BUFFER SIZING AND RESPONSE-TIME TRADE-OFFS FOR SMOOTHING SEED-COTTON FEEDER FLOW

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Abstract: A buffer upstream of a seed-cotton cleaner must moderate short-term feed fluctuations without producing excessive inventory excursions or slow throughput adjustment. This study evaluates that trade-off using an idealized proportional inventory-to-discharge relation and its first-order dynamic response. Sinusoidal inlet disturbances and a positive throughput step were analyzed, including a conservative bound for their superposition. All numerical inputs were hypothetical. At a mean flow of 1 kg/s, an inlet amplitude of 0.3 kg/s, and a disturbance period of 10 s, a 4-s time constant reduced the periodic coefficient of variation from 21.213% to 7.842%. Its combined inventory-excursion bound was 1.244 kg, and its isolated step component reached 95% of the final change in 11.983 s. Imposing an 8% variability limit, 1.3 kg of available inventory margin, and a 15-s step-response limit produced a feasible time-constant interval of approximately 3.909–4.263 s. No feasible interval existed for a 60-s disturbance under the same assumptions. The results distinguish short-period smoothing from rejection of sustained throughput changes and show that buffer capacity alone does not determine flow uniformity. The model is a screening tool requiring identification of real discharge behavior, actuator limits, and cotton handling constraints; it does not predict cleaning efficiency.

Keywords: seed-cotton feeding; buffer inventory; flow variability; first-order response; time constant; transient loading.

Introduction

Uniform delivery to a cleaner is a time-dependent material-handling problem. An average feed rate does not describe short surges, interruptions, or slow changes in throughput. USDA’s description of module feeding emphasizes continuity of cotton delivery [1]. At the cleaner inlet, feeder geometry and cotton deformation can also affect delivery: Veliev investigated the interaction between cotton properties and feed-roller mechanics in fine-impurity cleaners [2].

The handling system cannot be reduced to a nominal machine capacity. Hardin’s pneumatic-conveying experiments related conveying behavior to seed-cotton mass flow and operating conditions [3]. Such findings motivate measuring the actual flow reaching the next machine, but they do not establish a dynamic smoothing law for a storage hopper or feeder.

The present study addresses a narrower question: what combinations of response time and usable inventory margin can attenuate a specified inlet fluctuation? A local discharge relation is assumed explicitly, and standard first-order analysis [4] is used to derive the corresponding flow and inventory responses. The contribution is a joint feasibility assessment of variability, throughput adjustment, and capacity. It is not a comparison of cleaner geometries, an impurity-removal model, or an experimentally validated feeder design.

Materials and methods

Control volume and discharge assumption

The modeled subsystem is a buffer with a metered outlet immediately upstream of a cleaner. Its state is the stored cotton mass. Inlet and outlet flows refer to a common moisture basis, and there is no unmeasured loss or accumulation outside the defined buffer. The cleaner itself is not modeled.

The outlet is assumed to respond proportionally to inventory deviation around a positive operating mass. This could represent an idealized inventory-based metering arrangement, but it is not a universal property of bulk cotton. Storage by itself does not impose this relationship. The analysis assumes sufficiently rapid actuation, negligible transport delay, and no saturation, bridging, slip, or compaction-induced change in the discharge relation. All predictions are conditional on those assumptions.

The time constant characterizes the local inventory-to-flow response. It is not identified with average residence time or obtained by dividing nominal hopper capacity by throughput. An actual application must identify the discharge relation and check its validity over the intended operating range.

Hypothetical disturbances and screening limits

Table 1 lists all numerical assumptions. The short and long sinusoidal disturbances were evaluated separately. A positive step was then superposed on each periodic response to assess a conservative inventory bound. The 95% response time refers only to the incremental step component, not to the total output while a sinusoidal disturbance persists.

Table 1: Hypothetical inputs and screening limits; none were fitted to machine data.

Parameter	**Assigned value**
Baseline mean inlet and outlet flow	1.0 kg/s
Sinusoidal inlet amplitude	0.3 kg/s
Disturbance periods, evaluated separately	10 s and 60 s
Candidate response time constants	1, 2, 4, and 8 s
Operating inventory	5.0 kg
Assumed inventory limits	3.7–6.3 kg
Positive inlet-flow step	0.2 kg/s
Maximum baseline periodic output variation	8% coefficient of variation
Maximum 95% step-component response time	15 s

Analytical computation

Closed-form periodic and step responses were used to calculate amplitude attenuation, phase lag, flow variability, and inventory excursion. Feasible time constants were identified by com-bining

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the variability lower bound with response-time and capacity upper bounds. The nonlinear capacity boundary was found by bisection. The supplied Python script reproduces these calcu-lations and the CSV records each row as a hypothetical feeder-dynamics case. No experimental confidence intervals or cleaning-performance gains were assigned to the results.

