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ABSOLUTE STABILITY AND DRIFT ROBUSTNESS OF A SECTOR-BOUNDED NEURO-FUZZY CONTROLLER FOR A DEAD-TIME COTTON SEED LINTING PROCESS

Navruzbeq Kurbonov * and Mirshod Abdullayev

Department of Automation and Control of Technological Processes, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan.

* Corresponding Author

ORCID Details

Kurbonov Navruzbeq Muzaffar ugli: <https://orcid.org/0009-0001-9232-6811>

Abdullayev Mirshod Shuxratovich: <https://orcid.org/0000-0001-8539-291x>

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ABSTRACT

A saw linter that removes residual fibres from cotton seed is a dead-time plant whose gain depends on the operating point and falls as the saw set wears. This study checks whether a neuro-fuzzy controller for this plant stays stable over all operating conditions and the full saw-set life. The plant was modelled from industrial tests as a second-order lag with a dead time of 11.8 s; its gain changes 2.5-fold over the working speed range, and wear lowers it by 31.7% over a 248 h saw-set life. The controller is an incremental zero-order Takagi-Sugeno controller with 15 rules. Its input-output map was bounded by sectors, and stability was assessed by linear margins at the origin, a circle-type sector test on a 78×58 grid of operating points, a sensitivity study and simulation driven by an industrial record. Near the origin the phase margin is 78.6 to 86.2 deg and the gain margin 27.7 to 35.8 dB. The sector test is met on 99.7% of the domain and fails by at most 2.4% in a small corner of low saw speed and high feed rate, where simulation confirms stable operation. Wear lowers the loop gain and raises all margins: after about 18 h of operation the test holds on the whole domain. The binding limit is actuator saturation, which makes the 7.00% set-point unreachable after 142 h. The saw-set replacement time should therefore be set by the saturation share and the out-of-band share, not by stability.

Keywords: Cotton seed linting; Neuro-fuzzy control; Absolute stability; Circle criterion; Time delay; Parameter drift.

1 INTRODUCTION

Cotton seed leaving the gin still carries short fibres, which in the oil industry are removed on saw linters. Mechanical and chemical routes for fibre removal and their effect on seed quality are discussed in [1,2]. The quality index of linting is the residual linter content of the seed, and a deviation from the regulated band is costly in either direction: seed with too much residual linter is processed again and the lint yield falls, while over-linted seed has damaged hulls and more defective seed.

For control the linter is a difficult plant. The residual linter content responds to the saw cylinder speed with a transport delay, the gain depends strongly on the operating point, and the parameters drift as the saw teeth wear. Earlier automation studies treated the plant as stationary and did not close the loop on a continuous measurement of the quality index [3,4]. Fuzzy and neuro-fuzzy controllers are widely used for such plants in process industry [5]; Takagi-Sugeno inference [6] and adaptive neuro-fuzzy models [7] combine expert rules with measured data. In previous work the author designed a neuro-fuzzy controller for linting whose parameters and rule base were optimized jointly by a genetic algorithm [8], and a compensation channel for measured disturbances [9]. Those papers dealt with synthesis and performance. They did not answer the question an operator must ask before switching the controller on: is the closed loop stable at every operating point met in production, and does it stay stable as the saw set wears?

Stability of fuzzy control has been studied along two lines. The first uses Takagi-Sugeno plant models and Lyapunov functions, leading to linear matrix inequalities [10-13]. The second treats the fuzzy controller as a static nonlinearity bounded by a sector and applies input-output criteria, starting from Kickert and Mamdani [14] and the conicity and circle conditions of Zames [15,16]. Analytical structures of fuzzy PI, PD and PID controllers give their sector bounds explicitly [17-19], and the approach is still applied to drives and nonlinear PID loops [20,21]. Time delay is a further difficulty [22,23]; frequency-domain tests handle a pure delay exactly but are only sufficient, and less conservative tests use Zames-Falb multipliers [24,25] or integral quadratic constraints [26,27].

