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Robust Optimization Design of a Series RLC Band-Pass Filter Based on Multisim and Component-Tolerance Sensitivity Analysis

Shuwei Zhang

School of Physics, Southeast University, Nanjing, China

213240226@seu.edu.cn

Abstract. To address the deviations of center frequency, bandwidth, and quality factor from their theoretical design values in a series resistor-inductor-capacitor band-pass filter caused by practical component tolerances, this paper establishes a frequency-response model with the output voltage taken across the resistor and derives the center frequency, bandwidth, quality factor, and their first-order sensitivities to resistance, inductance, and capacitance. Using Multisim, baseline-model validation, comparison of equivalent parameter schemes, single-parameter sweeps, and worst-case tolerance-allocation experiments are conducted. The results show that resistance mainly affects bandwidth, capacitance mainly affects center frequency, while inductance affects both. Under the same total tolerance budget, the center-frequency-priority scheme reduces the maximum center-frequency error from 4.72% to 2.33%, while the bandwidth-priority scheme reduces the maximum bandwidth error from 10.54% to 4.08%. In summary, the results demonstrate that performance-oriented allocation of component precision can effectively improve filter robustness and provide a design basis for parameter selection in low-cost passive band-pass filters.

Keywords: series resistor-inductor-capacitor band-pass filter; component tolerances; frequency-response model; first-order sensitivities; low-cost passive band-pass filters.

1. Introduction

Band-pass filters are widely used in communication, measurement, audio, and sensing systems, where center frequency, bandwidth, and quality factor directly determine signal selectivity and interference-rejection capability [1-3]. A series resistor-inductor-capacitor band-pass filter has a simple structure, requires no active devices, and has a clear relationship between its parameters and frequency response; however, conventional designs are usually calculated using ideal component values. In practice, resistors, inductors, and capacitors exhibit manufacturing tolerances, nominal-value dispersion, and temperature drift, which cause the actual center frequency, bandwidth, and quality factor to deviate from the design targets. Therefore, investigating the influence of component tolerances on frequency response and developing an implementable precision-allocation method are of practical significance for improving the engineering reliability of low-cost filters.

Research on filter parameter deviations and robustness has been carried out from the perspectives of calibration, sensitivity, and component optimization. Wang et al. proposed a calibration method for band-pass filters to address frequency shifts caused by the nonideal behavior of practical passive components, thereby improving errors in center frequency and bandwidth [4]. Šverko et al. used SPICE and MATLAB to perform noise and sensitivity analyses of different band-pass-filter structures, providing a theoretical basis for filter-parameter optimization [5]. In addition, Zverev systematically summarized the relationships among frequency response, quality factor, and component selection in filter synthesis [6]. Williams et al. further discussed component constraints and implementation issues in engineering filter design, providing a reference for practical parameter selection [7]. In recent years, related studies have further focused on robust analog-circuit design under process and parameter variations, as well as realizable parameter selection for integrated passive band-pass filters, providing new engineering references for filter optimization under component-tolerance constraints [8-10].

To address the above issues, this paper investigates the rational allocation of resistor, inductor, and capacitor precision under fixed center-frequency and bandwidth requirements. First, the transfer

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function, center frequency, bandwidth, quality factor, and first-order sensitivity models are established. Second, Multisim is used for baseline validation, equivalent-parameter analysis, and single-parameter sweeps. Finally, uniform allocation, center-frequency-priority allocation, and bandwidth-priority allocation are compared under the same total tolerance budget. Based on these results, a performance-oriented component-precision allocation principle is developed to provide a reference for passive-filter design that balances performance and cost.

2. Basic Principles and Model

2.1. Circuit Configuration, Impedance Model, and Transfer Function

The object of this study is a series resistor-inductor-capacitor (RLC) band-pass filter whose output voltage is taken across the resistor. The resistor R, inductor L, and capacitor C are connected in series, the AC input voltage is applied across the entire series branch, and the output voltage is taken across resistor R. Because the same current flows through all components in the series branch, the resistor voltage can directly reflect the variation of loop current with frequency; therefore, this configuration produces a typical band-pass magnitude response [1][2].

