Transients in Reconfigurable Digital Signal Processing Systems

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***Abstract*— To solve measurement and control problems, the processing of input data is performed typically by model-based digital signal processing (DSP) systems, which contain a representation of our knowledge about the nature and the actual circumstances of the problem at hand. If the nature or the actual circumstances change, the corresponding model should also be changed. Similarly, if the amount of knowledge about the problem increases due to measurements, an improved model can be suggested which provides better performance. As a consequence, the real-time adaptation or reconfiguration of the DSP system to be applied can hardly be avoided. The transients caused by these adaptations/reconfigurations is investigated. It is shown that for feedback systems, i.e., for infinite impulse response (IIR) filters, these transients are strongly structure-dependent and that the so-called orthogonal filter structures also provide good performance in this respect.**

***Index Terms*—Adaptive filters, modeling, reconfigurable architectures, recursive digital filters, transient analysis.**

I. Introduction

The study of reconfigurable DSP systems is a very important area of research related mainly to larger-scale, distributed intelligence monitoring and control systems. To use reconfiguration techniques in monitoring and control system has real meaning if drastic changes occur in the physical system. Changes due to faults evolving into system degradation are typical examples. In such cases, our supervisory computer program should observe the changes and turn to another operating mode or program. In other words, the models used within the computer program must also to be changed to represent the physical system correctly. Model changes can be performed using different techniques [1]. For conventional models of systems the typical solution is the adaptation or direct change of the coefficients and/or the (signal processing) structure. These changes, however, can cause large transients, since there is a real difference between the stationary behavior of the system before and after the change.

This paper investigates the reconfiguration transients of DSP systems. For simplicity, we will consider systems with changing coefficients but a fixed structure. It is shown that reconfiguration transients depend significantly on the DSP structure applied. This dependence on structure is strongly related to the energy distribution within the processing structure. Therefore, the famous orthogonal structures provide good performance [2], [3]. The behavior of the widely used direct structure (e.g., [4]) is rather poor. The reconfiguration can be performed also in multiple steps. In parameter-adaptive systems this strategy corresponds to changing the coefficients gradually. However, to determine the best sequence of steps to modify the coefficients is not trivial.

The results of the above considerations also can contribute to the design problem of narrow-band measuring channels, especially to that of the null indicators. It is well known that narrow-band filters have long transients which increase the overall response time of our measuring system. To reduce this effect at the beginning of the measurement we can start with a wider bandwidth and switch to the narrow-band somewhat later as the energy storage devices of the filters are almost settled. If we apply reconfigurable filter structures having good transient properties, this strategy may result in remarkable improvements. In this paper the one-step reconfiguration issues will be illustrated by this idea, i.e., by the step responses of different low-pass filters with one-step bandwidth reduction.

Manuscript received May 11, 1998. This paper was supported by Hungarian Fund for Scientific Research under Grant OTKA T 017448, the Office of Higher Education Support Programs under Grant MKM 0250/1997, and the Office of Bilateral Intergovernmental Scientific Co-operation Programs under Grant 32/96.

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Publisher Item Identifier S 0018-9456(99)06695-4.

II. Structure Dependence of Reconfiguration Transients

The step response of time-invariant linear systems is well understood and seems to be an appropriate tool to characterize the transient properties of the system. It is also well known that if the internal energy of the system is originally zero, then the step response can be calculated from the corresponding differential or difference equation. If we change the coefficients of an already operating discrete IIR filter, then the output can be considered as the sum of different components. One is the response to the input, while the others are the responses due to the initial conditions, i.e., due to the stored values which equal state-variable values, if the state variable formulation is applied. These initial conditions generate an impulse response from the output of the storage device to the output of the filter.

