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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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 $D$

**Fact. 1 Output error**

$N = G; \quad D = I$

**Fact. 2 Input error**

$N = z^{-m}; \quad D = P_m^{-1}$

**Fact. 3 Equation error**

$N = B; \quad D = A$

**Fact. 4 Filtered equation error**

$N = BF \quad D = AF$
### Comparison of Methodologies

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

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

$n = \text{Number of narrow band disturbances}$
Performances to be measured on the residual force

<table>
<thead>
<tr>
<th>Transient Duration</th>
<th>Global Attenuation</th>
<th>Disturbance Attenuation</th>
<th>Maximum Amplification</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD(s)</td>
<td>GA(dB)</td>
<td>DA(dB)</td>
<td>MA(dB)</td>
</tr>
</tbody>
</table>

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
\[ MV = \max_m |y(i)| \]

Mean Square
\[ MSE = \frac{1}{m} \sum_{i=1}^{m} y(i)^2 \]

Measurements for simple step and step frequency changes test

Global attenuation
\[ GA = 20 \log_{10} \left( \frac{N^2Y_{cl}(s.s.)}{N^2Y_{cl}(s.s.)} \right) \]

Transient duration
Step applied at \( T=5s \)
\[ \alpha_i = \frac{N^2Y_{cl}(7:10)}{N^2Y_{cl}(17:20)} \]

\( \alpha_i \leq 1.21 \Rightarrow \text{transient duration} \leq 2s \)

Measurements for chirp test

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)

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th></th>
<th>Level 2</th>
<th></th>
<th>Level 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BSI1 - Sim</td>
<td>BSI1 - RT</td>
<td>BSI2 - Sim</td>
<td>BSI2 - RT</td>
<td>BSI3 - Sim</td>
<td>BSI3 - RT</td>
</tr>
<tr>
<td>Aranovskiy et al.</td>
<td>86.94%</td>
<td>80.22%</td>
<td>76.33%</td>
<td>73.58%</td>
<td>90.65%</td>
<td>84.89%</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>89.21%</td>
<td>49.37%</td>
<td>72.89%</td>
<td>29.08%</td>
<td>51.74%</td>
<td>8.40%</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>91.92%</td>
<td>72.89%</td>
<td>76.13%</td>
<td>44.33%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>98.31%</td>
<td>83.83%</td>
<td>98.48%</td>
<td>84.69%</td>
<td>98.01%</td>
<td>91.00%</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>100.00%</td>
<td>86.63%</td>
<td>100.00%</td>
<td>86.65%</td>
<td>99.78%</td>
<td>92.52%</td>
</tr>
<tr>
<td>Airimotoaie et al.</td>
<td>98.69%</td>
<td>81.11%</td>
<td>98.38%</td>
<td>88.51%</td>
<td>99.44%</td>
<td>90.64%</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>93.30%</td>
<td>80.87%</td>
<td>97.29%</td>
<td>89.56%</td>
<td>99.13%</td>
<td>97.56%</td>
</tr>
</tbody>
</table>

### Benchmark Satisfaction Index For Steady State Performance (Tuning)

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

\[ NPL_k = \left( \frac{BSI_{k,\text{sim}} - BSI_{k,\text{RT}}}{BSI_{k,\text{sim}}} \right) \times 100\% \]

\( k = \) Benchmark level (nb. of spikes)

Global criterion

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

\( (M=2 \text{ for Karimi et al}) \)
<table>
<thead>
<tr>
<th></th>
<th>NPL1</th>
<th>NPL2</th>
<th>NPL3</th>
<th>NPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aranovskiy et al.</td>
<td>7.73%*</td>
<td>3.61%*</td>
<td>6.35%*</td>
<td>5.90%*</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>44.46%*</td>
<td>60.11%*</td>
<td>83.77%*</td>
<td>62.85%*</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>20.70%</td>
<td>41.77%</td>
<td>-</td>
<td>31.24%</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>14.73%</td>
<td>14.01%</td>
<td>7.16%</td>
<td>11.96%</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>13.37%</td>
<td>13.35%</td>
<td>7.28%</td>
<td>11.33%</td>
</tr>
<tr>
<td>Airimitoae et al.</td>
<td>17.81%</td>
<td>10.03%</td>
<td>8.85%</td>
<td>12.23%</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>13.32%</td>
<td>7.95%</td>
<td>1.58%</td>
<td>7.62%</td>
</tr>
</tbody>
</table>

