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EFFICIENCY IMPROVEMENT OF A FILTER CIRCUIT THROUGH DESIGN OPTIMIZATION

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Key Words

Filter circuit; Circuit efficiency; Transfer function; Ideal function; Performance measure; Parameter design; Heuristic approach; Tolerance design.

Filtration Process

The floppy disk drive is a subsystem of a personal computer. Its function is to read data from a floppy disk and provide output data. The data-reading process is explained in Figure 1. The magnetic head in the floppy disk drive reads data from a floppy in a waveform. The waveform becomes contaminated from the presence of a magnetic field. The contaminated wave is passed through a preamplifier for amplification. This amplified wave (original data plus noise) is passed through the filter circuit. Original data enter at one frequency and the system noise (disturbances) enters the circuit at a different frequency. The function of the filter circuit is to maintain the original data signal in the undisturbed form as an output and to dampen the signal of the system noise. This process is known as the "filtration process" (1) and is explained in Figure 2.

Circuit Efficiency

Circuit efficiency is judged by the loss in amplitude in the output of the original data and the noise signal. The amplitude is the distance between the peak and the crest of the waveform. Efficiency will be 100% if there is no loss in amplitude of the original data while the amplitude of the noise signal tends toward zero. A term more often used to express this efficiency in electronic design is "gain in amplitude."

$$\text{Loss in amplitude} = \frac{V_{in} - V_{out}}{V_{in}},$$

$$\text{Gain in amplitude} = 1 - \text{Loss in amplitude} = \frac{V_{out}}{V_{in}},$$

where V_{out} is the amplitude of the output waveform measured in millivolts (mV) and V_{in} is the amplitude of the input waveform measured in millivolts (mV).

Here, the floppy disk drive is used for floppies with 360-kilobyte (KB) and 1.2-megabyte (MB) memories. The original data signal is read at 125 kHz and 250 kHz frequencies in 360-KB and 1.2-MB disks, respectively. Noise

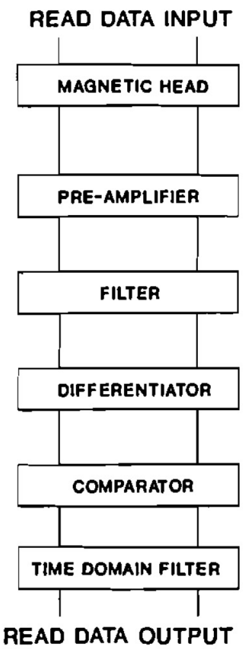

Figure 1. Waveform flow chart.

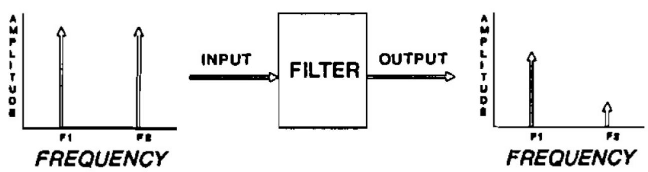

Figure 2. Filtration process.

is observed at frequencies above 375 kHz for 360-KB disks and above 750 kHz for 1.2-MB disks.

There are 80 tracks on the floppy disk and the circuit works in two phases. Phase 1 is active when data are read between track 0 and track 43, and phase 2 of the circuit is active when data are read from track 44 onward. (Fig. 3).

The efficiency of the existing circuit is computed in terms of gain in amplitude at relevant frequencies for the

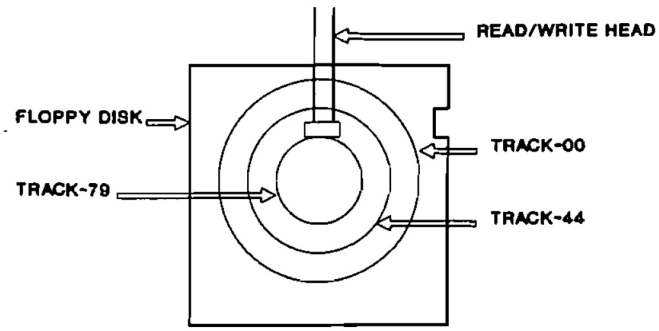

Figure 3. Tracks on the floppy disks.

two types of floppy disks using the input/output relationship (transfer function) given in Appendix 1. The gain in amplitude for an existing circuit along with the target value is given in Table 1.