A question rarely asked for plants that wear in service is whether slow parameter drift erodes the stability margin or another constraint becomes binding first. For the saw linter the answer decides what should trigger the replacement of the saw set. The contributions of this paper are: (i) a parameter domain of a saw linter built from industrial tests, including gain drift over a full saw-set life; (ii) a sector description of the genetically tuned incremental Takagi-Sugeno controller; (iii) a dense-grid sector test with a sensitivity study, which locates the only region where the test fails and shows that wear removes it; and (iv) evidence that actuator saturation, not stability, defines the saw-set replacement time.

2 MATERIALS AND METHODS

2.1 Plant and industrial data

The study object is a 5LP-type saw linter at Yangiyul Yog'-Moy JSC, Uzbekistan. The manipulated variable is the saw cylinder speed n , set by a variable frequency drive. The controlled variable is the residual linter content y , measured continuously by an optical transducer developed earlier by the author and co-workers [28]; its expanded uncertainty is 0.15% ($k = 2$). The seed feed rate Q is measured. The technological band is $7.00 \pm 0.30\%$.

Static characteristics were recorded at seven speed levels from 620 to 800 rpm (three repetitions each), and step tests at five operating points. The dead time was measured separately by a marker-batch method and the small time constant from the drive tachometer record, which avoids the poor conditioning of a joint estimate [29]. Around an operating point the plant is

$$W(s) = K e^{-\tau s} / [(T_1 s + 1)(T_2 s + 1)], (1)$$

where $\tau = 11.8$ s, $T_2 = 4.58$ s is the lag of the drive and the measuring channel, and T_1 follows from a mass balance of the working chamber as the replacement time of the seed roll:

$$T_1 = 3600 m_a / Q, \quad (2)$$

with the active roll mass $m_a = 31.0$ kg; at $Q = 2150$ kg/h, $T_1 = 51.9$ s. This hypothesis predicted the step-response time constants with a mean error of 9.5%, against 44% for a fully mixed chamber. The static characteristic is exponential in n ($R^2 = 0.9995$), and its derivative gives $K = -0.0207$ %·min/rpm at 620 rpm and -0.0071 %·min/rpm at 800 rpm. In hold-out tests T_1 was predicted within 10% for $Q = 2000$ to 2300 kg/h, while the error was +13% at 2413 kg/h and -22% at 1852 kg/h.

Wear drift was measured over 62 checkpoints spanning 247.5 h at a fixed speed of 715 rpm. The operating point shifted by 1.02% of residual linter content, and $|K|$ fell from 0.01219 to 0.00832 %·min/rpm (31.7%). The gain was estimated by refitting the static characteristic at each checkpoint, so wear is not fully separated from changes in the raw seed. The drift is about four orders of magnitude slower than the plant dynamics, which justifies a frozen-parameter analysis [30]. In the analysis wear is represented by a gain factor decreasing linearly from 1 to 0.683 over 247.5 h. Table 1 summarizes the domain.

Table 1: Parameter domain of the saw linter

Parameter	Symbol	Range	Source
Saw speed (working range)	n	620 to 774 rpm	static tests
Plant gain	$ K $	0.0083 to 0.0207 %·min/rpm	static fit
Seed feed rate	Q	1850 to 2420 kg/h	production record
Main time constant	T_1	46 to 60 s	Eq. (2)
Small time constant / dead time	T_2 / τ	4.58 s / 11.8 s	separate tests
Wear time; gain loss	$t; \Delta K $	0 to 247.5 h; -31.7%	drift test

2.2 Controller and sector description

The feedback controller is an incremental zero-order Takagi-Sugeno controller [6] with inputs $e = y_m - y_{sp}$ and its rate $\dot{e}$, estimated over a 15 to 20 s moving window because of the measurement uncertainty. Seven triangular membership functions cover the error axis. A genetic algorithm reduced the full base of 49 rules to 15 and tuned the scaling factors and consequents [8]; monotonicity and antisymmetry are enforced during decoding. With sampling period 1 s the control law is

$$\Delta u_k = -K_u f(K_e e_k, K_{\dot{e}} \dot{e}_k), \quad u_k = \text{sat}(u_{k-1} + \Delta u_k), \quad (3)$$

where $\text{sat}(\cdot)$ limits the speed to 616 to 774 rpm and the increment to 6 rpm per step. The upper limit follows from the seed standard: at 774 rpm defective seed is 4.97% against the permitted 5.0% (O'z DSt 597). Integration outside the fuzzy map prevents integrator windup [31]. The feedforward channel [9] lies outside the feedback loop.