Obviously, in the majority of the practical cases these state-variable values are not known. However, their possible range can be estimated. It is well known from the literature of digital signal processing (e.g., [4]) that different structures have quite different internal dynamic ranges. As an example, consider the first-order direct structure on Fig. 1(a). The state-variable description has the form of

$$\begin{aligned} x(n+1) &= a_1 x(n) + u(n) \\ y(n) &= b_0 x(n+1) + b_1 x(n). \end{aligned} \tag{1}$$

If $u(n) = 1$ for $\forall n$, then $x(n) \rightarrow 1/(1-a_1)$ as $n \rightarrow \infty$

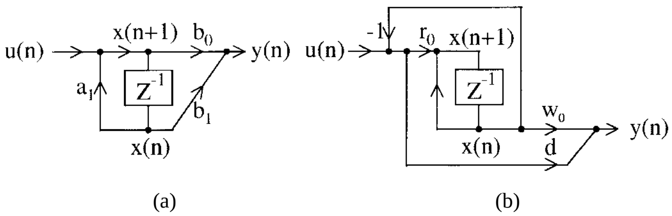

Fig. 1. (a) First-order direct structure and (b) first-order resonator-based structure.

and can be a large value if $a1(<1)$ is close to 1. Note that the dynamic range of this filter is parameter dependent. As a counterexample, consider the structure on Fig. 1(b). Its state-variable description is

$$\begin{aligned} x(n+1) &= x(n) + r_0[u(n) - x(n)] \\ y(n) &= w_0 x(n) + d[u(n) - x(n)]. \end{aligned} \tag{2}$$

If $u(n) = 1$ for $\forall n$, then $x(n) \rightarrow 1$ as $n \rightarrow \infty$, i.e., it is independent of the coefficients. These two examples show that the nature and the value of the state variables can differ considerably. Obviously, the coefficients of the two structures are different and the reconfiguration will change them differently. Therefore, a complete characterization without knowing the input samples is not possible. Under mild restrictions, however, a very interesting link can be established to structures having minimum roundoff noise [5], [6]. These structures can be characterized by relatively uniform energy distribution among the state variables. As a consequence, the output sensitivity to the rounding errors is relatively low, which results in a lower (or minimum) output noise level. In this model, the samples of the noise sources for modeling roundoff errors are directly added to the actual state-variable values. Concerning transients we have a similar situation, since the initial conditions behave like additive impulses to the actual state variables. In both cases, the additional energy introduced must be transferred from the state-variables to the output, but in the second case, the time-domain behavior is emphasized more. The requirement for relatively uniform energy distribution is met by the so-called orthogonal structures (see [3] and [4]). These have very good internal dynamic range, low roundoff noise, and can reduce zero-input limit cycles. From the above reasoning, it turns out that they also are good candidates for implementing reconfigurable IIR filters.

It is important to note that in the theory and practice of adaptive filters, this structure dependence is not recognized properly. In the majority of the adaptation schemes the correction terms are based on direct measurements of the output signal. Correction of the parameters can be considered as reconfiguration, producing transients at the output. Since these transients may disturb the overall performance of the adaptive filter, it is reasonable to apply DSP structures with low reconfiguration transients. Another reconsideration is whether adaptation at lower rate results in better performance.

As a simple illustration, the step responses of the direct and the resonator-based structures are presented on Figs. 2–7 for different filter orders. The idea behind is the assumption that the steady-state behavior can be reached faster if, as the first step, a filter with wider bandwidth is operated, followed

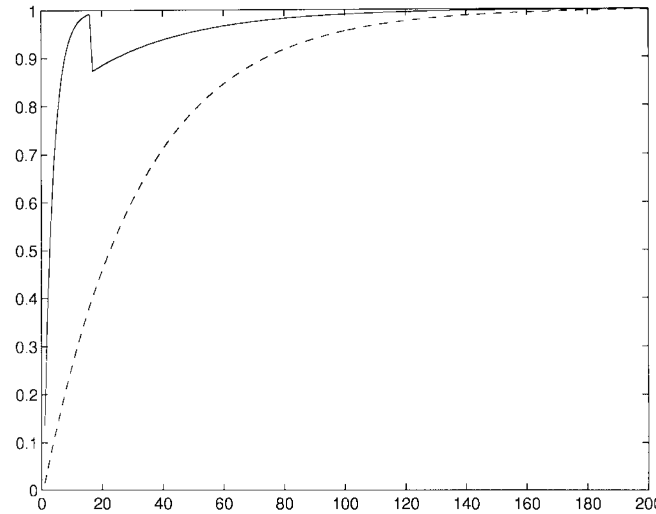

Fig. 2. Solid line: step response of a first-order direct structure reconfigured at step 16. Dashed line: step response of the narrow-band first-order direct structure.