The gain in amplitude for the original data signal varies from 32.6% to 58.9%, whereas noise varies between 12.5% and 38.1% against the targets of 100% and 0%, respectively. The low efficiency of filter circuit results in the following:

1. The computer gives data error in the presence of noise spikes (creates false pulses in the read data output).
2. Weak power to read the signal from original data (makes slightly worn floppy unusable).

Objective

The objective is to find the optimum design parameter values of the filter circuit so as to do the following:

(a) Maximize the gain in amplitude at a frequency of 125 kHz and minimize the gain in amplitude at frequencies above 375 kHz, for 360-KB floppy disks
(b) Maximize the gain in amplitude at a frequency of 250 kHz and minimize the gain in amplitude at

Table 1. Gain in Amplitude for Existing Circuit

	1.2 MB FLOPPY		360 KB FLOPPY	
	DESIRED SIGNAL (AT 250 kHz)	NOISE (AT 750 kHz)	DESIRED SIGNAL (AT 125 kHz)	NOISE (AT 375 kHz)
Track 0	0.3264	0.0370	0.4568	0.1844
Track 79	0.5061	0.1246	0.5893	0.3807
Target value	1	0	1	0

frequencies above 750 kHz for 1.2-MB floppy disks.

This will help to improve the basic function of the filter—the filtration process.

Circuit Design

The circuit diagram of the filter is given in Figure 4. The filter circuit consists of capacitors C_1, C_2, C_3, C_4, and C_5, resistors R_1, R_2, R_3, and R_4, and inductors L_1 and L_2. Here, $C_1 = C_2$, $R_1 = R_2$, $C_3 = C_4$, and $L_1 = L_2$. All components of the filter circuit operate when data are read between tracks 0 and 43. All components except C_5 and R_4 operate when data are read between tracks 44 and 79.

Inductors in the circuit are used primarily to provide stability to the system. Undesirable phenomena such as oscillation of the system are prevented by its use.

Capacitors C_1 and C_2 used here are known as "decoupling capacitors." Fluctuation in input DC voltage is stabilized by decoupling capacitors. They do not play any role in the filtration process.

The existing parameter values of the various components used in the circuit are given in Table 2.

The filter circuit has a total of seven different components. Due to technical constraints, the values of C_1 and C_2 are fixed at 0.033 μF. Hence, six control factors are considered as design parameters for design optimization.

The input/output relation for the filter circuit is given by the transfer function in Appendix 1.

Methodology

The methodology used to find an efficient filter circuit design consists of the following:

1. Selection of a performance measure for design optimization

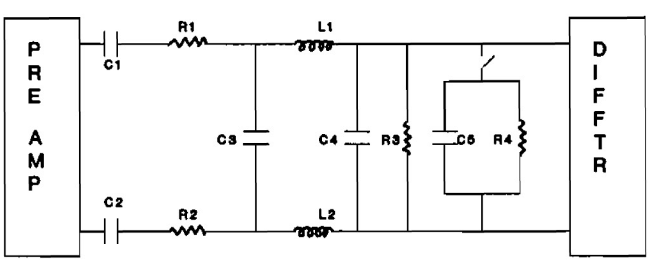

Figure 4. Circuit diagram.

Table 2. Existing Parameter Values of the Circuit Components

SL. NO.	COMPONENT	VALUE
1	Capacitors C1 and C2 (μF)	0.033
2	Resistors R1 and R2 (Ω)	220
3	Inductors L1 and L2 (μH)	330
4	Capacitors C3 and C4 (pF)	390
5	Resistor R3 (Ω)	680
6	Capacitor C5 (pF)	470
7	Resistor R4 (Ω)	1000

2. Selection of optimum parameter values—parameter design
3. Performing a sensitivity analysis
4. Selection of tolerances for optimum parameter values—tolerance design

Performance Measure

The gain in amplitude, for any given frequency, is computed from the transfer function. It is considered as a function of frequency f and parameters values α_1, α_2, α_3, α_4, α_5, and α_6 and is expressed as

$$\text{Gain} = g(f;\ \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6). \quad (1)$$

A curve obtained by varying the frequency for fixed (α_1, α_2, α_3, α_4, α_5, α_6) is known as the "amplitude response curve" [1]. This reflects the filter circuit performance. The shape of the curve depends on the parameter values. An amplitude response curve, or ARC, for a 100% efficient circuit is shown in Figure 5. This is also known as an "ideal curve."