In the incremental law the error channel gives integral action and the rate channel proportional action. Over the region of the $(e, \dot{e})$ plane covered by the data, the secant gain of the error channel is positive with upper bound $K_i = 1.52$ rpm/(%·s), and that of the rate channel lies in $[-27.9; 216.6]$ rpm/%. The upper bounds define an equivalent PI controller $C(s) = K_p + K_i/s$ with $K_p = 216.6$ rpm/%. At the origin the rate-channel gain is zero and the controller reduces to an integrator; its equivalent gain $K_{i0} = 0.1275$ rpm/(%·s) reproduces the margins of the closed loop computed from the control surface (Table 2).

2.3 Stability analysis procedure

Step 1, linear margins. With $L_0(s) = (K_{i0}/s)W(s)$ the phase margin $\Delta\phi$, the gain margin GM and the delay margin $\Delta\tau = \Delta\phi/\omega_c$ were computed at the corners and the centre of the domain and as functions of wear time. The design target was $\Delta\phi \geq 40$ deg.

Step 2, sector test. The nonlinear controller was treated as the equivalent PI scaled by a factor in $[0; 1]$, so that the linear part is $W_0(s) = C(s)W(s)$. For a sector $[0; 1]$ the circle criterion [15,16] reduces to

$$\min_{\omega} \text{Re } W_0(j\omega) > -1. \quad (4)$$

The delay enters exactly through $e^{-j\omega\tau}$. Condition (4) was evaluated on a 78×58 grid over n and Q (about 2 rpm and 10 kg/h steps) and, at the worst point, as a function of wear time. Two simplifications must be stated. $C(s)$ contains an integrator, so W_0 is not Hurwitz and (4) is an engineering indicator rather than a proof; and the negative part of the rate-channel sector is not included. For this reason Step 4 checks the critical region by simulation.

Step 3, sensitivity. At the worst point the test was repeated with an extra delay of 0.5 s and 1 s (sampling and hold), with the hold-out errors of T_1 applied at the domain edges, and with a 20% larger gain.

Step 4, simulation and saturation. The closed loop was simulated with a plant model driven by an eight-hour industrial disturbance record (1 s sampling) at the worst corner. Over the saw-set life the simulation was repeated at 32 checkpoints 8 h apart, and the share of time at the upper speed limit (saturation share) and outside the band (out-of-band share ε) were recorded. Computations used Python 3.11 with NumPy and SciPy.

3 RESULTS AND DISCUSSION

3.1 Linear margins

Table 2 shows large margins: $\Delta\varphi = 78.6$ to 86.2 deg, $GM = 27.7$ to 35.8 dB and $\Delta\tau = 526$ to 1425 s, more than forty times the dead time. The smallest margins occur at the largest plant gain ($n = 620$ rpm, $Q = 1850$ kg/h). The loop is slow near the origin, with crossover at 0.0011 to 0.0026 rad/s; fast disturbance rejection is left to the feedforward channel [9].

Table 2: Stability margins and sector test at the corners and centre of the domain (new saw set)

n , rpm	Q , kg/h	$\Delta\varphi$, deg	GM, dB	$\Delta\tau$, s	min Re W_0
620 (largest $ K $)	1850	78.6	27.7	526	-0.851
620	2420	80.6	27.9	537	-1.024
715 (nominal)	2150	84.2	32.7	981	-0.537
774 (smallest $ K $)	1850	85.4	35.7	1412	-0.341
774	2420	86.2	35.8	1425	-0.410

3.2 Sector test over the domain

Figures 1 and 2 show the left-hand side of (4). The level lines run diagonally, because both a lower speed (larger $|K|$) and a higher feed rate (shorter T_1) push the Nyquist curve to the left. The minimum of $\text{Re } W_0$ occurs at $\omega \approx 0.060$ to 0.068 rad/s, a period of about 90 to 105 s, well above the crossover of the origin loop; at this frequency the proportional upper bound dominates (with K_p alone the worst value is -0.948). The condition is met on 99.7% of the grid. It fails only for $n \leq 622$ rpm and $Q \geq 2350$ kg/h, and by at most 2.4% (-1.024 at $n = 620$ rpm, $Q = 2420$ kg/h). In the simulation at this corner the loop was stable: the output standard deviation was 0.096%, the out-of-band share 0.59%, and the saw speed stayed between 616 and 688 rpm. The failure therefore reflects the conservatism of the test, which combines the largest secant gains of both channels, rather than a real loss of stability.

