Part IV

Signal-to-Noise Ratio

Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

11 Introduction to the Signal-to-Noise Ratio

11.1. Definition 224
11.2. Traditional Approach for Variability 224
11.3. Elements of the SN Ratio 224
11.4. Benefits of Using SN Ratios 225
Direct Relationship with Economy 225
Simplification of Interaction Calculations 227
Efficient Robust Design Achievement 227
Efficient Adjustment or Calibration 227
Efficient Evaluation of Measuring Systems 228
Reduction of Product/Process Development Cycle Time 228
Efficient Research for a Group of Products: Robust Technology Development 228
11.5. Various Ideal Functions 228
Machining Technology 229
Injection Molding Process 229
Fuel Delivery System 229
Engine Idle Quality 230
Wiper System 230
Welding 230
Chemical Reactions 230
Grinding Process 232
Noise Reduction for an Intercooler 232
Wave Soldering 233
Development of an Exchange-Coupled Direct-Overwrite Magnetooptical Disk 233
Equalizer Design 233
Fabrication of a Transparent Conducting Thin Film 233
Low-Pass Filter Design 233
Development of a Power MOSFET 234
Design of a Voltage-Controlled Oscillator 234
Optimization of an Electrical Encapsulant 234
Ink Formulation 234
11.6. Classification of SN Ratios 234
Continuous Variables and Classified Attributes 234
Classification Based on Intention 236

Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

Fixed and Multiple Targets 236
Classification Based on Input and Output 236
Other Ways of Classifying SN Ratios 237
References 237

11.1. Definition

The signal-to-noise ratio (SN ratio) is a measurement scale that has been used in the communication industry for nearly a century. A radio measures the signal or the wave of voice transmitted from a broadcasting station and converts the wave into sound. The larger the voice sent, the larger the voice received. In this case, the *magnitude of the voice* is the input signal, and the *voice received* is the output. Actually, the input is mixed with the audible noise in the space. Good measuring equipment catches the signal and is not affected by the influence of noise.

The quality of a measurement system is expressed by the ratio of signal and noise. SN ratio is expressed in decibels (dB). For example, 40 dB means that the magnitude of the output is 10,000 times the magnitude of noise. For example, if the SN ratio of a transistor radio is 45 dB, the power of the input is about 30,000 times the magnitude of noise. The larger the SN ratio, the better the quality.

Taguchi has generalized the concept of SN ratio as used in the communication industry and applied it for the evaluation of measurement systems as well as for the function of products and processes.

11.2. Traditional Approach for Variability

Traditionally, the analysis of data for variability has been traditionally studied by decomposing data into deviation and variation. Such an approach is applicable only when one object is to be measured. Using a watch as an example, say that we want to measure the variability after 24 hours. But that is not the best way to measure. It is important to determine the error within a certain range. We would want to measure the variation of the watch from actual time at any time. This same principle is true for a scale, which has a smaller error when objects of different weight are measured. The quality of any measurement system must be evaluated using the dynamic characteristics of the items measured.

In the automobile industry, the quality of measurement systems is traditionally evaluated by studying repeatability, reproducibility, and stability. *Repeatability* is the variability when the *same person* measures the *same sample* repeatedly. *Reproducibility* is the variability when *different persons* measure the *same sample*. *Stability* is the variability when the *same person* measures the same sample repeatedly at *different times*. But those three types of variability belong to one category: *noise*. Using quality engineering, there is no necessity to study these three types of variability separately. It is only necessary to conduct a study including signal.

11.3. Elements of the SN Ratio

Conceptually, the SN ratio is the ratio of signal to noise in terms of power. Another way to look at it is that it represents the ratio of sensitivity to variability.

In a measurement system, the input-to-output relationship is studied. The true value of the object is the input, and the result of measurement is the output. In a good measuring system, the result of measurement must be proportional to the true value; thus the input/output relationship must be linear. A good measurement system must also be sensitive to different inputs (whatever different objects are measured); thus, the slope showing the input/output relationship must be steep. Of course, the variability must be small. When an SN ratio is used to evaluate a measuring system, the three elements sensitivity, slope, and variability are combined into a single index. As a result, engineers can easily evaluate and improve a system by using SN ratios. Figure 11.1 shows the three elements in the SN ratio.