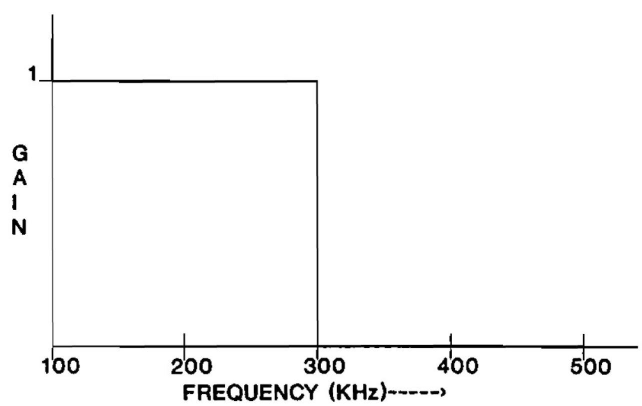

Figure 5. Ideal amplitude response curve.

This function, $g(f;\, x)$, satisfies the constraints

$$g(f;\, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6) = \begin{cases} 1.0 & \text{for } 100 \le f \le 300 \\ 0 & \text{for } 300 < f \le 500. \end{cases} \quad (2)$$

It is called an "ideal function."

The objective of the parameter design is to bring the function of Eq. (1) closer to the ideal relationship; that is, select design parameter values such that the function is closest to the ideal function (2).

The ideal and the existing curves are shown in Figure 6. The deviation of the existing curve from the ideal one is shown by the shaded portion of the figure. The curve will be closest to the ideal curve when the shaded portion is reduced to a minimum. This phenomenon is explained by considering the sum of the squared deviations at different points from the ARC to the ideal curve. If this is minimum, then the ARC will be closest to the ideal curve. Therefore, the sum of the squared deviations from the ideal curve is taken as the performance measure.

The total squared deviation is estimated by the function $D(x)$ for a given set of values of α_1, α_2, α_3, α_4, α_5, and α_6:

$$D(\alpha_1, \alpha_2, \ldots, \alpha_6) = \int_{100}^{300} [1 - g(f;\, \alpha_1, \alpha_2, \ldots, \alpha_6)]^2\, df + \int_{300}^{500} [g(f;\, \alpha_1, \alpha_2, \ldots, \alpha_6)]^2\, \text{df}. \quad (3)$$

The exact value of the expression $D(\alpha_1, \alpha_2, \ldots, \alpha_6)$ is difficult to compute because the explicit form of the function $g(f;\, \alpha_1, \alpha_2, \ldots, \alpha_6)$ is very complex. Therefore, the range of frequency is discretized into 20 parts, as shown in Figure 7 and the "measure of deviation" from the ideal curve is redefined as

$$r(\alpha_1, \alpha_2, \ldots, \alpha_6) = \left(-\frac{1}{20} \left\{ \sum_{i=1}^{10} [1 - g(f_i;\, \alpha_1, \alpha_2, \ldots, \alpha_6)]^2 + \sum_{i=11}^{20} [g(f_i;\, \alpha_1, \alpha_2, \ldots, \alpha_6)]^2 \right\} \right)^{1/2}, \quad (4)$$

where $f_i = 100 + 20i$ (for $i = 1, 2, 3, \ldots, 20$) and $r = 0$ for the ideal function.

The value of r is taken as a measure of the circuit design performance. Circuit efficiency increases as the value of r decreases. As the ARC comes closer to the ideal curve, the basic function of the filter circuit design improves.

Parameter Design

The objective is to select values for design parameters such that r is a minimum. This means we have to minimize r over the following:

1. All possible parameter values for the components R_1, L_1, C_3, and R_3 at track 79
2. All possible parameter values for the remaining components C_5 and R_4 at track 0

First, an optimal selection of parameter values for components R_1, L_1, C_3, and R_3 is made, and later, optimal selection of parameter values for components C_5 and R_4 are obtained. Design is first optimized for track 79 and then for track 0.