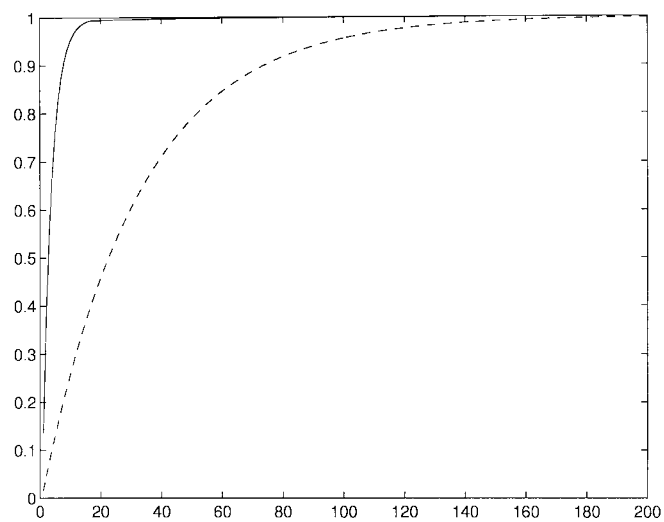

Fig. 3. Solid line: step response of a first-order resonator-based structure reconfigured at step 16. Dashed line: step response of the narrow-band first-order resonator-based structure.

by a one-step bandwidth reduction. The coefficients for the first-order filters are given in Table I.

III. Multiple Step Reconfiguration

The multiple-step strategy and the structure dependence are illustrated by a simple pole migration example. The reason for this illustration is the observation that gradually changing the coefficients in certain filter structures may move the poles temporarily out of the unit circle. Even if for time-invariant systems, it is hard to give the proper interpretation of the poles, unstable temporary pole positions can indicate the danger of larger transients. An eighth-order Butterworth low-pass filter was reconfigured from a cut-off frequency of 0.1 f_s to 0.01 f_S. In Figs. 8–11, the pole-migration of four different structures are recorded

1) direct [4];

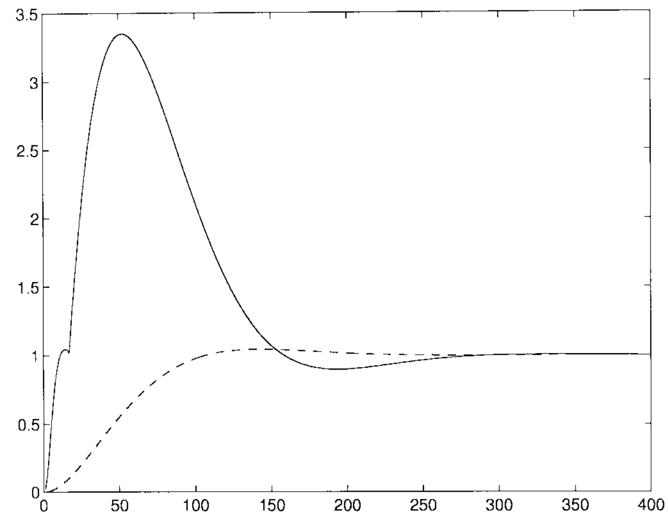

Fig. 4. Solid line: step response of a second-order direct structure reconfigured at step 16. Dashed line: step response of the narrow-band second-order direct structure.

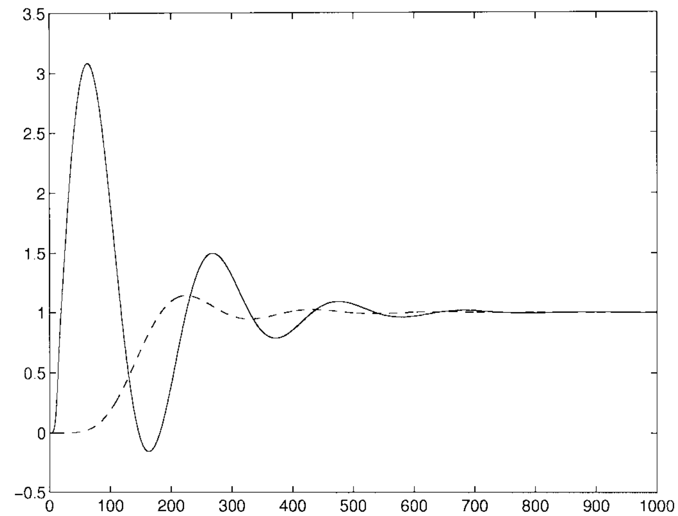

Fig. 6. Solid line: step response of a sixth-order direct structure reconfigured at step 16. Dashed line: step response of the narrow-band sixth-order direct structure.