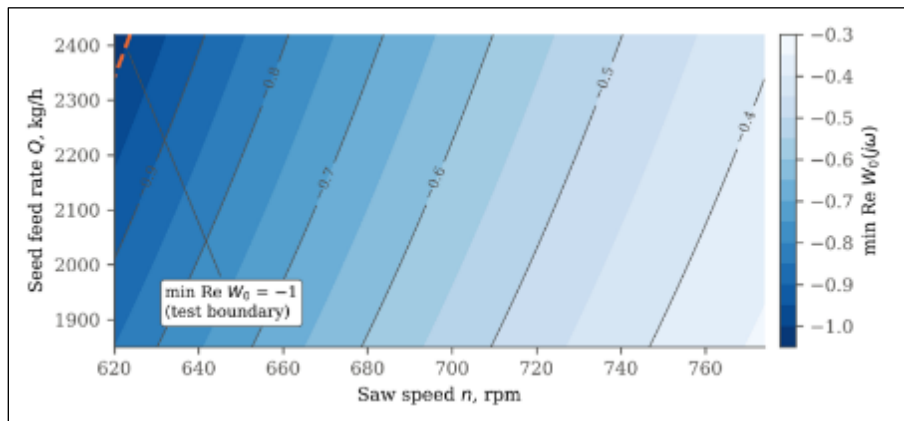


Figure 1: Sector test (4) over the operating domain for a new saw set. The thick line is the test boundary $\min \text{Re } W_0 = -1$; it is crossed only in the upper-left corner.

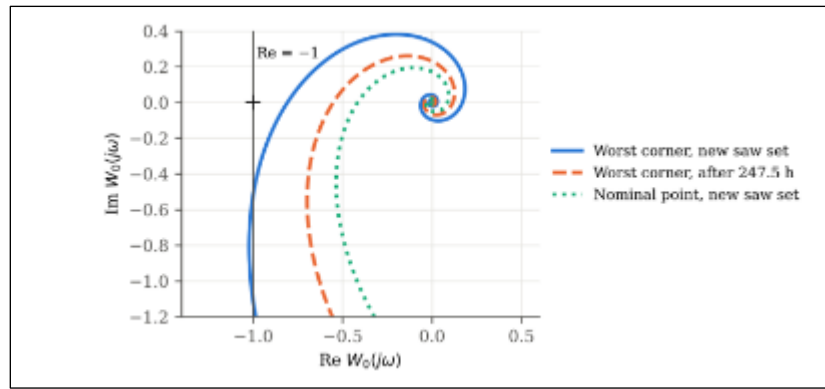


Figure 2: Nyquist curves of the equivalent loop $W_0(j\omega)$. At the worst corner ($n = 620$ rpm, $Q = 2420$ kg/h) the curve of the new saw set touches $\text{Re} = -1$ near $\omega \approx 0.07$ rad/s but passes to the right of $-1 + j0$; after 247.5 h it lies well inside the admissible half-plane.

3.3 Sensitivity of the result

Table 3 shows how the worst value and the failing region respond to model and implementation errors. Sampling and hold, modelled as an extra delay, enlarge the region only slightly: with 1 s it covers 2.2% of the grid ($n \leq 632$ rpm, $Q \geq 2170$ kg/h). The time-constant error matters in one direction only. At high feed rate the model overestimates T_1 by 13%, and correcting this lowers the worst value to -1.111; at low feed rate the true T_1 is larger and the margin improves. A gain 20% above the model is the most demanding case: the region grows to 13.3% of the grid ($n \leq 654$ rpm). All failing regions lie at the low-speed end of the domain, where the new saw set operates and where simulation is the appropriate check.