There are two modes in the SN ratio: dynamic and nondynamic. The measurement system described above belongs to the *dynamic* mode. In the design of a product for a fixed target, there is no need to adjust the target from time to time. For example, we may want to design an electric circuit having an output of 110 V. Once the product is designed and put into production, it is not necessary to change the output voltage as long as we want to manufacture and sell this particular product only. In a nondynamic mode, therefore, mean is considered as being equivalent to sensitivity and is placed in the numerator of the SN ratio. In this case, the SN ratio is the ratio of average to variability in square terms. But in a dynamic system, such as a control system, there is always a need to adjust the output to the target by varying a certain input signal. In such a case, *adjustability* becomes critical for the design. Here it is important that the input/output relationship be proportional, or linear. In other words, linearity becomes critical for adjusting systems. The better the linearity and the steeper the input/output relationship, the better the adjustability. Therefore, the slope is used as being equivalent to sensitivity and is placed in the numerator of the SN ratio.

The concept of the dynamic-type SN ratio evolved further in the area of technology development. The activity is defined by the development of technology for a group of products instead of developing a particular product with a fixed target, so as to avoid redundant research and thereby reduce research and development cycle time. (For technology development, see Chapter 14.)

11.4. Benefits of Using SN Ratios

There are many benefits to using SN ratios in quality engineering, as discussed below.

Direct Relationship with Economy

The SN ratio is defined as follows:

$$\text{SN ratio} = \frac{\text{power of signal}}{\text{power of noise}} = \frac{(\text{sensitivity})^2}{(\text{variability})^2} = \frac{\beta^2}{\sigma^2} \tag{11.1}$$

As seen from equation (11.1), the SN ratio is the ratio of sensitivity to variability squared. Therefore, its inverse is the variance per unit input. In the loss function, the loss is proportional to variance. Therefore, monetary evaluation is possible.