Results

Joint assessment of smoothing, inventory, and response time

For a 10-s disturbance, increasing the time constant reduced periodic output variation but increased the combined inventory requirement and step-response time (Table 2). The 4-s candidate was the only listed value satisfying all three assumed limits. The 8-s candidate smoothed more strongly, but its inventory bound exceeded the available 1.3 kg margin and its response exceeded 15 s. Those unconstrained predictions are diagnostic failures, not feasible operating trajectories.

Table 2: Calculated responses to the 10-s disturbance and positive step.

Time constant (s)	Output variation (%)	Combined inventory bound (kg)	95% step time (s)	All assumed limits met
1	17.962	0.454	2.996	No
2	13.209	0.774	5.991	No
4	7.842	1.244	11.983	Yes
8	4.139	2.068	23.966	No

Time traces and the role of disturbance period

Figure 1 separates periodic smoothing from the step-induced inventory shift. The periodic output is delayed as well as attenuated. Following a sustained positive step, inventory approaches a new level rather than returning to its original value. The depicted 8-s step response eventually leaves the assumed inventory band, beyond which the linear prediction is not physically admissible.

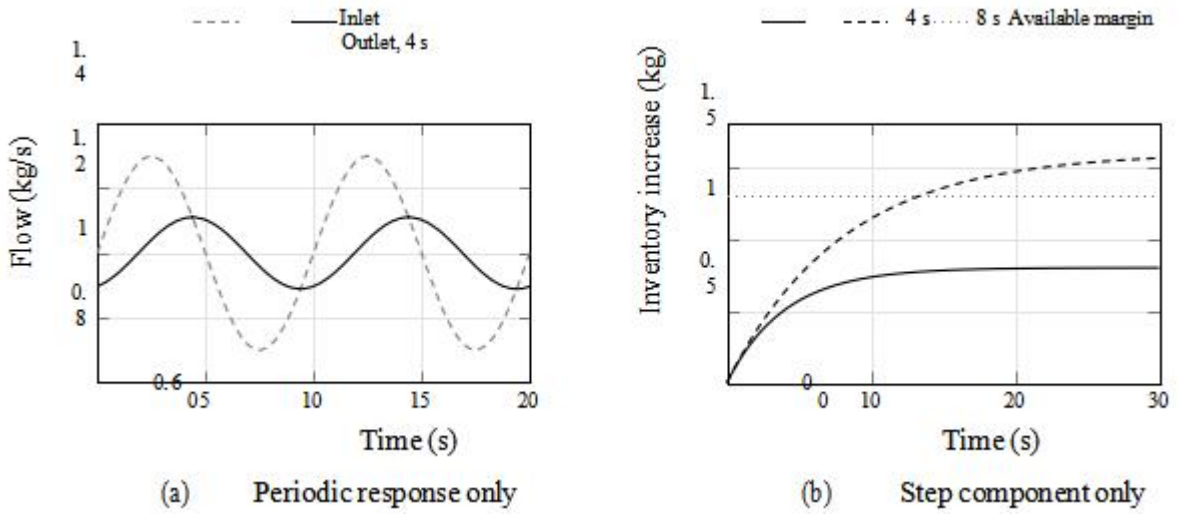

Figure 1: Analytical responses, not measurements. Panel (b) shows the unconstrained model; predictions above the available margin are infeasible. The panels represent separate response components.

At a 60-s disturbance period, the 4-s candidate produces 19.566% periodic output variation instead of 7.842%. None of the candidate time constants satisfies all limits. A continuous search also gives no feasible interval under these long-period assumptions. A feeder that moderates a rapid fluctuation therefore need not suppress a slow throughput drif **Dynamic model and periodic-flow attenuation**

Let $M(t)$ denote stored mass in kg, M_0 the operating mass, and q_{in} and q_{out} the inlet and outlet flows in kg/s. Define inventory deviation $x(t)=M(t)-M_0$. Conservation gives

$$\dot{x}(t)=q_{\text{in}}(t)-q_{\text{out}}(t). \quad (1)$$

The assumed local discharge law and the resulting flow equation are

$$q_{\text{out}}(t)=q_0+\frac{x(t)}{\tau},\ \tau\dot{q}_{\text{out}}(t)+q_{\text{out}}(t)=q_{\text{in}}(t), \quad (2)$$

where $q_0>0$ is the baseline flow and $\tau>0$ is the response time constant in seconds. The second relation follows by differentiating the first and applying Eq. (1). The coefficient $1/\tau$ is an assumed inventory-to-flow gain. It is not inferred from a hopper volume or a material density.