Table 3: Sensitivity of the sector test (new saw set; n in rpm, Q in kg/h)

Case	min Re W_0 (worst)	Failing share of grid, %	Failing region
Nominal model	-1.024	0.27	$n \leq 622, Q \geq 2350$
Extra delay 0.5 s	-1.050	0.99	$n \leq 628, Q \geq 2260$
Extra delay 1.0 s	-1.077	2.17	$n \leq 632, Q \geq 2170$
T_1 -11.5% at $Q = 2420$	-1.111	not mapped	corner only
T_1 +29% at $Q = 1850$	-0.711 (corner 620/1850)	0	none
$ K $ +20%	-1.228	13.26	$n \leq 654, \text{all } Q$

3.4 Effect of saw wear

Wear lowers $|K|$ and therefore the loop gain. Figure 3 shows the consequence. At the nominal point $\Delta\phi$ rises from 84.2 to 86.0 deg, GM from 32.7 to 36.0 dB and $\Delta\tau$ from 982 to 1467 s over 247.5 h; at the corner of largest gain the margins rise from 78.6 to 82.1 deg and from 27.7 to 31.1 dB. The worst value of the sector test rises from -1.024 to -0.699, and the test holds on the whole domain after about 18 h of operation. Drift thus makes the loop slower but not less stable.

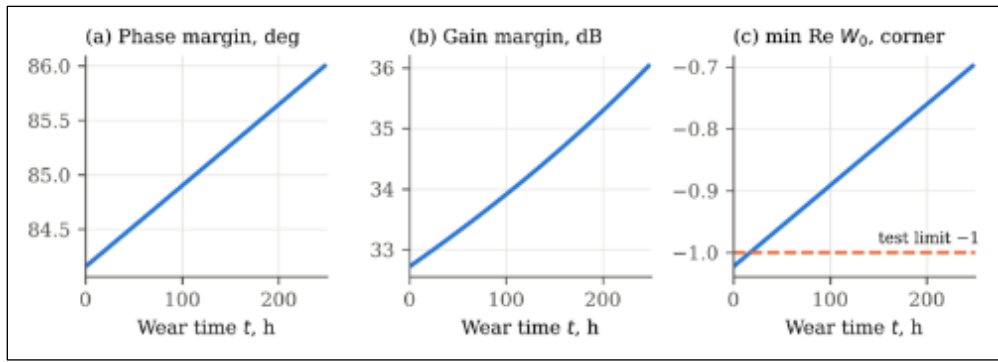


Figure 3: Effect of wear: (a) phase margin and (b) gain margin at the nominal point; (c) sector test at the worst corner ($n = 620$ rpm, $Q = 2420$ kg/h).

The constraint that does bind is actuator saturation (Figure 4). Wear shifts the static characteristic upward, so a higher speed is needed to hold the set-point. Up to 88 h the out-of-band share stays at zero and the mean speed rises slowly to 745 rpm. Between 96 and 142 h the speed approaches 774 rpm, the saturation share grows from 13 to 38%, and the out-of-band share exceeds the 5% limit at 120 h. After 142 h the 7.00% set-point cannot be reached at all; the upper band limit of 7.30% can be held until about 205 h. The values scatter because each point is computed over a two-hour window, so a replacement rule should rely on two consecutive checkpoints. Since the measured mechanical life of the saw set is 248 h, part of it is unusable for control, and the replacement time should be set by the out-of-band share, which is violated first, together with the saturation share as an early warning. An economic evaluation for the enterprise, not reported here, selected an adapted set-point of 6.85% and a replacement period of 112 h.

