al.	**100.00%**	**86.63%**	**100.00%**	**86.65%**	**99.78%**	92.52%
Airimitoaie et al.	98.69%	81.11%	98.38%	**88.51%**	99.44%	90.64%
Castellanos et al.	93.30%	80.87%	97.29%	**89.56%**	99.13%	**97.56%**



(≈4% uncertainties in the real-time results)

Steady State (Tuning) Performance: Comments

- The benchmark specifications are achievable (100% level 1 and 2, 99.78% level 3).
- The *steady state performance* is the most important.
- The designs of Wu, Xu, Airimitoaie, Castellanos give the **best** results
- They use YK parametrization.
- Wu, Xu, Castellanos :**direct** adaptation, Airimitoaie: **indirect** adaptation.
- Simulation results: evaluate the proposed method for *design model = plant model*.
- Real time results evaluate robustness with respect to plant model and noise errors.



Robustness with respect to plant model and noise uncertainties

Differences between simulator and the real –time test bed experiments:

- Noise is different (magnitude and spectral content)
- Uncertainties on low damped complex zeros
- Some uncertainties in the plant model around 130 Hz- 180 Hz

The differences come from the difficulty of correctly identifying very low damped complex zeros and noise spectral content

Objective:

•Assess the robustness in performance for those which use the **same controller** in simulation and in real-time.

• A *Normalized Performance Loss* index was defined.

Normalized performance loss for each level

$$NPL_k = \left(\frac{BSI_{k,sim} - BSI_{k,RT}}{BSI_{k,sim}}\right) 100\%$$

k= Benchmark level (nb. of spikes)

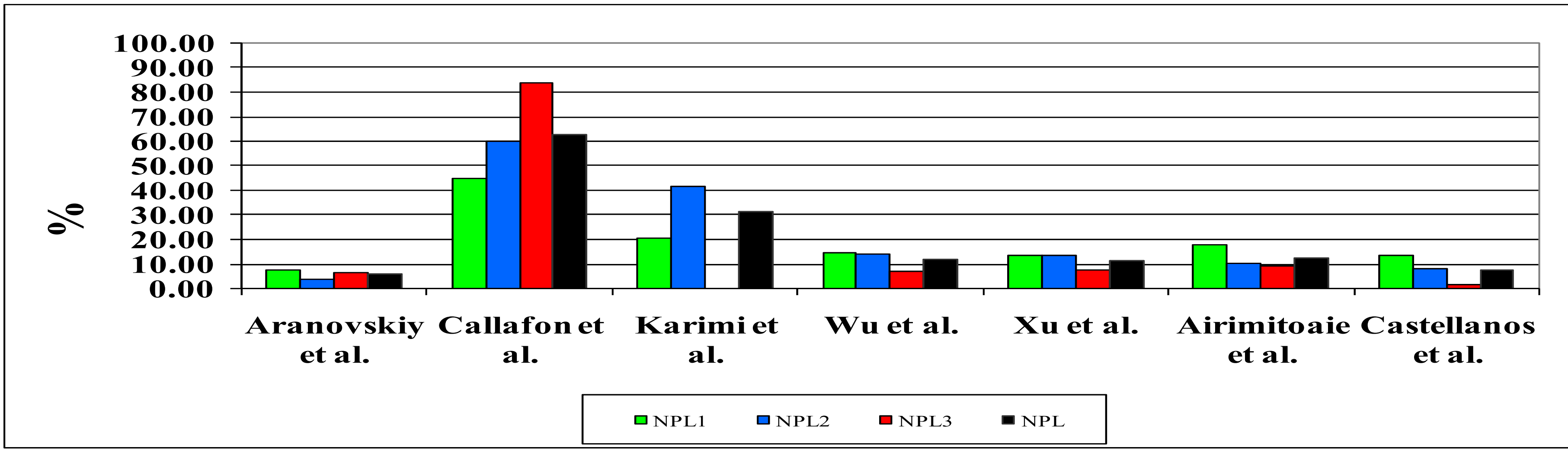
Global criterion

$$NPL = \frac{1}{M}\sum_{k=1}^{M} NPL_k \quad M = 3$$

(*M*=2 for Karimi et al)

Normalized performance loss: *real-time vs. simulation*

	NPL1	NPL2	NPL3	NPL
Aranovskiy et al.	7.73%*	3.61%*	6.35%*	5.90%*
Callafon et al.	44.46%*	60.11%*	83.77%*	62.85%*
Karimi et al.	20.70%	41.77%	-	31.24%
Wu et al.	14.73%	14.01%	7.16%	11.96%
Xu et al.	13.37%	13.35%	7.28%	11.33%
Airimitoaie et al.	17.81%	10.03%	8.85%	12.23%
Castellanos et al.	**13.32%**	**7.95%**	**1.58%**	**7.62%**



