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BIASED LINEAR FEEDBACK MACHINING PROCESS FOR ASYMMETRIC COST FUNCTIONS

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ABSTRACT

This paper presents a feedback control rule for the machine start-up adjustment problem when the cost function of the machining process is not symmetric around its target. In particular, the presence of a bias term in the control rule permits the process quality characteristic to converge to a steady-state target from the lower cost side, thus reducing the process quality losses incurred during the transient phase of adjustment. A machining application is used to demonstrate the savings generated by the biased linear feedback adjustment rule compared to an adjustment rule due to Grubbs (1954, 1983) and to an integral (or EWMA) controller. The performance of the different adjustment schemes is studied from a small-sample point of view, showing that the advantage of the proposed rule is signi¯cant especially for expensive parts which are usually produced in small lots. In this paper, two asymmetric cost functions { constant and quadratic { are considered. Optimal biased control rules for both cost functions are derived.

Keywords: Process Control, Feedback Adjustment, Stochastic Approximation, One-Sided Convergence.

1. INTRODUCTION

After an imprecise setup or maintenance operation, a machine can produce a systematic process error which will show on the quality characteristic of the machined items. Adjustments are necessary for eliminating such error if there are some controllable variables that can be manipulated on the machine. However, the start-up error is unobservable directly due to the inherent randomness of both the machining and measurement processes. Therefore, a sequence of adjustments that utilizes the process information obtained on-line is useful for eventually removing the start-up error. Grubbs (1954, 1983) proposed such an adjustment rule which has been more recently discussed by Trietsch (1998) and del Castillo and Pan (2001). The latter reference shows the connections between Grubbs rule and stochastic approximation techniques.

Former research on the start-up adjustment procedure only dealt with the case of symmetric cost functions. It is well-known that in industrial practice asymmetric cost functions can be more appropriate, since the cost of oversized and undersized quality characteristics are often different, like, for instance, in hole-finishing or milling operations. The impact of asymmetric cost functions has been studied from several perspectives. Wu and Tang (1998) and Maghsoodloo and Li (2000) have considered tolerance design with asymmetric cost functions, while Moorhead and Wu (1998) have analyzed the effect of this type of cost function on parameter design. Ladany (1995) presented a solution to the problem of setting the optimal target of a production process prior to starting the process under a constant asymmetric cost function. Harris (1992) discussed the design of minimum-variance controllers with asymmetric cost functions for a process characterized by a linear dynamic model and ARIMA (Auto Regressive Integrated Moving Average) noise. Despite of the generality of this model, a possible process start-up error has not been included into consideration.

When start-up errors exist under an asymmetric cost function, it is intuitive to have the value of the quality characteristic converge to the optimal setting from the lower cost side. This is related to certain stochastic approximation techniques in which a bias term is added to allow for one-side convergence, as discussed by Anbar (1977) and Krasulina (1998). However, these approaches are oriented to asymptotic or long-term performance, and the conditions they impose on the control rule parameters are too complicated for practical engineering application. Since short-run production processes have become more common with the advent of modern manufacturing environments, small sample properties of sequential adjustment procedures need to be studied.

In this paper, we propose a generic framework for the start-up adjustment problem for asymmetric cost functions and focus on its small sample performance. First, two asymmetric cost functions representing two different cost models used in manufacturing are presented. We include a bias term into a general linear control rule. The optimal value of this bias term in the sense of minimizing the expected manufacturing cost at each time step is then derived. The proposed procedure is com-pared with other adjustment methods in the literature by evaluating and comparing their short-run costs. Finally, a real manufacturing process is used to demonstrate the practical application of our adjustment procedure for asymmetric cost functions.

2. PROCESS AND COST MODELS

Suppose the quality characteristic Y_n of each machined part is measured with reference to a nominal value, which is assumed, without loss of generality, to be equal to 0. After the start-up, the process is supposed to be off target by d units, i.e., $Y_1 = d+{}_1$, where ${}_1$ models both the inherent production variability and the error of measurement. After the first quality characteristic is measured the value of the control parameter U_1, which is assumed to have an immediate effect on the process output, is set, thus inducing a change in the next quality characteristic: $Y_2 = d + U_1 + {}_2$.