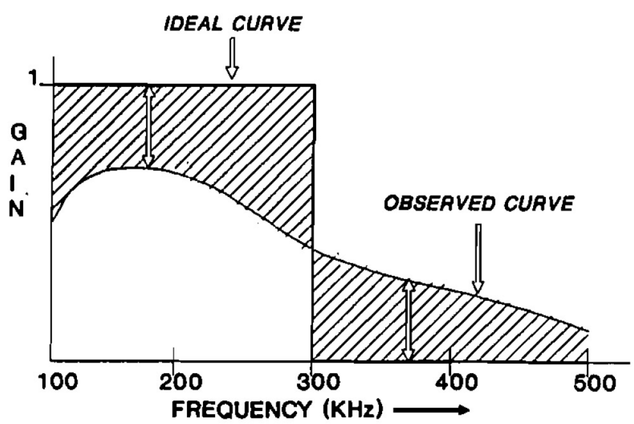

Figure 6. Deviation between observed and ideal curves.

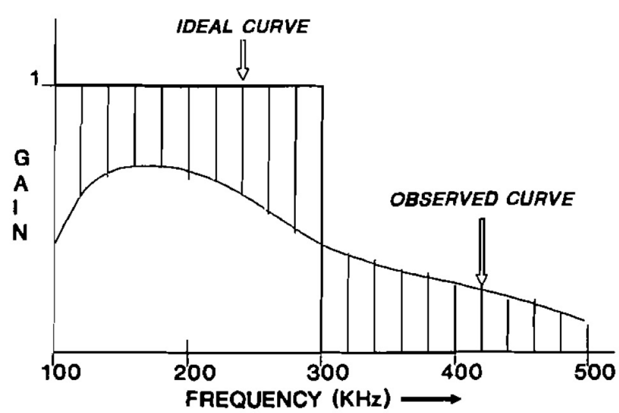

Figure 7. Division of frequency into 20 discrete points.

The range of values and the number of possible choices considered for each component is based on market availability. The range of values and possible choices considered for the four components used in track 79 is given in Table 3. This means that in order to find an optimum combination of parameter values, we need to compute the value of r for 3,529,470 ($=30 \times 49 \times 49 \times 49$) combinations. It has been observed that an IBM PC 486 takes 0.136 sec to evaluate r for each combination; that is, it requires more than 120 hr of continuous time to enumerate all combinations and find the best one. Considering the computer time constraints, a two-stage heuristic approach is adopted to find the best value of the design parameters. The two stages of the method are (1) the global search and (2) the local search.

Global Search

Step 1: Five levels for each parameter are chosen to cover the entire feasible range. These levels are given in Table 4.

Step 2: The value of r is computed for all 625 ($=5 \times 5 \times 5 \times 5$) combinations and these values are arranged in ascending order of magnitude. The first 10 combinations are given in Table 5. The first five combinations are chosen as potential solutions. These five combinations are then used for the local search.

Local Search

Step 3: At each of the five potential solutions, an iterative local search is carried out by considering, for each parameter, five successive levels close to the parameter level obtained in the global search. (For example, if the global search gives $R_3 = 5600$, the five successive levels to be chosen in the local search are 4700, 5100, 5600, 6200, and 6800.)

In each iteration, we go from a feasible solution, say α, to another feasible solution, say β. The value of r is computed for 625 feasible solutions around α first. The level combination with minimum r value is selected and this solution is designated β. This combination is then used for the next iteration consisting of five successive levels for each parameter.

The iterative search stops when the difference in the value of r is not more than 0.0002 for two successive iterations. The iterative procedure for the first combination (2, 3, 4, 4) is given for illustration in Appendix 2.

Step 4: The solutions obtained in Step 3 are taken as the local optimal solutions. Four different local optimal solutions have emerged from the five potential combinations. The value of r is 0.2064 for each of these four combinations (see Table 6).

Now, we select one of the four as the best solution. This will be done after considering the performance at track 0. The range of values and the number of possible choices, based on market availability for the two components C_5 and R_4 used for track 0, are given in Table 7.