For a sinusoidal disturbance with amplitude $a<q_0$ and period T, the steady periodic response is

$$q_{\text{in}}(t)=q_0+a\sin(\omega t),\ \omega=\frac{2\pi}{T}, \quad (3)$$

$$q_{\text{out}}(t)=q_0+aR\sin(\omega t-\phi). \quad (3)$$

Substitution into Eq. (2), or the standard first-order frequency response [4], yields

$$R=\frac{1}{\sqrt{1+(\omega\tau)^2}},\ \phi=\arctan(\omega\tau),\ G(s)=\frac{1}{1+\tau s}. \quad (4)$$

Here R is the output-to-input amplitude ratio, ϕ the phase lag in radians, and $G(s)$ the transfer function for flow deviations with zero initial deviation. It has unit steady-state gain: a persistent change in average inlet flow is ultimately transmitted to the outlet. The model smooths temporal fluctuations; it does not permanently reject an inlet-flow bias.

For an integer number of periods after the transient has decayed, the coefficients of variation are

$$\text{CV}_{\text{in}}=\frac{a}{\sqrt{2}q_0},\ \text{CV}_{\text{out}}=\frac{aR}{\sqrt{2}q_0}=R\text{CV}_{\text{in}}. \quad (5)$$

These are dimensionless ratios; multiplication by 100 gives percentages. They describe variation around the baseline mean and are not estimates of cleaning efficiency. With q_0=1 kg/s and =0.3 kg/s, the inlet value is 21.213%. For T=10 s and =4 s,$R\approx0.369698$, giving an outlet amplitude of approximately 0.110909 kg/s and variation of 7.842%.

A short measurement record containing startup transients or incomplete periods need not give Eq. (5). Such a discrepancy should be assessed before attributing it to a different feeder property. Slow drift, irregular surges, and colored fluctuations require their own input descriptions rather than substitution of a single convenient period.

Inventory capacity and feasible response-time range

Consider an additional positive inlet step Δq starting at time zero. The outlet step component and its 95% response time are

$$\Delta q_{\text{out}}(t)=\Delta q\left(1-e^{-t/\tau}\right),\ t_{95}=-\tau\ln(0.05). \quad (6)$$

If the sinusoidal input remains present, this component is added to the periodic response. The total flow does not settle to a constant while oscillations persist. Thus t_{95} applies to the isolated incremental step response, not to entry of the total signal into a narrow constant-output band.

The sinusoidal inventory amplitude B and step-induced inventory change follow from Eq. (2):

$$B=\tau aR,\ x_{\text{step}}(t)=\tau\Delta q\left(1-e^{-t/\tau}\right),\ \Delta M_{\text{step},\infty}=\tau\Delta q. \quad (7)$$

A larger time constant increases the storage required by a sustained flow change. For τ=4 s and Δq=0.2 kg/s, the final inventory increase is 0.8 kg . For τ=8 s it is 1.6 kg , exceeding the assumed 1.3 kg upper margin even before any sinusoidal excursion is added.

For limits $M_{\min}$ and $M_{\max}$ around M_0, a conservative bound for the superposed disturbance is

$$B+\tau|\Delta q|\le H,\ H=\min(M_0-M_{\min},M_{\max}-M_0). \quad (8)$$

The bound covers arbitrary sinusoidal phase, assuming the sinusoid was already in its periodic state and the step component starts at zero. It is sufficient, not necessarily the least restrictive condition for a known phase and finite event duration. A negative step would additionally require checking nonnegative outlet flow and the variability measure against its lower mean.