To evaluate the costs associated with the control procedure, two cost models often adopted in industrial practice are considered. In the first case, costs are assumed to arise only when the part processed is non-conforming, i.e., when the quality characteristic is out of the Specification Limits. In particular, it will be assumed that the violation of the Lower or the Upper Specification Limit could lead to different costs. For example, consider the case of a quality characteristic related with a dimension obtained after a finishing operation. In such operation, the costs associated with oversized and undersized items, which are mainly determined by either scrapping or re-working, are almost always different.

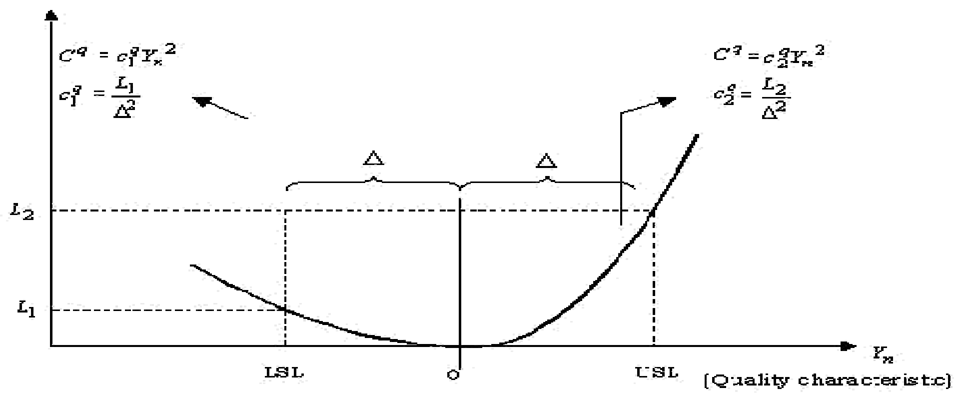

Figure 1: The asymmetric constant cost function with different costs when the quality characteristic is below LSL or above USL

Since most of the recently developed devices for on-line inspection and measurement can transmit the data acquired to the controller of the machine, the assumption of an automatic feedback procedure is realistic. In this scenario, the cost of the adjustments can be neglected and therefore has not been considered in the following analysis.

The asymmetry in the cost function implies two issues that have to be considered in designing the adjustment rule. The first is related to the long-term or steady-state target T ² that has to be entered on the machine at start-up, where the superscript ² is replaced by either c or q to indicate either constant or quadratic cost function. The problem of determining this value, referred to in the literature as the optimum target point, has been addressed for asymmetric cost functions in manufacturing by Ladany (1995) and Wu and Tang (1998).

The second issue is related to the way in which, starting from an initial offset, the quality characteristic should converge to the target as determined by the adjustment procedure. Both of these issues are considered in the remainder of the paper. In particular, the steady-state target

T ² will be derived by minimizing the long term expected costs, and the adjustment rule will be determined by considering all the costs associated with the transient period, evaluating the Average

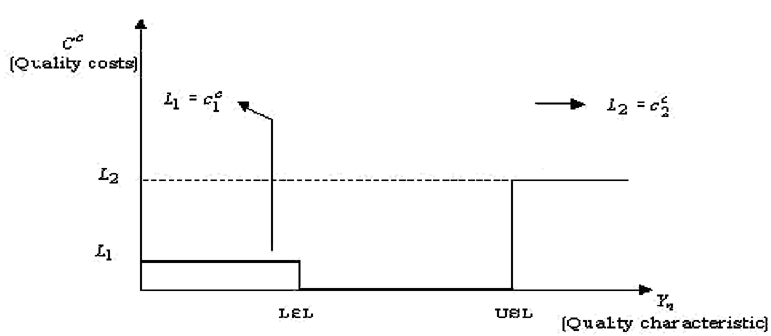

Figure 2: The asymmetric quadratic cost function with different costs when the quality character-istic is below LSL or above USL

3. AN APPLICATION TO A REAL MACHINING PROCESS

In this section, the biased linear adjustment procedure for start-up errors will be applied to a real machining problem. The performance of the biased rule will be compared with that of Grubbs' rule and with the EWMA (integral) controller. The latter two procedures follow the adjustment rules of the form (6) where k_n is equal to 1=n for Grubbs' rule and equal to a constant ¸ for the EWMA controller.