Table 3. Range and Possible Choices for Components

COMPONENT	RANGE	NO. OF POSSIBLE CHOICES
R_1	$110 \le R_1 \le 1800$	30
L_1	$33 \le L_1 \le 3300$	49
C_3	$39 \le C_3 \le 3900$	49
R_3	$68 \le R_3 \le 6800$	49

Table 4. Parameters and Levels

PARAMETER	LEVELS 1	2	3	4	5
R_1 (Ω)	110	220	430	910	1800
L_1 (H)	33	100	330	1000	3300
C_3 (pF)	39	120	390	1200	3900
R_3 (Ω)	68	220	680	2200	6800

Table 5. First 10 Combinations

SL. NO.	r	COMBINATION
1	0.2267	2 3 4 4
2	0.2301	1 2 5 4
3	0.2351	1 2 5 5
4	0.2362	4 4 3 5
5	0.2394	3 3 4 5
6	0.2730	1 2 5 3
7	0.2753	3 4 3 5
8	0.2818	2 3 4 5
9	0.2920	1 4 3 4
10	0.2967	1 5 2 5

Table 6. Local Optimal Solutions

COMBINATION	COMPONENT R_1	L_1	C_3	R_3
1	360	360	1000	6200
2	430	430	820	6800
3	390	360	1000	6800
4	390	390	910	6200

Table 7. Range and Possible Choices for Components C_5 and R_4

COMPONENT	RANGE	NO. OF POSSIBLE CHOICES
C_5	$47 \le C_5 \le 4{,}700$	49
R_4	$100 \le R_4 \le 10{,}000$	49

The value of r is minimized using the computer over all 2401 (= 49 × 49) combinations of C_5 and R_4 for each one of the local optimal solutions arrived at for track 79. It is interesting to note that the optimal values of C_5 and R_4 are 47 and 10,000, respectively, for all local optimal solutions of track 79. The values of r at track 0 for all the four solutions are given in Table 8.

Sensitivity Analysis

Sensitivity analysis is carried out to select among the four solutions the one that minimizes variability in the performance measure resulting from the variation of parameter values within their respective tolerances. Taguchi's signal-to-noise ratio (S/N ratio) for smaller-is-better is used to measure and compare the variation in the performance measure. The smaller-the-better type S/N ratio is considered because the value of r is being minimized. Larger values of the S/N ratio indicate the better performance of the system.

For the smaller-the-better type, the S/N ratio is given as

$$\text{S/N ratio} = -10\log\left(\frac{r_1^2 + r_2^2 + \cdots + r_k^2}{k}\right),$$

where $r_1, r_2, \ldots, r_k$ are k response values.

Following Taguchi's methodology, we have taken the parameters C_1, R_1, L_1, C_3, and R_3 as five factors and carried out an L_{18} experiment for track 79 and evaluated the S/N ratio for each of the four local optimal solutions. The three levels chosen for each parameter are the optimal parameter value and ±5% of this value. Similarly, for track 0, an L_{18} experiment is carried out considering the seven parameters C_1, R_1, L_1, C_3, R_3, C_5, and R_4 as factors and taking the levels as explained above. The layouts for the L_{18} experiments for track 79 and track 0 are given in coded form in Appendices 3 and 4, respectively. The S/N ratio values for all four combinations are given in Table 9 for both tracks.

Solution 1 has a maximum S/N ratio at track 0 and is the second best at track 79. Hence, it is selected as the optimum solution. The existing and the optimum values of the parameter are given in Table 10. The optimal solution brings down the value of r from 0.4145 to 0.2064 at track 79 and from 0.4630 to 0.2174 at track 0.

Performance Reliability

We have accomplished the objective of the parameter design by bringing the ARC closest to its ideal shape. Consistency in the circuit design performance is another requirement to be satisfied. The main sources of variation in circuit performance are the component parameter values and the component tolerances. Usually, the parameter design helps to reduce this variation. Further reduction in variation is accomplished through tolerance design techniques developed by Taguchi.

The variation in circuit design performance is evaluated for both the existing and the optimal combinations by simulating 1000 times the parameter values within their respective tolerances (3).

In each of the 1000 simulated trials for the existing combination,

(i) The value of any parameter is randomly generated from a Normal probability distribution with the parameter level given by the existing combination as the mean and one-sixth of the tolerance as the standard deviation.
(ii) The performance measure is evaluated for the randomly generated parameter values.