Normalized performance loss (NPL) for all levels and all participants (smaller = better)

*** Participants who use different controllers for simulation and real-time.**

Benchmark satisfaction index for transient performance

Simple step test – Transient duration spec.: ≤ 2s

	Level 1 - BSI_{Trans}		Level 2 - BSI_{Trans}		Level 3 - BSI_{Trans}	
	Simulation	RT	Simulation	RT	Sim	RT
Aranovskiy et al.	100%	100%	100%	100%	100%	100%
Callafon et al.	100%	100%	100%	100%	100%	81.48%
Karimi et al.	100%	97.69%	100%	91.79%	-	-
Wu et al.	100%	99.86%	94.85%	100%	100%	92.40%
Xu et al.	100%	100%	100%	100%	100%	100%
Airimitoaie et al.	100%	99.17%	83.33%	100%	100%	100%
Castellanos et al.	100%	96.45%	100%	95.74%	100%	100%

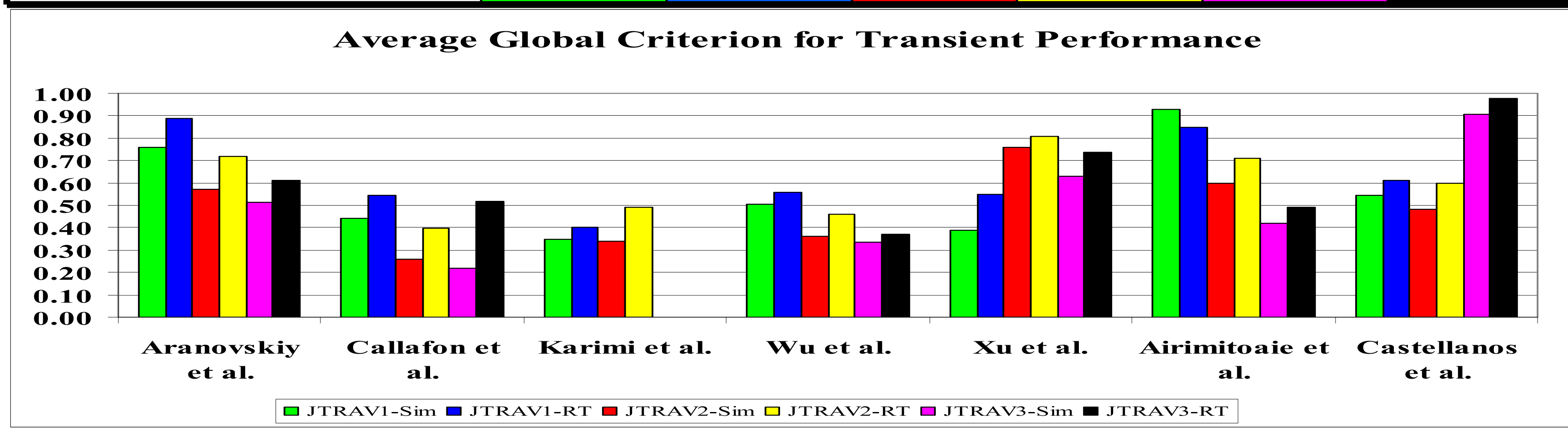
- **Most of the approaches have met the specifications** (100%) or are very close (over 90%) in real-time experiments.

Transient duration evaluation: $$\alpha_i = \frac{N^2 Y_{cl}(7:10)}{N^2 Y_{cl}(17:20)}$$

$\alpha_i \leq 1.21 \Rightarrow transient \quad duration \leq 2s$ ➡ $BSI_{Trans} = 100\%$

Further transient performance evaluation (truncated norm+ max. value)

	JTRAV1		JTRAV2		JTRAV3	
	Sim	**RT**	**Sim**	**RT**	**Sim**	**RT**
Aranovskiy et al.	0.76	0.89	0.57	0.72	0.51	0.61
Callafon et al.	0.44	0.54	**0.26**	**0.40**	**0.22**	0.52
Karimi et al.	**0.35**	**0.40**	0.34	0.49	-	-
Wu et al.	0.50	0.56	0.36	0.46	0.34	**0.37**
Xu et al.	0.39	0.55	0.76	0.81	0.63	0.74
Airimitoaie et al.	0.93	0.85	0.60	0.71	0.42	0.49
Castellanos et al.	0.55	0.61	0.48	0.60	0.90	0.98



Average global criterion for transient performance (JTRAV) for all levels (smaller = better).