A hole-finishing operation is performed on a pre-existing hole in a raw aluminum part made by pressure casting. The Specification Limits on the final hole diameter are at 57.000 **§0:030mm**. After the execution of the operation, the diameter of the hole (D) is measured in an automatic inspection station constituted by a probe that acquires the diameter while the work piece rotates 360 degrees around the axis of the hole. The mean diameter is computed and recorded. Due to the materials machined and the tools used (polycrystalline inserts), the tool wear can be neglected and no trend is present in the data collected.

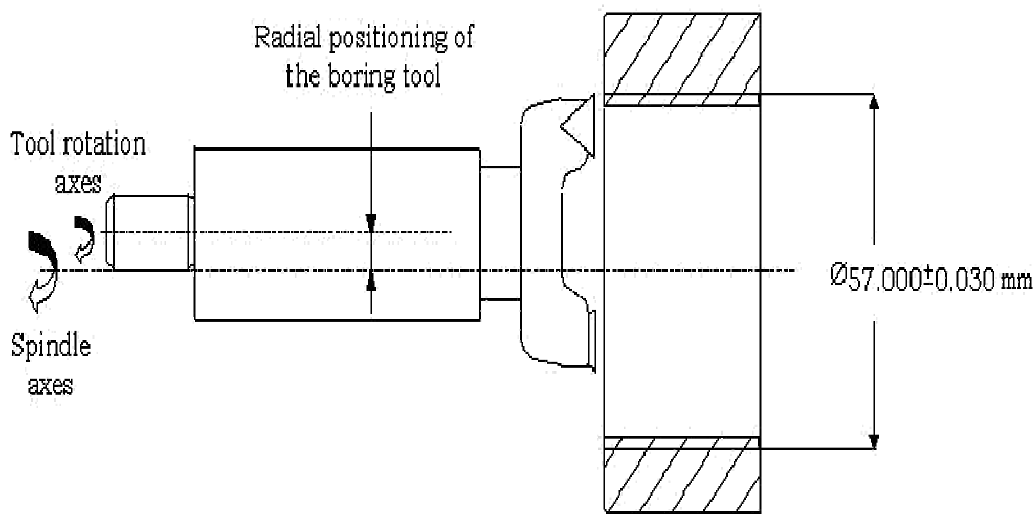

Figure 3: The hole finishing operation

Figure 4 reports the plots of the expected value of the quality characteristic obtained with both the Biased and Grubbs' procedures. In particular, the piecewise behavior of the biased mean converging to the target value is due to the approximation (rounding) adopted to consider the precision of the machine in setting the tool position. In fact, changing the precision of the approximation to the second decimal place, the mean at each step of the Biased procedure is represented by the dotted line in Figure 4. As it can be observed, the adoption of the Biased procedure induces a convergence of the mean to the steady-state target value T^c from the side of lower nonconforming costs.

The savings in cost obtained by the Biased rule are shown in Figure 5, where the percentage difference in SAIEC determined by the Biased and Grubbs' procedures is reported as a function of the items processed (computed from data in Table 1).

A further comparison between the Biased and different EWMA control rules, characterized by values of the parameter ¸ ranging from 0.2 to 0.8 (Box and Luce~no, 1995), has been carried out. Since the performance of an EWMA controller depends on the initial offset d, a constant

A = (d ¡ T ²)=¾", i.e., the difference between d and the target value in standard deviation units is assumed equal to 3 according to the practical case we have discussed.

The Scaled Average Integrated Expected Costs SAIEC obtained with the Biased procedure and the EWMA controllers are reported in Table 1 and plotted in Figure 6. As it can be observed, the Biased procedures has the smallest expected cost compared to all the EWMA controllers and the advantage reduces as ¸ increases, So a value ¸ = 0:8 was used in the next comparison. It should