The variances of the performance measure for 1000 values is computed for the existing combinations. Similar

Table 8. Results at Track 0

SOLUTION	r (TRACK 0)	C_5	R_4
1	0.2174	47	10,000
2	0.2209	47	10,000
3	0.2228	47	10,000
4	0.2193	47	10,000

Table 9. S/N Ratios of the Four Solutions

SOLN. NO.	S/N RATIO	
	TRACK 79	TRACK 0
1	13.5352	13.1441
2	13.5302	13.0079
3	13.5382	12.9357
4	13.5317	13.0679

Table 10. Existing and Optimum Parameter Values

SL. NO.	COMPONENT	EXISTING VALUE	OPTIMUM VALUE
1	Capacitors C_1 and C_2 (μF)	0.033	0.033
2	Resistors R_1 and R_2 (Ω)	220	360
3	Inductors L_1 and L_2 (μH)	330	360
4	Capacitors C_3 and C_4 (pF)	390	1,000
5	Resistor R_3 (Ω)	680	6,200
6	Capacitor C_5 (pF)	470	47
7	Resistor R_4 (Ω)	1000	10,000

computations are made for the optimal combination. The results are given in Table 11.

The optimal combination has significantly reduced the variation in r for track 79. However, this is not true for track 0. Using Taguchi's tolerance design technique, we can determine the tolerances for critical components in order to reduce the variation in r further.

Tolerance Design

All seven different components of the filter circuit are considered for the tolerance design (4). Table 12 gives the three levels of these factors. The three levels considered in the Tolerance Design are

Level 1 ⇒ Optimum value + 5%
Level 2 ⇒ Optimum value
Level 3 ⇒ Optimum value - 5%

The error factors are assigned to the columns of the L_{18} orthogonal array. The layout is given in Appendix 5. The values of r are computed at track 0 for the 18 sets of conditions, and an analysis of variance (ANOVA) is performed in which linear and quadratic terms are separated. Smaller effects are pooled with the residual. The summarized ANOVA table is given in Table 13.

It can be seen from Table 13 that 80% of the variation in the value of r is contributed by three components R_1, L_1, and C_3. Further reduction in variance can be accomplished by using the components R_1, L_1, and C_3 with ±1% tolerance instead of ±5% used at present. The variance is computed using the method explained earlier and the results of the tolerance design is given in Table 14. The tolerance design has reduced the performance variance considerably both at Track 0 and at Track 79.

Table 11. Variances Comparison for Existing and Optimal Combinations

	VARIANCE AT TRACK 79 (IN UNITS 10^{-6})	VARIANCE AT TRACK 0 (IN UNITS 10^{-6})
Existing combination	3.03	7.84
Optimum combination	0.81	7.18

Results

The gain in amplitude for the improved filter circuit (after parameter and tolerance designs) is computed with the help of an input/output relationship. A comparison between the existing and improved circuit designs is given in Table 15.

There is a significant improvement in amplitude gain from the improved filter circuit design under different operating conditions. The amplitude response curve is also very close to the ideal curve, as can be seen in Figure 8.

The benefits of improved design are as follows:

1. Minimum data error due to system noise
2. Increase in life for floppy disks

Trial runs have been conducted by making prototypes of filter circuits with optimal parameter values (R_1, L_1, C_3, R_3, C_5, R_4) = (360, 360, 1,000, 6,200, 47, 10,000). The

Table 12. Factor and Levels

FACTOR	LEVELS 1	2	3
C_1 (pF)	0.03135	0.033	0.03465
R_1 (Ω)	342	360	378
L_1 (μH)	342	360	378
C_3 (pF)	950	1,000	1,050
R_3 (Ω)	5,890	6,200	6,510
C_5 (pF)	44.65	47	49.35
R_4 (Ω)	9,500	10,000	10,500

Table 13. Analysis of Variance Table

SOURCE	D.F.	SS	MS	CONTRIBUTION %
C_1 (linear)	1	0.000030	0.000030	3.9[a]
C_1 (quad.)	1	0.000018	0.000018	2.1
R_1 (linear)	1	0.000104	0.000104	15.1
L_1 (linear)	1	0.000117	0.000117	17.1
C_3 (linear)	1	0.000320	0.000320	47.8
R_4 (linear)	1	0.000023	0.000023	2.8
Res (pool)	11	0.000048	0.0000044	11.2
Total	17	0.000660		100.0