Under sinusoidal steady-state conditions, the complex impedances of the resistor, inductor, and capacitor are R, $j\omega L$, and $1/(j\omega C)$, respectively. Therefore, the total impedance of the series branch is:

$$Z = R + j(\omega L - 1/(\omega C)) \tag{1}$$

Where R, L, and C denote resistance, inductance, and capacitance, respectively; ω denotes angular frequency.

According to Ohm's law, the loop current satisfies $I=V_in/Z$. Since the output voltage is taken across the resistor, it follows that $V_o=IR$. Therefore, the voltage transfer function can be written as:

$$H(j\omega) = V_o/V_in = R / [R + j(\omega L - 1/(\omega C))] \tag{2}$$

Where V_in and V_o denote the input voltage and the output voltage across the resistor, respectively.

Its magnitude response is:

$$H_m(\omega) = R / \sqrt{[R^2 + (\omega L - 1/(\omega C))^2]} \tag{3}$$

At very low frequencies, the capacitive reactance is large and the loop current is small. At very high frequencies, the inductive reactance increases and likewise suppresses the loop current. Only when the reactive components of the inductor and capacitor nearly cancel does the loop current, and hence the output voltage across the resistor, become large, producing a band-pass characteristic.

2.2. Resonant Frequency, Bandwidth, and Quality Factor

The series-resonance condition is that the inductive reactance equals the capacitive reactance:

$$\omega L = 1/(\omega C) \tag{4}$$

The resonant angular frequency and center frequency are therefore obtained as follows.

$$\omega_0 = 1/\sqrt{(LC)} \tag{5}$$

$$f_0 = 1/(2\pi\sqrt{(LC)}) \tag{6}$$

It follows that, under ideal conditions, the center frequency is determined jointly by L and C and is not directly related to R. At resonance, the imaginary parts of the inductor and capacitor cancel each other, and the total impedance reduces to R, so the current reaches its maximum value.

The lower and upper cutoff frequencies f_L and f_H of a band-pass filter are defined as the frequencies at which the output amplitude falls to $1/\sqrt{2}$ of its peak value, corresponding to the -3 dB half-power points. For an ideal series RLC band-pass filter, the bandwidth is given by the following expression [1] [3].

$$BW = f_H - f_L = R/(2\pi L) \tag{7}$$

Where f_L and f_H denote the lower and upper cutoff frequencies, respectively.

The quality factor Q is defined as the ratio of the center frequency to the bandwidth, as shown in Eq.(8).

$$Q = f_0/BW \tag{8}$$

Combining the preceding equations, it can also be written as:

$$Q = \omega_0 L/R = (1/R)\sqrt{(L/C)} \tag{9}$$

Therefore, R mainly participates in bandwidth adjustment, L affects both center frequency and bandwidth, and C mainly participates in center-frequency adjustment. Meanwhile, f_0, BW, and Q are not independent and satisfy $Q=f_0/BW$.

2.3. Parameter Degrees of Freedom under Fixed Performance Specifications

The engineering problem considered in this paper is not merely to obtain one set of R, L, and C values that satisfies the specifications, but to investigate how different parameter combinations and tolerance allocations affect actual errors when the target center frequency and bandwidth are fixed. According to the center-frequency equation, the capacitance C can be expressed as

$$C = 1 / [(2\pi f_0)^2 L] \tag{10}$$

Based on the bandwidth equation, the resistance R is given by

$$R = 2\pi L \cdot BW \tag{11}$$

Therefore, once f_0 and BW are specified, L can be treated as a design degree of freedom. After L is selected, C and R are uniquely determined by the above relationships. This shows that the same filtering requirements can be realized by multiple theoretically equivalent sets of RLC parameters, providing a basis for the subsequent study of the robustness of different designs under tolerance conditions.

2.4. Component Tolerances and First-Order Sensitivity Model

Actual component values differ from their nominal values because of tolerances. Let the relative component variations be $\Delta R/R$, $\Delta L/L$, and $\Delta C/C$. By taking first-order differentials of the center frequency, bandwidth, and quality factor, the following approximate sensitivity relationships are obtained [3].

The relative variation of the center frequency is:

$$\Delta f_0/f_0 \approx -(1/2)\Delta L/L - (1/2)\Delta C/C \tag{12}$$

Where ΔL and ΔC denote small variations of inductance and capacitance relative to their nominal values, respectively.