With a required baseline variability limit $c_{\max}$ and maximum step-response time $t_{\max}$, Eqs. (5) and (6) give

$$\tau\ge\frac{1}{\omega}\sqrt{\max\left(0,\frac{a^2}{2q_0^2c_{\max}^2}-1\right)},\ \tau\le\frac{t_{\max}}{-\ln(0.05)}. \quad (9)$$

The capacity inequality supplies another upper bound. For $c_{\max}$ =0.08,$t_{\max}$ =15 s,H=1.3 kg, and the 10-s disturbance, the variability lower bound is 3.908623 s. The response-time upper bound is approximately 5.007 s; the tighter capacity boundary, calculated by bisection, is 4.263433 s. Their intersection is

$$3.908623\ \text{s}\le\tau\lesssim 4.263433\ \text{s}. \quad (10)$$

This interval is specific to the hypothetical assumptions, not a production recommendation. At T=60 s the variability lower bound becomes 23.451739 s , whereas the combined-capacity upper bound is 2.658434 s. The requirements are incompatible within the assumed first-order model. A

numerical search cannot resolve that conflict without changing the specifications or the physical arrangement.

Discussion

Why attenuation alone is an incomplete design target

Choosing the largest time constant would minimize the periodic output variation in this model, but it would ignore the associated inventory demand and slower adjustment. The 8-s candidate demonstrates this failure: it gives the smallest short-period variation among the listed values while violating the other limits. The relevant result is therefore the intersection of constraints, not the best individual response.

The distinction between fluctuation frequency and response speed is equally important. A long-period disturbance resembles a slowly changing mean flow, which a system with unit steady-state gain must eventually pass. If such changes must be rejected, additional regulation of upstream supply or a different metering policy is needed. A finite buffer cannot absorb a permanent excess of incoming material while holding the outlet fixed indefinitely.

The 5-kg operating inventory and 1-kg/s baseline would give an inventory-to-throughput ratio of 5 s. That ratio does not set the model's dynamic time constant. Conflating the two would conceal the dependence on the assumed discharge gain. Likewise, the required mass margin is not a geometric hopper volume: translating it into volume requires a measured bulk-density range and allowances for the actual cotton packing state.

Relation to cotton feeding and conveying

The proposed abstraction complements, rather than replaces, studies of cotton–roller interaction. Veliev's work addresses how raw-cotton characteristics and feed-roller arrangement affect the mechanical process [2]. Those effects could alter the discharge gain or introduce nonlinearity. They must not be represented by an assumed time constant without identification tests.

The wider conveying system also imposes constraints. Hardin developed mass-flow-dependent conveying models and considered changes in air velocity [3]. A feeder's smoothed outlet trace cannot establish acceptable pneumatic transport by itself. Airflow, pressure behavior, and the range of material conditions would need separate evaluation. No energy savings or improvement in cleaning quality is inferred from the calculated reduction in flow variation.

Validation and limitations

A validation experiment should first record inlet and outlet mass flow and buffer inventory on a synchronized time base. Small step or periodic perturbations within the operating envelope can then test the assumed gain, response order, delay, and repeatability. The fit should be checked on disturbances not used for identification. Persistent residual structure, asymmetric responses, or frequent inventory-limit encounters would argue against the simple model.

Measurement intervals must distinguish fast fluctuations from slower changes, and variation should be reported over a stated window. A sample average or rated feed capacity cannot establish temporal uniformity. Step-component response time and periodic variation should be measured in separate controlled tests or separated explicitly in the signal analysis.

The analysis excludes actuator bandwidth, metering saturation, dead time, bridging, moisture-dependent compaction, and irregular input spectra. It also presumes that the inventory-to-discharge law can be implemented or locally observed. The feasible interval is consequently a conditional screening result. Its narrow width in the example highlights the need to propagate parameter uncertainty before assigning real equipment settings.

Conclusions

1. A proportional inventory-to-discharge assumption produces a first-order feeder model that links flow attenuation, response time, and required inventory margin. Storage capacity alone does not establish this response law.
2. For the hypothetical 10-s fluctuation, a 4-s time constant reduces periodic flow variation from 21.213% to 7.842%, with a combined inventory bound of 1.244 kg and an isolated step-response time of 11.983 s.
3. Imposing all three assumed limits gives a conditional feasible interval of approximately 3.909–4.263 s. Stronger attenuation alone does not establish a preferable feeder setting.
4. The same limits are incompatible for the 60-s disturbance. Short-period smoothing must therefore be distinguished from regulation of slow throughput changes.
5. Real application requires measured discharge behavior, inventory limits, and actuator char-acteristics. The model does not establish cleaner efficiency, fiber quality, or production-scale operating recommendations.

Declarations

Data and code availability. No machine trials were performed. The hypothetical feeder calculations are reproduced by uchinchi_hisoblash.py; numerical outputs are supplied in uchinchi_hisoblar.csv.

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AI-assisted preparation. Generative AI assisted drafting, model development, and calculation-code preparation. [Authors must verify and approve the final content and adapt the disclosure to the selected journal.]

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