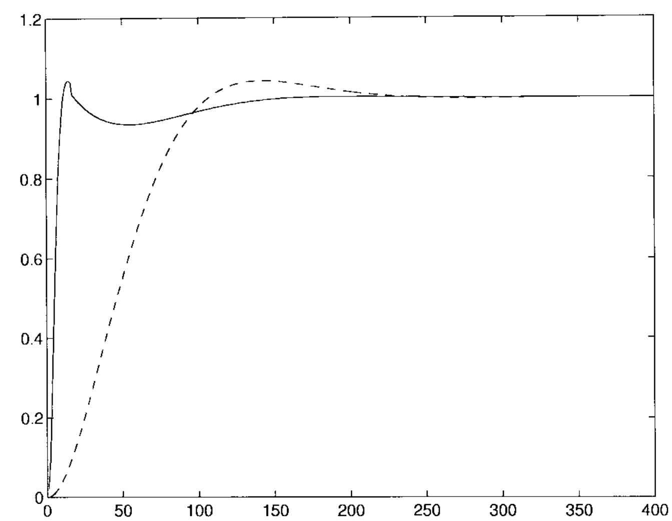

Fig. 5. Solid line: step response of a second-order resonator-based structure reconfigured at step 16. Dashed line: step response of the narrow-band second-order resonator-based structure.

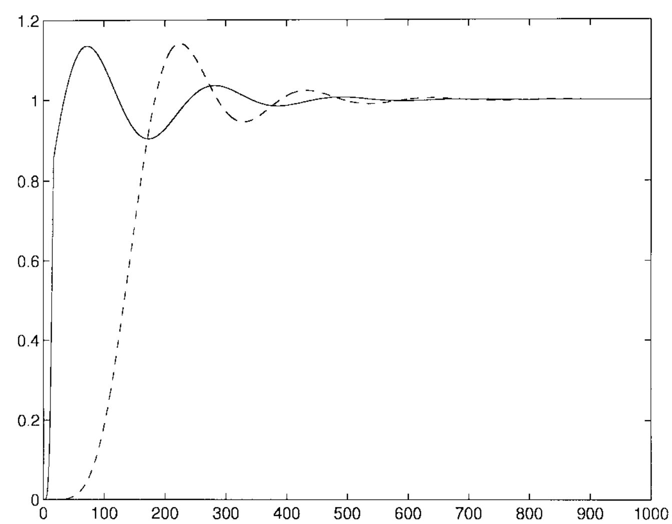

Fig. 7. Solid line: step response of a sixth-order resonator-based structure reconfigured at step 16. Dashed line: step response of the narrow-band sixth-order resonator-based structure.

2) normalized lattice [2];
3) resonator-based [3];
4) parallel [4].

The filter coefficients were linearly interpolated in 100 steps. The direct structure temporarily has lost stability because his poles have migrated out of the unit circle. The parallel structure seems to provide rather good behavior.

A better behavior can be achieved if instead of linearly interpolating the coefficients, the filter design is performed at every step, and in the multiple-step reconfiguration the corresponding coefficients are applied. In this case, the "interpolation" is on the level of the filter specification, i.e., we gradually change the bandwidth and/or the center frequency. The optimal strategy of this "interpolation" is still an open question. However, the results related to measurements with sweep generators may help.

TABLE I
COEFFICIENTS FOR THE FIRST-ORDER FILTERS

direct		resonator-based	
$b_{0,old}$	0.1367	$r_{0,old}$	0.2735
$b_{1,old}$	0.1367	$w_{0,old}$	1.0000
$a_{1,old}$	-0.7265	d_{old}	0.1367
$b_{0,new}$	0.0155	$r_{0,new}$	0.0309
$b_{1,new}$	0.0155	$w_{0,new}$	1.0000
$a_{1,new}$	-0.9691	d_{new}	0.0155

IV. CONCLUDING REMARKS

We have reported our investigations related to reconfiguration transients. This topic is of real importance if our models, representing our knowledge about the reality, are to be changed during operation. Illustrations show that these transients are structure-dependent, therefore, in the design of