The relative variation of the bandwidth is:

$$\Delta BW/BW \approx \Delta R/R - \Delta L/L \tag{13}$$

Where ΔR denotes a small variation of resistance relative to its nominal value.

The relative variation of the quality factor is:

$$\Delta Q/Q \approx -\Delta R/R + (1/2)\Delta L/L - (1/2)\Delta C/C \tag{14}$$

The first-order sensitivity relationships describe the approximate proportional relationship between relative component variations and relative variations of the performance metrics.

The above relationships provide theoretical predictions for the subsequent experiments. The first-order sensitivity of the center frequency to R is 0, whereas the sensitivity of the bandwidth to R is +1. The sensitivities of the center frequency and bandwidth to L are approximately -0.5 and -1, respectively. The sensitivity of the center frequency to C is approximately -0.5, while the first-order sensitivity of the bandwidth to C is approximately 0. Therefore, component precision should be allocated according to the actual performance objective rather than assigning the same tolerance grade to all components.

3. Experimental Design Procedure

Multisim is used to perform AC small-signal frequency-response simulations. The input-source amplitude is set to 1 V, the output is taken across the resistor, and AC Sweep is used to determine the peak frequency and the left and right -3 dB cutoff frequencies. The overall experiment is divided into four stages: baseline validation, equivalent-parameter design, single-parameter sensitivity analysis, and robust tolerance allocation.

3.1. Baseline Model and Equivalent Parameter Schemes

First, a baseline series RLC filter is established with R=750 Ω, L=100 mH, and C=160 nF. This parameter set is selected because it provides a center frequency of approximately 1.26 kHz and a bandwidth of approximately 1.2 kHz and can serve as the reference point for all subsequent error analyses. An AC Sweep is performed in Multisim over a frequency range from 100 Hz to 10 kHz. The values of *f_L*, *f_0*, and *f_H* are recorded, after which the bandwidth and quality factor are calculated using *BW=f_H-f_L* and *Q=f_0/BW*. The baseline design parameters are listed in Table 1.

Table 1. Baseline Model Design Parameters

Parameter	Specified Value
R	750 Ω
L	100 mH
C	160 nF
Target center frequency	Approx. 1265 Hz
Target bandwidth	Approx. 1200 Hz

To verify that the design is not unique when the center frequency and bandwidth are fixed, three different inductance values are selected, and the corresponding capacitance and resistance are calculated using Eqs. (10) and (11). The three designs are then implemented separately in Multisim and subjected to the same AC Sweep to compare their lower cutoff frequency, center frequency, upper cutoff frequency, bandwidth, and quality factor. The three equivalent parameter schemes are listed in Table 2.

Table 2. Equivalent RLC Parameter Schemes

Scheme	R (Ω)	L (mH)	C (nF)
Scheme 1	750	100	160
Scheme 2	377	50	316
Scheme 3	151	20	791

3.2. Single-Parameter Sensitivity Experiment

Based on the baseline model, the control-variable method is used to vary *R*, *L*, and *C* separately while keeping the other two components unchanged. Each component is assigned five levels: -10%, -5%, 0, +5%, and +10%. Parameter Sweep is used to obtain multiple frequency-response curves in a single run. For each parameter point, *f_L*, *f_0*, and *f_H* are recorded, and *BW*, *Q*, the relative error of *f_0*, and the relative error of *BW* are subsequently calculated. The specific sweep levels are listed in Table 3.

Table 3. Single-Parameter Sweep Settings

Swept component	Baseline value	Sweep values
R	750 Ω	675, 712.5, 750, 787.5, 825 Ω
L	100 mH	90, 95, 100, 105, 110 mH
C	160 nF	144, 152, 160, 168, 176 nF

All relative errors are referenced to the baseline simulation values and are defined as:

$$E_{f0} = \left|\frac{f_0 - f_{0,ref}}{f_{0,ref}}\right| \times 100\% \tag{15}$$

$$E_{BW} = \left|\frac{BW - BW_{ref}}{BW_{ref}}\right| \times 100\% \tag{16}$$

Where *f_0*,ref and *BW*_ref denote the center frequency and bandwidth of the baseline simulation, respectively.

Using the baseline simulation values rather than the ideal target values as the reference for relative error avoids repeatedly including the fixed offset caused by standard component values in the tolerance-sensitivity analysis, thereby allowing a more accurate comparison of the effect of a single component variation on system output.