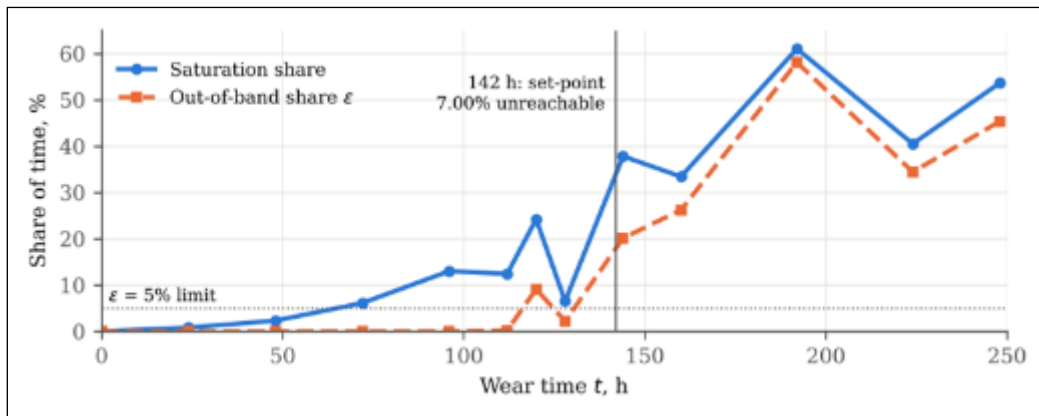


Figure 4: Saturation share and out-of-band share over the saw-set life (set-point 7.00%; simulation at 32 checkpoints, selected points shown).

Table 4 shows that the margins grow monotonically while the saturation and out-of-band shares grow from zero to about half of the operating time.

Table 4: Stability and saturation indicators over the saw-set life (margins in deg / dB; set-point 7.00%)

t, h	$\Delta\phi$ / GM nominal	$\Delta\phi$ / GM at 620/1850	min Re W_0 at 620/2420	Saturation share, %	ε , %
0	84.2 / 32.7	78.6 / 27.7	-1.024	0	0
96	84.9 / 33.9	80.0 / 28.9	-0.898	13.0	0
144	85.2 / 34.5	80.7 / 29.5	-0.835	37.8	20.11
248	86.0 / 36.0	82.2 / 31.1	-0.699	53.6	45.31

3.5 Comparison with related work

Sector and circle-type arguments for fuzzy PI and PID controllers are usually applied to delay-free or low-order plants [17-21]; here they are applied to a plant whose dead time is about a quarter of its main time constant. In line with the known conservatism of circle-type tests [24,25], the test fails only where the largest secant gains of both channels are

combined, while simulation of the actual controller remains stable. Unlike model-based fuzzy designs [10-13], no Takagi-Sugeno plant model is needed, since the sector bounds are read from the control surface of the genetically tuned controller [8]. The wear result rests on wear acting mainly as a gain reduction; if wear also lengthened the dead time, Table 3 shows that the failing region would grow.

3.6 Practical implications

Two rules follow for operation. First, the stability test needs attention only during the first hours of a new saw set and only when low speed coincides with high feed rate; the failing corner disappears if the rate-channel secant is limited to about 210 rpm/% (3% below 216.6 rpm/%, giving $\min Re W_0 = -0.995$), a bound that can be added as a constraint in the genetic tuning [8]. Second, the saturation share computed by the controller is a cheap online indicator of saw wear; combined with the out-of-band share over two consecutive checkpoints it gives a replacement rule that a single noisy window cannot trigger.

3.7 Limitations

The data come from one linter at one enterprise. The wear-induced gain loss was estimated indirectly. The sector test uses the upper secant gains of both channels together, excludes the negative part of the rate-channel sector, and is applied to a linear part with an integrator, so it is not a formal proof; the critical region was checked by simulation only. A rigorous proof for the sampled, saturated and slowly varying loop could use Zames-Falb multipliers for the monotone rule base [24,25] or integral quadratic constraints with uncertain delay [26,27,32], and is left for future work.

4 CONCLUSION

The stability of an incremental Takagi-Sugeno controller for a saw linter was assessed over the operating domain and the saw-set life. Near the origin the phase margin is at least 78.6 deg and the gain margin at least 27.7 dB. A circle-type sector test holds on 99.7% of the domain; it fails by at most 2.4% only at the lowest speed and highest feed rate, where simulation shows stable operation, and remains confined to the low-speed end under a 20% gain error. Saw wear reduces the loop gain and increases every margin, so the test holds everywhere after about 18 h. The limiting factor is actuator saturation: the 7.00% set-point becomes unreachable after 142 h and the 5% out-of-band limit is exceeded at 120 h. The replacement of the saw set should therefore be scheduled by the out-of-band and saturation shares rather than by stability or mechanical life.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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