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.: $\leq 2s$

<table>
<thead>
<tr>
<th></th>
<th>Level 1 - BSI&lt;sub&gt;Trans&lt;/sub&gt;</th>
<th>Level 2 - BSI&lt;sub&gt;Trans&lt;/sub&gt;</th>
<th>Level 3 - BSI&lt;sub&gt;Trans&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulation</td>
<td>RT</td>
<td>Simulation</td>
</tr>
<tr>
<td>Aranovskiy et al.</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>100%</td>
<td>97.69%</td>
<td>100%</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>100%</td>
<td>99.86%</td>
<td>94.85%</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Airimitoaie et al.</td>
<td>100%</td>
<td>99.17%</td>
<td>83.33%</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>100%</td>
<td>96.45%</td>
<td>100%</td>
</tr>
</tbody>
</table>

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

Transient duration evaluation:

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

$$\alpha_i \leq 1.21 \Rightarrow \text{transient duration } \leq 2s \quad \Rightarrow BSI_{\text{Trans}} = 100\%$$
Further transient performance evaluation (truncated norm+ max. value)

<table>
<thead>
<tr>
<th>JTRAV1</th>
<th>JTRAV2</th>
<th>JTRAV3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sim</td>
<td>RT</td>
<td>Sim</td>
</tr>
<tr>
<td>Aranovskiy et al.</td>
<td>0.76</td>
<td>0.89</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>0.44</td>
<td>0.54</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>0.35</td>
<td>0.40</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>0.50</td>
<td>0.56</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>0.39</td>
<td>0.55</td>
</tr>
<tr>
<td>Airimitoaie et al.</td>
<td>0.93</td>
<td>0.85</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>0.55</td>
<td>0.61</td>
</tr>
</tbody>
</table>

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

- Wu, (Karimi, Callafon) have the best results
Complexity evaluation using the task execution time

- Complexity of each approach is evaluated using the average task execution time (ATET) measured in $\mu$sec on the xPC target real-time environment.

- Computing time in the presence of the controller ($\Delta$TET) was obtained by subtracting the open loop execution time.

- $\Delta$TET has been evaluated for each type of test and then averaged

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

$X=\text{Simple step, Step Freq.changes, Chirp}$

Global criteria defined for each level

\[ \Delta TET_k = \frac{1}{3} (\Delta TET_{Simple,k} + \Delta TET_{Step,k} + \Delta TET_{Chirp,k}) \]
### Controller average task execution time (ΔTET) for all levels

<table>
<thead>
<tr>
<th></th>
<th>ΔTET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 (μs)</td>
</tr>
<tr>
<td>Aranovskiy et al.</td>
<td>3.71</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>210.68</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>2.37</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>14.73</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>2.96</td>
</tr>
<tr>
<td>Airimitoaie et al.</td>
<td>254.24</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>3.26</td>
</tr>
</tbody>
</table>

The table compares the controller average task execution time (ΔTET) for different levels (L1, L2, L3) across various research groups. The ΔTET values are given in microseconds (μs). The graphical representation further illustrates these values, with different colors representing the levels (L1, L2, L3) and the comparison of direct vs. 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

<table>
<thead>
<tr>
<th></th>
<th>Level 2 - ( BSI_{\text{Trans}} )</th>
<th>Level 3 - ( BSI_{\text{Trans}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>RT</td>
<td>Sim</td>
</tr>
<tr>
<td>Aranovskiy et al.</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Callafon et al.</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Karimi et al.</td>
<td>100%</td>
<td>78.53%</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>83.02%</td>
<td>100%</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Airimotoaie et al.</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Castellanos et al.</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
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.
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