3.3. Robust Tolerance Allocation and Evaluation Metrics

Based on the single-parameter sensitivity experiment, three component-precision configurations with the same "total tolerance budget" are further designed to compare uniform allocation with objective-oriented allocation. To ensure comparability, all three schemes satisfy *T_R*+*T_L*+*T_C*=15%. The three tolerance-allocation schemes are listed in Table 4.

Table 4. Robust Tolerance-Allocation Schemes

Scheme	R tolerance	L tolerance	C tolerance	Design objective
P1	±5%	±5%	±5%	Uniform allocation as the baseline
P2	±11%	±2%	±2%	Center-frequency priority
P3	±2%	±2%	±11%	Bandwidth priority

Because *f_0* is more sensitive to *L* and *C* and insensitive to *R*, P2 allocates more precision resources to *L* and *C*. Because *BW* is sensitive to *R* and *L* but insensitive to *C*, P3 allocates more precision resources to *R* and *L*. To facilitate comparison among the schemes, worst-case boundary analysis is used. The worst-case boundary combinations for each performance metric are listed in Table 5.

Table 5. Worst-Case Boundary Settings

Performance metric	Worst-case upper bound	Worst-case lower bound
Center frequency f0	Minimum L, minimum C	Maximum L, maximum C
Bandwidth BW	Maximum R, minimum L	Minimum R, maximum L

For each tolerance-allocation scheme, four boundary conditions are tested: maximum center frequency, minimum center frequency, maximum bandwidth, and minimum bandwidth, yielding a total of 12 robustness-verification data sets. The maximum f_0 error, maximum BW error, and variation in Q are then compared to determine how component precision should be allocated under different performance priorities.

For all experiments, R, L, C, f_L, f_0, and f_H are recorded, and BW and Q are calculated. In the sensitivity analysis, relative errors are further calculated and curves of f_0, BW, and Q versus component variation are plotted. In the robust-design analysis, the maximum errors under the three strategies are compared. This experimental design establishes a continuous logic from theoretical derivation to simulation validation and engineering optimization: first establishing the model, then identifying sensitive parameters, and finally using the sensitivity results to guide tolerance allocation.

4. Validation of the Circuit Model

This section discusses whether the established series RLC band-pass-filter model can effectively describe the Multisim simulation results and examines whether the theoretical sensitivity relationships are consistent with the parameter-sweep results.

4.1. Validation of the Nominal Point and Equivalent Designs

The baseline parameters are R=750 Ω, L=100 mH, and C=160 nF. The Multisim results are f_L=795.7 Hz, f_0=1258.9 Hz, f_H=1989.8 Hz, and BW=1194.1 Hz. A quantitative comparison between the theoretical values and Multisim results is presented in Table 6.

Table 6. Comparison between Theoretical Values and Multisim Results for the Baseline Model

Metric	Theoretical value	Multisim value	Relative difference
Center frequency f0	1258.23 Hz	1258.9 Hz	0.053%
Bandwidth BW	1193.66 Hz	1194.1 Hz	0.037%
Q	1.0541	1.0543	0.017%

The theoretical values and Multisim results for all three metrics are very close, with differences far below 1%. This indicates that, under the present ideal-component model and AC small-signal analysis conditions, the series RLC transfer function obtained by the impedance method accurately describes the simulated circuit. The model can therefore serve as a reliable basis for the subsequent sensitivity and tolerance analyses.

Table 7. Simulation Results of Equivalent Parameter Schemes

Scheme	R (Ω)	L (mH)	C (nF)	f0 (Hz)	BW (Hz)
1	750	100	160	1258.9	1194.1
2	377	50	316	1258.9	1199.0
3	151	20	791	1258.9	1202.0

Although the absolute parameter values of the three schemes differ substantially, their center frequencies are all 1258.9 Hz, and their bandwidths vary only from 1194.1 to 1202.0 Hz. These results verify the theoretical relationships that a fixed LC product maintains the center frequency and a fixed R/L ratio maintains the bandwidth, and they also demonstrate that the model correctly reflects equivalence under parameter scaling. The simulation results of the three schemes are shown in Table 7.