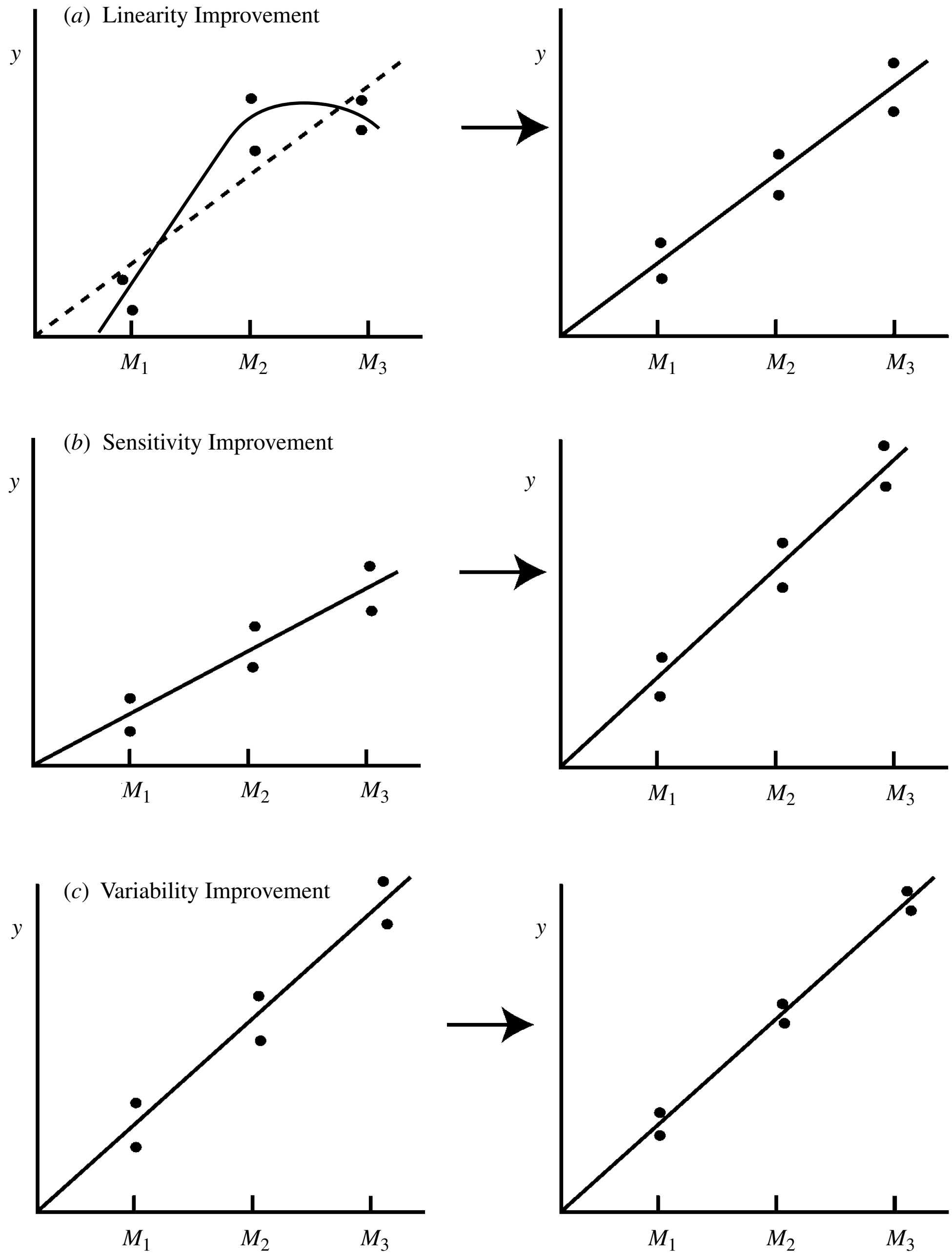

Figure 11.1
Three elements of SN ratio

Simplification of Interaction Calculations

In the early days of quality engineering applications, research for robustness was conducted by discovering the interactions between control and noise factors. When there is a significant interaction between a control and a noise factor, it shows that different levels of a control factor behave differently under different noise factors. If this is true, there is a possibility that robustness can be improved. Such a study method was called *direct product design,* where the experiment was laid out in such a way that every interaction between a control and a noise factor may be calculated. But such calculations were so tedious that many people had to work full-time on them. By using the SN ratio, such calculations are no longer necessary. Instead, a comparison of SN ratios between control factor levels is made, and the one with a higher SN ratio is selected as the robust condition.

Efficient Robust Design Achievement

This is one of the most important benefits of using the SN ratio in product or process design. Using traditional methodology, engineers tend to design a product or a process by meeting the target first instead of by maximizing robustness first. This “hitting target first” approach is very inefficient, for the following reasons. After the target is met, the engineer has to make sure that the product works under noise conditions: for example, temperature.

If the product does not work at a certain extreme temperature, the engineer has to change or adjust the design parameters to meet the target. But while studying the effects of temperature, the engineer needs to keep other noise factors, such as humidity, fixed. If the product does not work in a certain humidity environment, the engineer tries to vary some parameter levels and change parameter levels again to meet the target. In the first trial, where the aim was to meet the target at a certain temperature, the control factor levels selected would probably be different from the control factor levels selected in the second trial, where the aim was to meet the target at a certain humidity condition.

To meet the target under a certain temperature as well as under a certain humidity condition, the study must be started again from the beginning. The engineer has to do the same for any other noise conditions that ought to be considered. Generally, there are a lot of noise factors. Not only is this type of approach tedious and time consuming, it is not always successful. Designing in this fashion is similar to solving many simultaneous equations, not by calculation but by trial-and-error experimentation on hardware.

In contrast, use of the SN ratio enables the engineer to maximize robustness simply by selecting the levels of control factors that give the largest SN ratio, where many noise factors are usually compounded into one. After robustness is achieved, the next step is to adjust the mean to the target by adjusting the level of a control factor, the factor having a maximum effect on sensitivity and a minimum effect on robustness. In this way it is possible that meeting the target will have scant effect on robustness. Very often, the efficiency of research can be improved by a factor of 10, 100, or 1000.

Efficient Adjustment or Calibration

Linearity, one of the three elements in an SN ratio discussed earlier, is very important for simplifying adjustment in product or process design and for calibration in measurement systems. Because the relationship between the value of an SN ratio and linearity is so simple and clear, adjusting the output of control systems and calibration of measurement systems is easier than when traditional methods are used. When the input/output relationship is not linear, deviation from linearity is evaluated as the error after the decomposition of variation. Therefore, the SN ratio becomes smaller.

Efficient Evaluation of Measuring Systems

In a measuring system, there are two types of calibration: zero-point calibration and slope calibration. *Zero-point calibration* is used to calibrate the output to zero when the input is equal to zero (when nothing is measured). *Slope calibration* is used to calibrate the input/output ratio (slope) to 1. Since the slope of the input/output becomes 1, the inverse of the SN ratio is equal to the variance of the measuring system. *Such estimation is possible without conducting physical calibration.* This greatly improves the efficiency of measurement system optimization.

Reduction of Product/Process Development Cycle Time

An SN ratio is written and calculated based on the ideal function of a product or process. When the input/output relationship of the ideal function is related to energy, the effects of control factors are cumulative (additive).

While interaction between a control factor and a noise factor enables us to find a robust condition, interaction between control factors shows the inconsistency of conclusions. If the conclusions are inconsistent, the conclusion obtained from a study might be different when control factors change. How to deal with or avoid interactions between control factors is one of the most important issues in quality engineering.