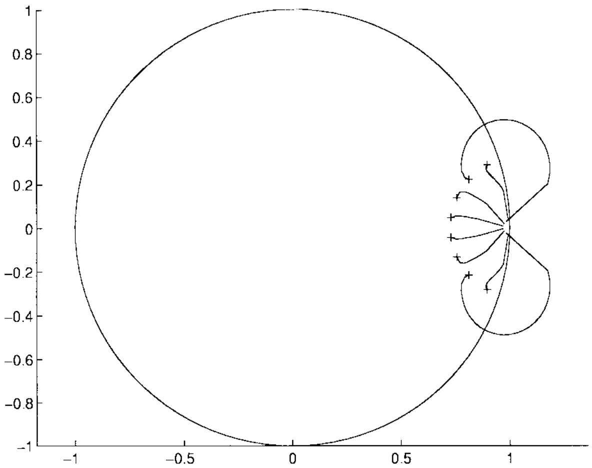

Fig. 8. Pole migration of an eighth-order direct filter.

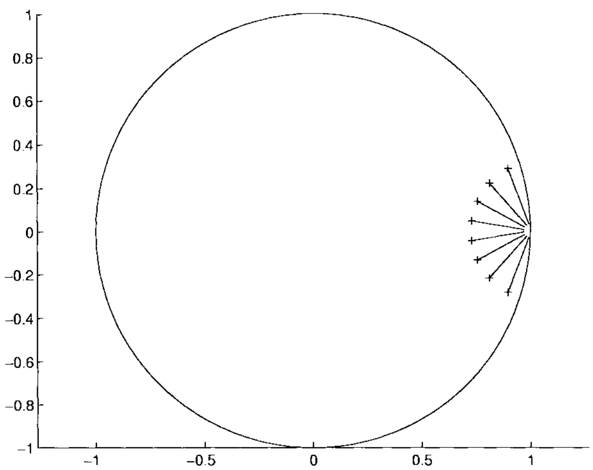

Fig. 9. Pole migration of an eighth-order parallel filter.

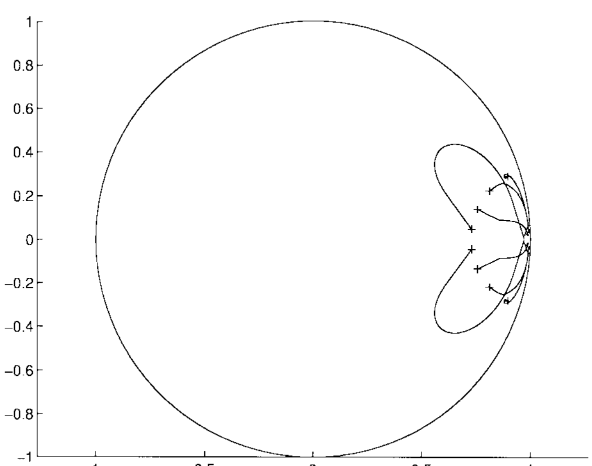

Fig. 10. Pole migration of an eighth-order normalized Lattice filter.

adaptive/reconfigurable system structures with better transient behavior should be preferred. The large transients caused by drastic changes can be reduced by multiple step adaptation/reconfiguration, as well. The optimal strategy is still an open question. Up till now in our investigations we have

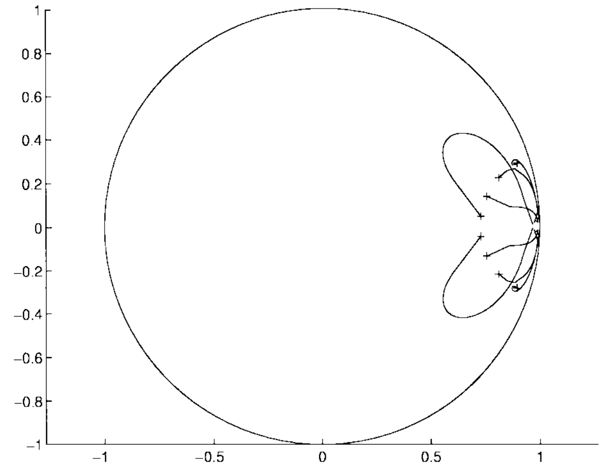

Fig. 11. Pole migration of an eighth-order resonator-based filter.

considered only parameter changes. The next step is the evaluation and design of reconfiguration if the order and/or the structure of the filter is also to be changed.

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