4.2. Parameter Sensitivity and Graphical Validation

The single-parameter sweep results further validate the first-order sensitivity predictions. As R increases from 675 Ω to 825 Ω, f_0 remains at 1258.9 Hz, while BW increases from 1074.7 Hz to 1313.6 Hz. When L varies, both f_0 and BW change noticeably. When C varies, f_0 changes while BW remains approximately 1194 Hz. The correspondence between theoretical sensitivities and simulation behavior is summarized in Table 8.

Table 8. Comparison between Theoretical Sensitivities and Simulation Behavior

Parameter	Theoretical S_f0	Theoretical S_BW	Simulation behavior
R	0	+1	f0 remains unchanged; BW varies approximately in proportion to R
L	-0.5	-1	Both f0 and BW decrease as L increases
C	-0.5	0	f0 decreases as C increases; BW is nearly unchanged

The parameter-sweep results are generally consistent with the theoretical sensitivities, but different performance metrics show clearly different dependencies on the components. To avoid relying only on qualitative judgment, Figs. 1-3 compare the results from three perspectives: center-frequency error, bandwidth error, and robust tolerance strategy.

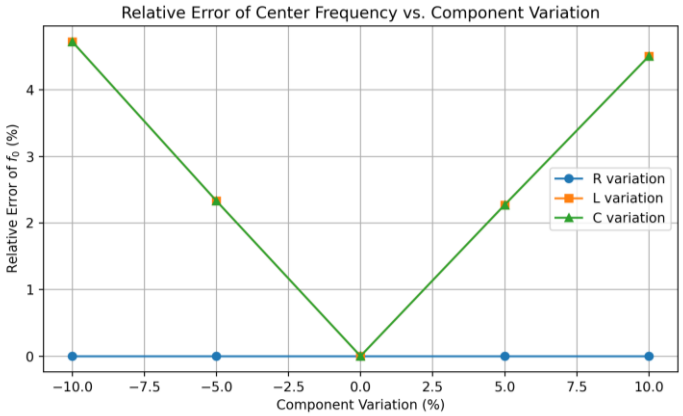

Fig. 1 Sensitivity of Relative Center-Frequency Error to Component Variation. (Picture credit: Original)

Fig. 1 shows the relative center-frequency error when the resistance, inductance, and capacitance vary within ±10%. The resistance curve remains close to 0, indicating that resistance variation does not change the resonance condition of an ideal series resistor-inductor-capacitor circuit. The inductance and capacitance curves nearly overlap: a ±5% variation produces a center-frequency error of approximately 2.3%, while a ±10% variation produces an error of approximately 4.5%-4.72%. These results are consistent with the preceding theoretical prediction from the first-order sensitivity analysis; that is, inductance and capacitance variations have essentially the same degree of influence on the center frequency. Therefore, when center-frequency stability is the primary design objective, the tolerances of the inductor and capacitor should be controlled preferentially.

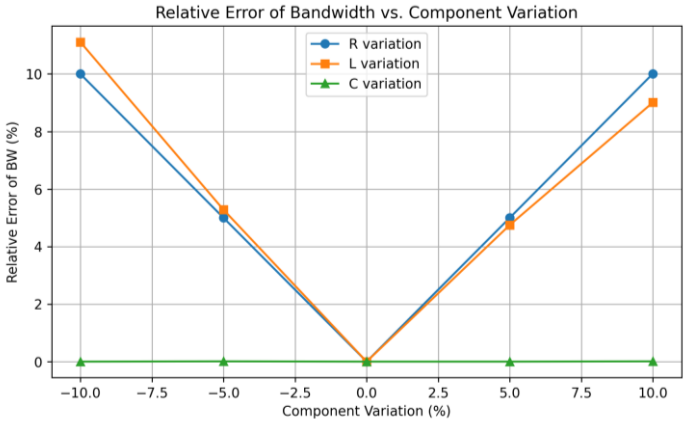

Fig. 2 Sensitivity of Relative Bandwidth Error to Component Variation. (Picture credit: Original)

Fig. 2 shows the relative bandwidth error as the components vary. For ±5% and ±10% changes in R, the bandwidth errors are approximately 5% and 10%, respectively, reflecting the approximately proportional relationship between BW and R. Variations in L also produce significant bandwidth errors: -10% and +10% variations result in deviations of approximately 11.11% and 9.01%, respectively, consistent with the nonlinear relationship between BW and $1/L$. By contrast, C produces a bandwidth error close to 0 over the entire sweep range, further verifying the theoretical conclusion that C does not appear in $BW=R/(2\pi L)$.