- Wu, (Karimi, Callafon) have the best results

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Complexity evaluation using the task execution time

•Complexity of each approach is evaluated using the **average task execution time** (ATET) measured in μsec on the xPC target real-time environment.

•**Computing time in the presence of the controller** (ΔTET) was obtained by subtracting the open loop execution time.

•ΔTET has been evaluated for each type of test and then averaged

Complexity criteria defined for each test

$$\Delta TET_{X,k} = ATET_{X,k} - ATET_{OL,X,k}$$

X=Simple step, Step Freq.changes, Chirp

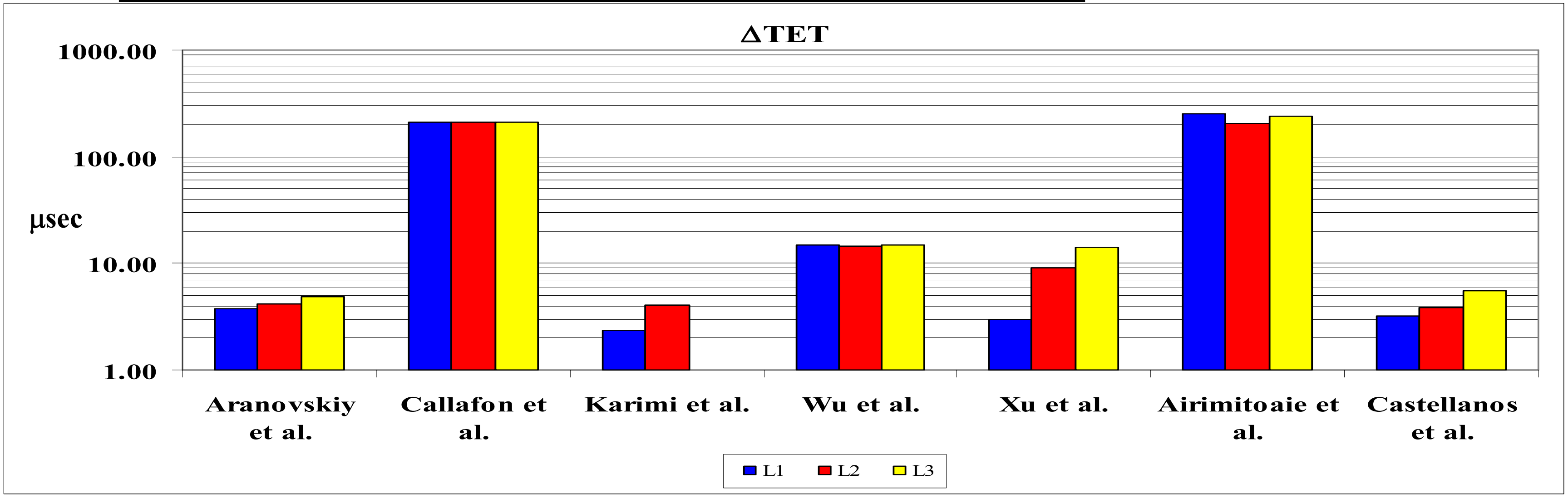
Global criteria defined for each level

$$\Delta TET_k = \frac{1}{3}\left(\Delta TET_{Simple,k} + \Delta TET_{Step,k} + \Delta TET_{Chirp,k}\right)$$

Controller average task execution time (ΔTET) for all levels

	ΔTET		
	L1 (μs)	L2 (μs)	L3 (μs)
Aranovskiy et al.	3.71	4.18	**4.92**
Callafon et al.	210.68	209.90	212.62
Karimi et al.	**2.37**	4.08	-
Wu et al.	14.73	14.65	14.74
Xu et al.	2.96	9.11	14.27
Airimitoaie et al.	254.24	203.83	241.22
Castellanos et al.	3.26	**3.90**	5.60

Direct adaptive approach	Indirect adaptive approach



Disturbance Scenario Change -New Protocols

What happens if the experimental protocols are changed ?
(without re-designing the controllers)