[a]Contribution ratio for factor C_1
$$= \frac{SS(C_1) - DF(C_1)[MS(res)]}{TSS} = \frac{0.000030 - (1)(0.000004)}{0.000660} = 3.9\%.$$

Table 14. Variance Comparison

	VARIANCE AT TRACK 79 (IN UNITS 10^{-6})	VARIANCE AT TRACK 0 (IN UNITS 10^{-6})
Existing combination	3.03	7.84
After parameter design	0.81	7.18
After tolerance design	0.01	0.46

results are found to be very close to the predicted theoretical results.

Conclusion

Problems related to electronic circuit performance were most often problems of design. The usual method followed to find a solution to such a problem is to identify the most influential component and change its parameter value to a more favorable value. If a solution is not found, the search continues until it stops at a possible suboptimal solution.

The present scientific investigation involves the concept of an ideal function and brings the existing function closest to the ideal function by finding optimum parameter values. It has provided a solution to a complex real-life problem. This exercise has demonstrated the potential of a new approach that defines a performance measure and then finds an optimal solution using a heuristic approach combined with Taguchi's tolerance design technique.

In brief, the investigation has resulted in improving the efficiency of the filter circuit (1) from 32.6% to 89.6% at track 0 and 50.6% to 100% at track 79 for 1.2-MB floppy disks and (2) from 45.7% to 78.3% at track 0 and from 58.9% to 83.3% at track 79 for 360-KB floppy disks. The

Table 15. Gain in Amplitude for Existing and Improved Designs

	1.2-MB FLOPPY		360-KB FLOPPY	
	DESIRED SIGNAL (AT 250 kHz)	NOISE (AT 750 kHz)	DESIRED SIGNAL (AT 125 kHz)	NOISE (AT 375 kHz)
Track 0				
Before	0.3264	0.0370	0.4568	0.1844
After	0.8955	0.0182	0.7830	0.1922
Track 79				
Before	0.5061	0.1246	0.5893	0.3807
After	1.0417	0.0200	0.8332	0.2150
Target value	1	0	1	0

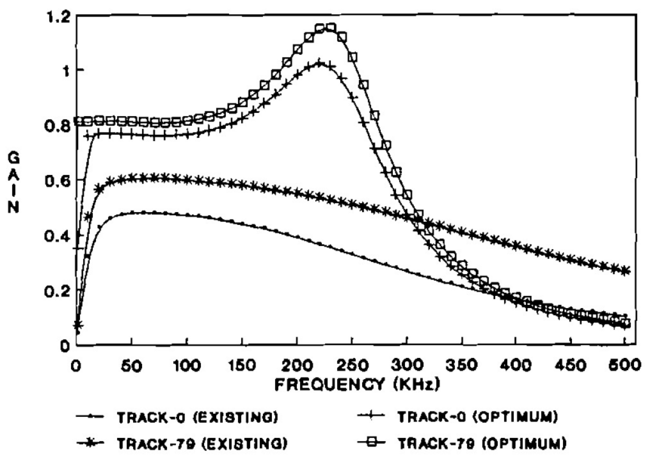

Figure 8. Comparison of existing and optimum ARCs.

noise signals for both tracks have also been reduced substantially. Variation in performance measures caused by variation in parameter values within specified tolerances has also been reduced significantly after parameter and tolerance design procedures were performed.

Appendix 1: Transfer Function

The input/output relationship of the filter circuit is given by the transfer function,

$$V_{out} = V_{in}\sqrt{A^2 + B^2},$$

where V_{in} is the amplitude of the input wave measured in millivolts, and A and B are real and imaginary parts, respectively, of the complex number obtained from

$$A + jB = \frac{Z_4 I_2 - Z_4 I_1}{V_3},$$

where

$$I_1 = \frac{V_3}{Z_T},$$

$$I_2 = \frac{V_3 - 2I_1 Z_1}{Z_2},$$

$$Z_T = \frac{2Z_2Z_3 + Z_2Z_4 + 2Z_1Z_2 + 4Z_1Z_3 + 2Z_1Z_4}{Z_2 + 2Z_3 + Z_4},$$