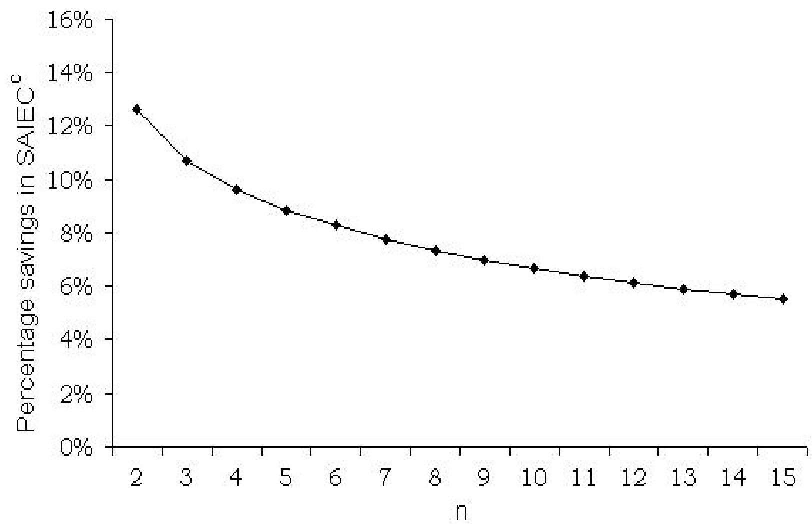

Figure 4: Trajectory of the optimal mean of the quality characteristic (m^c_n) using Grubbs' and the Biased procedures (considering 0 and 2 decimal places) under the constant cost model (r = 6:5 and N = 15)

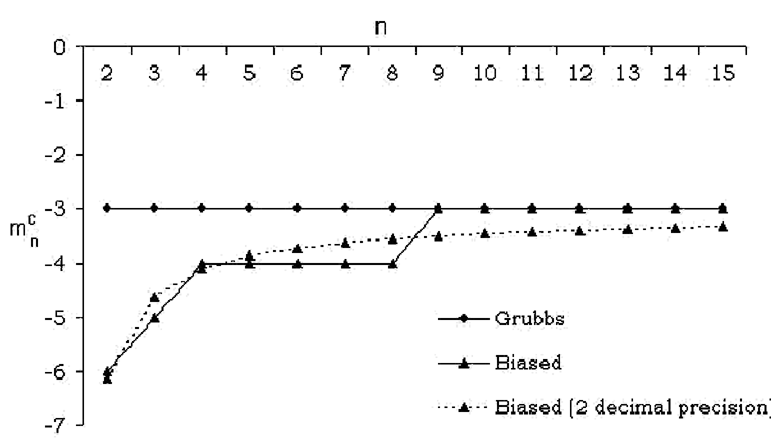

Figure 5: The percentage savings in SAIEC procedure compared to Grubbs' rule under the constant cost function model (r = 6:5 and N = 15)

n	EWMA0.2	EWMA0.4	EWMA0.6	EWMA0.8	Grubbs	Biased
2	1.227	0.532	0.234	0.119	0.092	0.080
3	0.898	0.341	0.149	0.088	0.064	0.057
4	0.689	0.245	0.112	0.076	0.051	0.046
5	0.553	0.192	0.092	0.070	0.043	0.039
6	0.461	0.158	0.080	0.067	0.037	0.034
7	0.393	0.135	0.072	0.065	0.033	0.031
8	0.342	0.118	0.066	0.063	0.030	0.028
9	0.303	0.106	0.062	0.062	0.028	0.026
10	0.271	0.096	0.058	0.061	0.026	0.024
11	0.246	0.089	0.055	0.060	0.024	0.023
12	0.225	0.082	0.053	0.059	0.023	0.022
13	0.207	0.077	0.051	0.059	0.022	0.021
14	0.193	0.072	0.050	0.058	0.021	0.020
15	0.180	0.068	0.048	0.058	0.020	0.019

Table 1: The SAIEC adopting different control rules (r = 6:5, N = 15 and A = 3)

The cost comparison between the EWMA controller with ¸ = 0:8 and the Biased controller is given in Figure 7, where the percentage saving in SAIEC induced by the Biased procedure over the EWMA is plotted. It is interesting to ¯nd that the advantage induced by the Biased procedure is even higher as the number of parts produced increases. The reason for this behavior lies on the long-term performance of the EWMA control rule. In fact, as n tends to infinity, the mean of the Y_n regulated by the EWMA controller approaches zero, but the variance approaches to the value 2¾"^{2}=(2 ¡ ¸), which is greater than ¾"^{2}. This inflation in variance has been discussed by Box and Luce~no (1997) and del Castillo (2001).