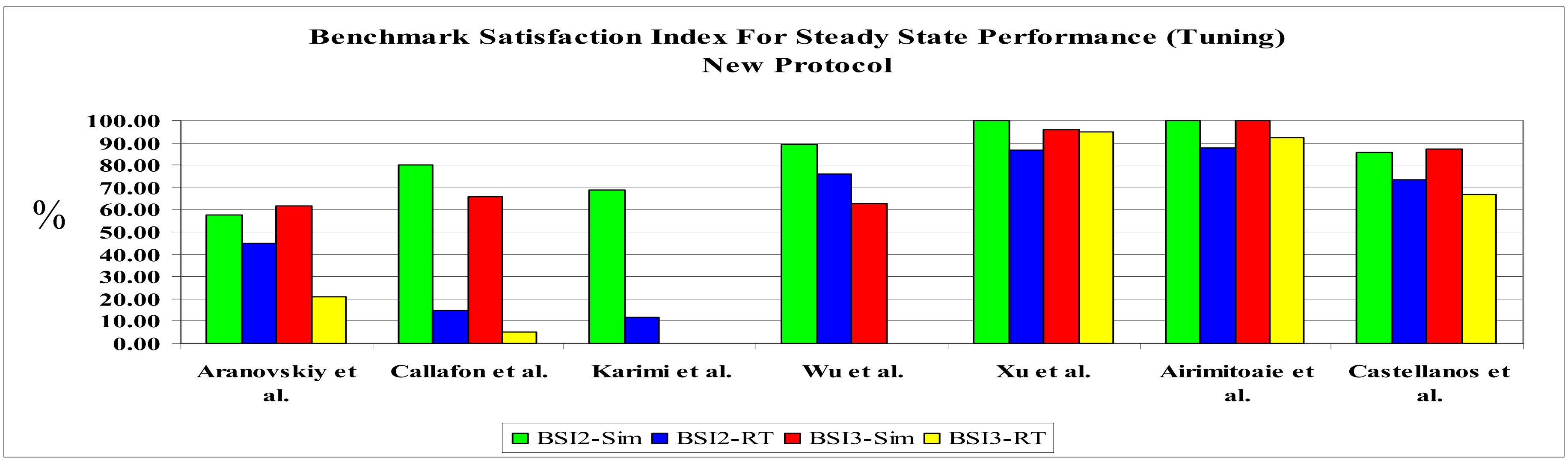
- Tests : Simple Step and Step Frequency Changes, for levels 2 and 3.
- Separation between the sinusoidal disturbances of 10 Hz (instead of 15Hz).
- Non integer central frequencies : [61.5-71.5] Hz /Level 2; [61.5-71.5-81.5] Hz /Level 3
- Change of disturbance application time: 3.75 seconds (instead 5 seconds).
- Same measurements and criteria for evaluation: BSI for transient and steady state.

Benchmark satisfaction index for transient duration - new protocol

	Level 2 - BSI_{Trans}		Level 3 - BSI_{Trans}	
	Simulation	RT	Sim	RT
Aranovskiy et al.	100%	100%	100%	100%
Callafon et al.	100%	100%	100%	100%
Karimi et al.	100%	78.53%	-	-
Wu et al.	83.02%	100%	100%	100%
Xu et al.	100%	100%	0%	100%
Airimitoaie et al.	100%	100%	100%	100%
Castellanos et al.	100%	100%	100%	100%

Benchmark satisfaction index (BSI_{SS}) for the new protocols

(steady state)	Level 2		Level 3	
	BSI2 - Sim	BSI2 - RT	BSI3 - Sim	BSI3 - RT
Aranovskiy et al.	57.78%	44.65%	61.62%	20.92%
Callafon et al.	79.95%	14.55%	65.68%	5.13%
Karimi et al.	68.76%	11.89%	-	-
Wu et al.	89.48%	76.00%	62.90%	0.00%
Xu et al.	**100.00%**	**86.63%**	95.96%	**95.05%**
Airimitoaie et al.	**100.00%**	**87.71%**	**100.00%**	**92.30%**
Castellanos et al.	85.57%	73.52%	87.30%	66.67%



Best results: Xu et al. and Airimitoaie and al.

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Some Conclusions

- The benchmark system structure is relevant of practical situations
- The benchmark specifications are achievable (hard!)
- Most of the control schemes were designed **thousands Kms**. away from Grenoble but they worked on the test bed in Grenoble
- The *Simulator* despite some imperfections, allowed to do a relevant design
- Real-Time Difficulties:
  - Matlab versions compatibility
  - Need for lowering the input sensitivity fct. over 95 Hz (wrt. Simulator)
- **Best results** (taking in account steady state, transient, robustness, complexity)**:** *Xu et al., Airimitoaie et al., Castellanos at al.*

New challenges:

- smaller frequency intervals (less then 10% of nominal frequency)
- re-tuning in the presence of slow plant model variations