$$Z_1 = R_1 + \frac{1}{sC_1} = R_2 + \frac{1}{sC_2},$$

$$Z_2 = \frac{1}{sC_3},$$

$$Z_3 = sL_1 = sL_2,$$

$$Z_4 = \frac{(R_3/sC_4)}{R_3 + (1/sC_4)} \quad \text{(for track 79)},$$

$$Z_4 = \frac{[(R_3 + R_4)/(R_3R_4)][s(C_4 + C_5)]^{-1}}{(R_3 + R_4)/(R_3R_4) + (1/s)(C_4 + C_5)} \quad \text{(for track 0)},$$

$$s = 2j\Pi f; \quad j = \sqrt{-1}$$

$$v_3 = 0.3.$$

where

L_1, L_2 : inductance
C_1, C_2, C_3, C_4, C_5 : capacitance
R_1, R_2, R_3, R_4 : resistance
f : frequency
Z_1, Z_2, Z_3, Z_4, Z_T : impedance
I_1, I_2 : current
V_1, V_2, V_3 : voltage
s : angular frequency.

Note: It is possible to express A and B as explicit functions of C_1, R_1, L_1, C_3, R_3, C_5, R_4, and f, but this function will be highly cumbersome.

Appendix 2: Procedure for the Local Iterative Search

Local search for the first potential solution (2 3 4 4) stops after six iterations. These six iterations are given below:

Combination 2 3 4 4 means R_1 = 220, L_1 = 330, C_3 = 1200, and R_3 = 2200.

ITERATION 1

R_1 =	180	200	220	240	270
L_1 =	270	300	330	360	390
C_3 =	1000	1100	1200	1300	1500
R_3 =	1800	2000	2200	2400	2700

Minimum r = 0.2125;
Combination: 4 1 4 5

ITERATION 2
R_1 = 200 220 240 270 300
L_1 = 220 240 270 300 330
C_3 = 1100 1200 1300 1500 1600
R_3 = 2200 2400 2700 3000 3300
Minimum r = 0.2093;
Combination: 2 1 5 5

ITERATION 3
R_1 = 180 200 220 240 270
L_1 = 180 200 220 240 270
C_3 = 1300 1500 1600 1800 2000
R_3 = 2700 3000 3300 3600 3900
Minimum r = 0.2084;
Combination: 4 4 2 5

ITERATION 4
R_1 = 200 220 240 270 300
L_1 = 200 220 240 270 300
C_3 = 1200 1300 1500 1600 1800
R_3 = 3300 3600 3900 4300 4700
Minimum r = 0.2073;
Combination: 5 5 1 5

ITERATION 5
R_1 = 240 270 300 330 360
L_1 = 240 270 300 330 360
C_3 = 1000 1100 1200 1300 1500
R_3 = 3900 4300 4700 5100 5600
Minimum r = 0.2066;
Combination: 5 5 1 5

ITERATION 6
R_1 = 300 330 360 390 430
L_1 = 300 330 360 390 430
C_3 = 820 910 1000 1100 1200
R_3 = 4700 5100 5600 6200 6800
Minimum r = 0.2064;
Combination: 3 3 3 4

The iterative local search stops at iteration 6. The final solution and the corresponding value of r is considered. In this example, the final solution is (R_1, L_1, C_3, R_3) = (360, 360, 1000, 6200) and the value of r is 0.2064.

Appendix 3: Layout of L_{18} (2×3^7) Experiment for Track 79

EXP. NO.	FACTOR/COLUMN e 1	C_1 2	R_1 3	L_1 4	C_3 5	R_3 6	e 7	e 8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Appendix 4: Layout of L_{18} (2×3^7) Experiment for Track 0

	FACTOR/COLUMN							
EXP. NO.	e 1	C_1 2	R_1 3	L_1 4	C_3 5	R_3 6	C_5 7	R_4 8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Appendix 5: Layout of L_{18} (2×3^7) for Assignment of Error Factors

	ERROR FACTORS							
EXP. NO.	e 1	C_1 2	R_1 3	L_1 4	C_3 5	R_3 6	C_5 7	R_4 8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

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