6 SENSITIVITY ANALYSIS

A numerical comparison of the performance obtained with the Biased procedure, Grubbs' rule and the EWMA controllers was conducted to characterize situations in which the adoption of the feedback adjustment could be more portable. The comparison has been carried out ¯rst for the Biased procedure versus Grubbs' rule, since the performance in this case does not depend on the initial offset. The variables affecting the results in this case are the coefficient r, representing the asymmetry of the cost function, and N, the number of parts processed in each lot. The value of r was varied from 1 to 11 as in Ladany (1995). We point out that two real cases of asymmetric cost functions considered in Wu and Tang (1998) and Moorhead and Wu (1998) have r to be 4 and 6, respectively, and they are inside the range examined. The number of parts in the lot, N, was varied from 1 to 40.

Figures 12 and 13 present the savings in cost obtained with the Biased procedure over Grubbs' rule for the constant and quadratic cost models, respectively. As it can be observed, the Biased procedure has an advantage especially on the first parts produced (this suggests the adoption of the

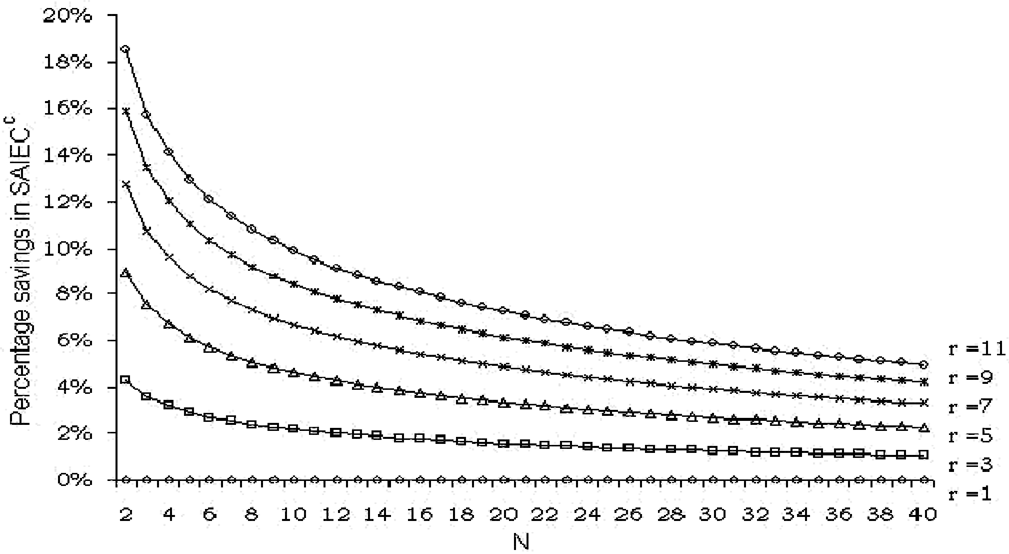

Figure 12: Sensitivity analysis: the percentage saving in SAIEC by using the Biased procedure compared to Grubbs' procedure under the constant cost function model, when the asymmetry ratio is varied

Biased rule when parts are produced in small lots) and this advantage increases as the asymmetry in the function becomes more evident (i.e., as r increases).

Since the performance of the EWMA controllers depend on the initial offset , standardized by the constant the comparison between the Biased rule and the EWMA controller has been performed by considering A ranging from ¡4 to 4. Figures 14 and 15 report the difference in the Scaled Average Integrated Expected costs obtained with the EWMA and the Biased controller, under the constant and the quadratic cost models, respectively. In particular, the difference is reported for the two extreme values of ¸ (i.e., ¸ = 0:2 and ¸ = 0:8) and the lot size (i.e., N = 5 and N = 40).

Depending on the initial offset, the advantage of using the Biased procedure varies dramatically. Considering the case in which ¸ = 0:2, when A is greater than 1 the performance of the Biased procedure dominates that of the EWMA controller, but the difference between the two procedures is almost negligible as A is close to zero. Furthermore, the advantage is asymmetric too. In particular, if A is positive, i.e. the offset d arises from the side in which non-conforming items are more expensive, the advantage of adopting the Biased procedure is significantly greater, compared with the case in which the initial shift has the same magnitude but different sign. As the number of parts processed in the lot increases, the difference between the two procedures maintains the same