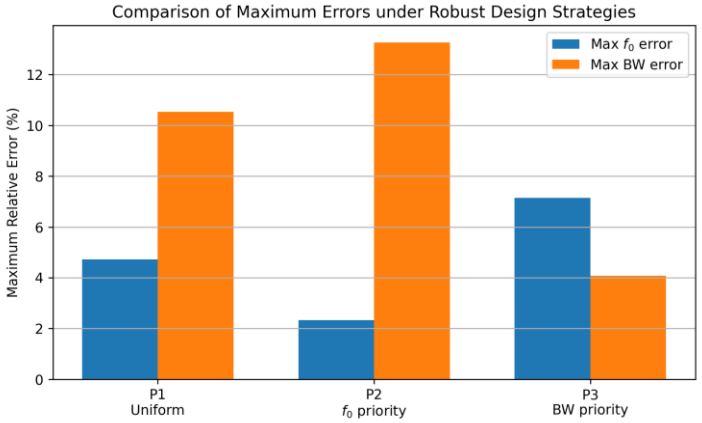

Fig. 3 Comparison of Maximum Errors under Three Tolerance-Allocation Strategies. (Picture credit: Original)

Fig. 3 compares the maximum errors of three precision-allocation strategies under the same total tolerance budget of 15%. With uniform allocation P1, the maximum center-frequency error and bandwidth error are 4.72% and 10.54%, respectively. After P2 concentrates precision on L and C, the maximum center-frequency error decreases to 2.33%, a reduction of approximately 50.6% relative to P1, but the bandwidth error increases to 13.27%. After P3 concentrates precision on R and L, the maximum bandwidth error decreases to 4.08%, a reduction of approximately 61.3% relative to P1, while the center-frequency error increases to 7.15%. The results show that robust design involves a clear trade-off among performance metrics and that component precision should be allocated according to the priority of the actual application.

4.3. Robust Design and Engineering Significance

The results of the three tolerance-allocation schemes further demonstrate that the sensitivity model can be used for engineering design rather than merely for post hoc explanation. With uniform allocation P1, the maximum center-frequency error is 4.72% and the maximum bandwidth error is 10.54%. After P2 concentrates precision on L and C, the maximum center-frequency error decreases to 2.33%, but the bandwidth error rises to 13.27%. After P3 concentrates precision on R and L, the maximum bandwidth error decreases to 4.08%, while the center-frequency error increases [4,5,7,8]. The maximum errors of the three schemes are compared in Table 9.

Table 9. Comparison of Maximum Errors for the Three Robust-Design Schemes

Scheme	Maximum f0 error	Maximum BW error	Description
P1	4.72%	10.54%	Uniform allocation
P2	2.33%	13.27%	Improved frequency accuracy at the expense of bandwidth
P3	7.15%	4.08%	Improved bandwidth accuracy at the expense of center frequency

Therefore, the experimental results support the conclusion that no single tolerance-allocation scheme is simultaneously optimal for all performance metrics of a series RLC filter. A reasonable approach is to allocate precision directionally according to the sensitivity of the target metric. When center frequency is the priority, L and C should be controlled more tightly; when bandwidth is the priority, R and L should be controlled more tightly. Experiment 3 extends theoretical sensitivity from merely describing the relationship" to an engineering design method that "guides parameter selection."

5. Conclusion

This paper addresses performance deviations in a series RLC band-pass filter caused by component tolerances by establishing models for center frequency, bandwidth, quality factor, and first-order sensitivity, and by using Multisim to validate the nominal point, parameter sweeps, and robust tolerance allocation. The results show that R mainly affects bandwidth, C mainly affects center frequency, and L affects both. Uniformly improving the precision of all components is not the only effective approach. Under the same total tolerance budget of 15%, the center-frequency-priority scheme reduces the maximum frequency error from 4.72% to 2.33%, while the bandwidth-priority scheme reduces the maximum bandwidth error from 10.54% to 4.08%. Therefore, component precision in a series RLC filter should be allocated directionally according to the sensitivity of the target metric so as to improve the stability of key performance characteristics at limited cost.

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