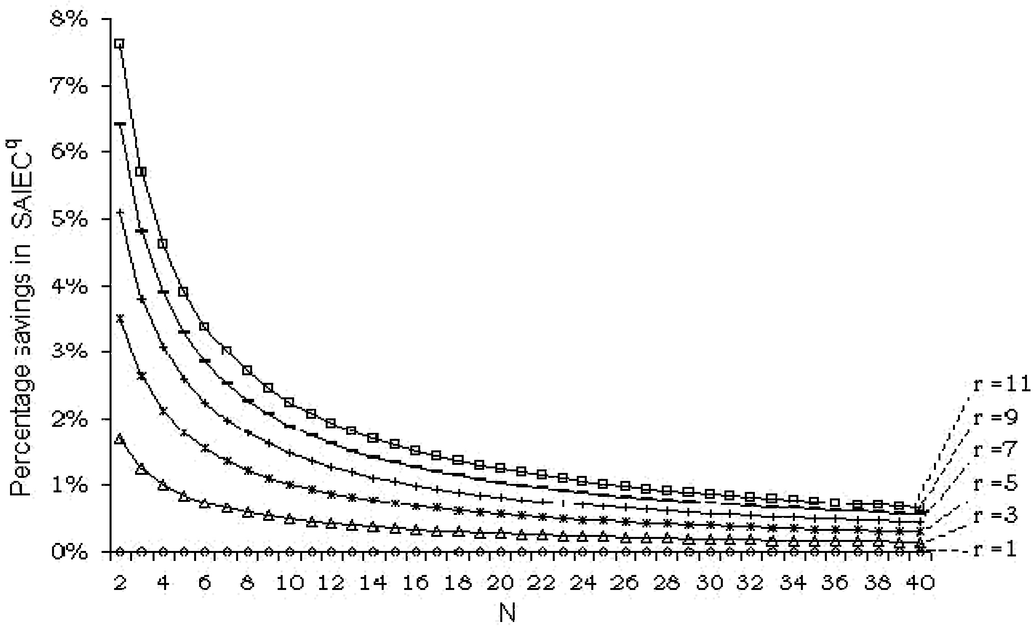

Figure 13: Sensitivity analysis: the percentage saving in SAIEC by using the Biased procedure compared to Grubbs' rule under the quadratic cost function model, when the asymmetry ratio

behavior while reducing in magnitude (both approaches tend to reach their asymptotic performance, which are different only with respect to the variance of the quality characteristic).

The advantage determined by the Biased approach is reduced but is always greater than zero, regardless of the direction of the initial offset. Also in this case, the effect of A becomes even less significant when N increases. The problem with the EWMA controller, of course, is that it is not clear how to choose.

7 CONCLUSIONS

The problem of designing an adjustment rule to correct a process start-up error has recently received a renewed attention in the literature. This attention is related to two tendencies that are shown in modern manufacturing. The first one is the adoption of small lot sizes, which leads to an increase in the number of setups required on the machine. The second one is the growing frequency in changing product specifications, which increases the chance of systematic errors at the start-up of a manufacturing process. Therefore, applying feedback adjustments for process start-up errors becomes an effective way to reduce the number of non-conforming parts. Up to now, previous approaches to setup adjustment problems have only considered symmetric cost functions. This paper presented a feedback adjustment rule that can be adopted when an asymmetric cost model can better represent the process quality losses entailed.

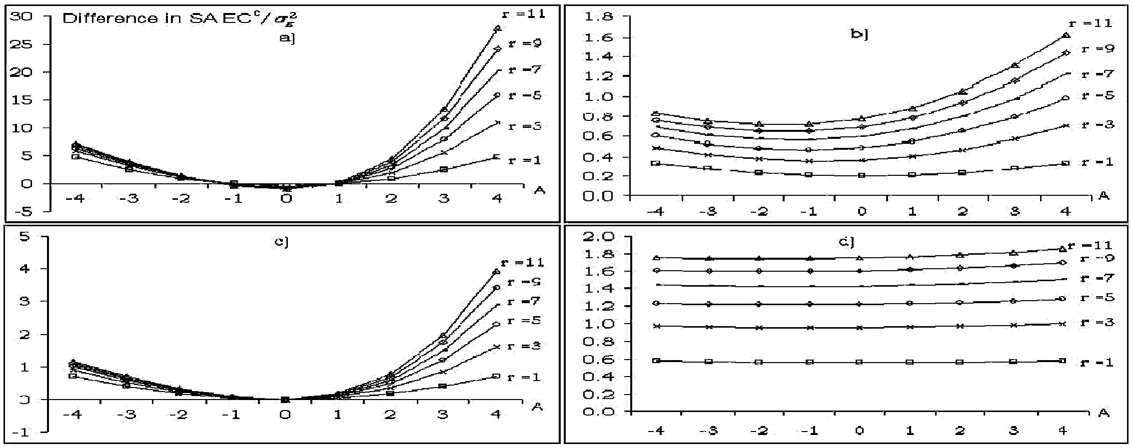

Figure 14: Sensitivity analysis: the difference in SAIEC obtained by using the EWMA controller and the Biased rule under the constant cost model

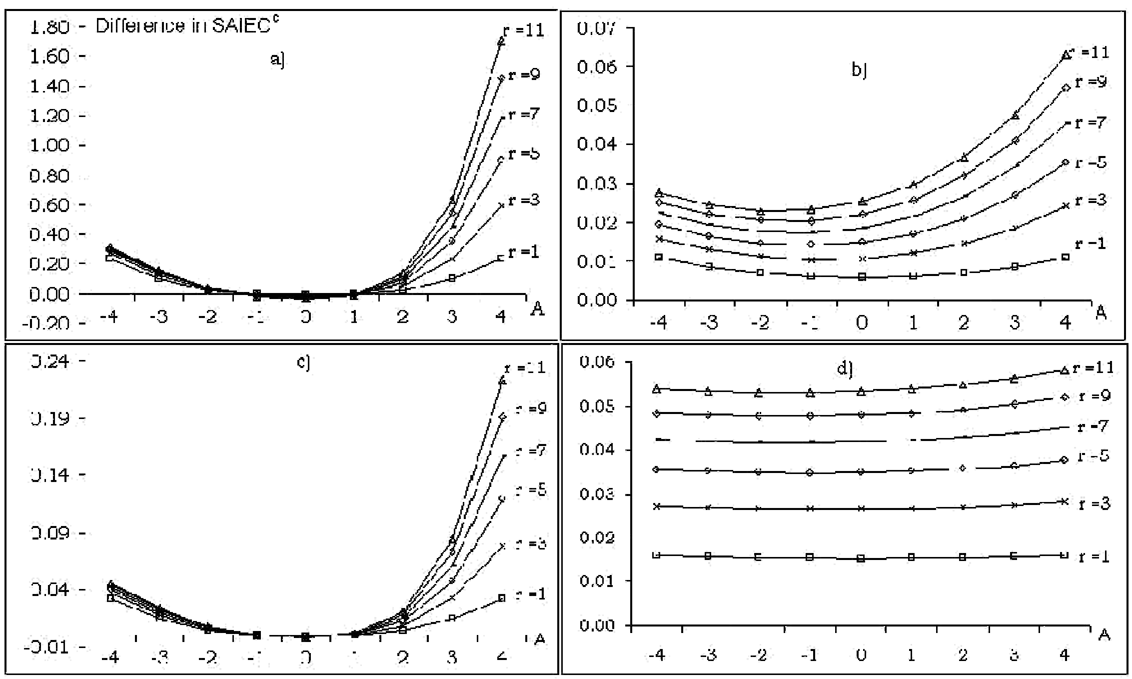

Figure 15: Sensitivity analysis: the difference in SAIEC using the EWMA controller and the Biased under the quadratic cost model

In particular, two asymmetric cost functions that are often encountered in manufacturing have been considered. In the first case, the cost of a non-conforming item is assumed constant but changes depending whether the quality characteristic is below the Lower or above the Upper Specification Limit. In the second case, costs are supposed to be proportional to the square of the distance of the quality characteristic from the nominal value, but the proportional constant is allowed to change with the sign of this difference.

Starting from the general form of a linear controller, the biased feedback adjustment rule has been derived by minimizing all the costs incurred during the transient phase in which the quality characteristic converges to its steady-state target. A numerical comparison of the cost incurred by the adjustment rule proposed and other rules assessed in the literature showed that the proposed procedure is effective, especially when the asymmetry in the cost function or the initial process offset are significant. Compared to Grubbs' rule, the proposed Biased adjustment rule is recommended especially for manufacturing expensive parts which usually are produced in small lots (e.g., in the aerospace industry).

Besides the two specific cost functions studied herein, the proposed approach can be easily extended to deal with different production situations in which the cost function is asymmetric, such as a piece-wise linear function used in filling processes (Misiorek and Barnett, 2000).

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