Various case studies in the past have shown that using SN ratios based on the ideal function that relates to input/output energy transformation enables us to avoid interactions between control factors. This means that the conclusions obtained in a small-scale laboratory study can be reproduced downstream in a large-scale manufacturing process and in the marketplace. That is why using dynamic SN ratios can reduce product/process development cycle time.

Efficient Research for a Group of Products: Robust Technology Development

Traditionally, research is conducted every time a new product is planned. But for a group of products having the same function within a certain output range, it would be wasteful to conduct research for each product. Instead, if we could establish an appropriate SN ratio based on the ideal function of a group of products and maximize it, the design of a specific product with a certain output target would be obtained easily by adjusting the input signal. This approach, called *robust technology development,* is a breakthrough in quality engineering. It is believed that such an approach will soon become the core of quality engineering.

11.5. Various Ideal Functions

The traditional problem-solving approach generally brings about quality improvement. In the problem-solving approach, root-cause analysis is important, and the engineer analyzes whatever data are measured (such as symptoms or defect rates, called *responses*). There is no consideration of what type of data should be avoided and what type of data must be analyzed. In the Taguchi Methods Symposium held by the American Supplier Institute in 1989, the theme was: “To get quality, don’t measure quality.” This meant that to improve quality, do not measure and analyze “response,” because the conclusions obtained from such analyses are not reproducible in most cases.

Instead, we should try to think about the *ideal function* and use for analysis the dynamic SN ratio based on that ideal function. It is not an easy task to determine the ideal function, and it takes a lot of discussion. The ideal function is different from product to product, from one system to another, and there are no generalizable approaches or solutions. Ideal functions must be discussed case by case.

Generally, it is desirable that the ideal function be identified based on the product function, which is energy related, since energy has additivity. This type of ideal function is called a *generic function.* A generic function can be explained in physics, for example, by Ohm's law or Hooke's law. In some cases, however, the data to be collected for the study of such relationships are not available, due to lack of measurement technology. In such cases, a function that describes an objective may be used. This is called the *objective function.* Many published cases are available for engineers to use as a reference to establish an ideal function. Following are some examples.

Machining Technology

In a machining process, the dimensions of an actual product are traditionally measured for analysis. To reduce error and to optimize the process to cover a range of the products the machine can process, it is recommended that test pieces be used for study.

In a study entitled "NC Machining Technology Development [1], the concept of *transformability* was developed. The ideal function in this case was that product dimension be proportional to programmed dimension:

$$y = \beta M,$$

where y is the product dimension, β a constant, and M the programmed dimension. The function of machining was studied using different ideal functions [2]. There were two functions in the study: function 1, $y = \beta M$, where y is the square root of total power consumption and M is the square root of time (per unit product); and function 2, $y = \beta M$, where y is the square root of total power consumption and M is the square root of total amount removed. The objective of the first function is to improve productivity, and the second is to improve machining quality.

Injection Molding Process

In the injection molding process, quality characteristics such as reject rate, flash, or porosity have traditionally been measured. In a study of a carbon fiber–reinforced plastic injection molding process [3], the following function was studied: $y = \beta M$, where y is the product dimension and M is the mold dimension. In a study of an injection molding experiment [4], the function above was used together with another function, $y = \beta M$, where y is the deformation and M is the load. In this case study, the former function was the objective-related function, whereas the latter belonged to the generic function.

Fuel Delivery System

An automobile's fuel delivery system must provide a consistent supply of liquid fuel in the expected operating range, regardless of external (environmental) conditions. Traditionally, symptoms such as difficulty of starting, rolling engine idles, and engine stumbles have been measured. In a study conducted by Ford Motor Company [5], the ideal function was defined as follows. The pump efficiency is defined as

$$\text{pump efficiency} = \frac{QP}{VI}$$

where Q is the fuel pump flow rate, P the fuel system back pressure, V the fuel pump voltage, and I the fuel pump current. Letting the fuel pump flow rate be y, the system input signal be M (= VI), and the adjustment signal be M^* (= P), the output response, y, is rewritten as

$$y = \frac{\beta M}{M^*}$$

Engine Idle Quality

Idle quality is a major concern on some motor vehicles. It contributes to the vibration felt by vehicle occupants. A commonly used process for evaluating engine idle quality involves running an engine at idle for several cycles and collecting basic combustion data, such as burn rates, cylinder pressure, air/fuel ratio, and actual ignition timing.

In a study conducted by Ford Motor Company [6], it was considered that *indicated mean effective pressure* (IMEP) is an approximately linear function of fuel flow at idle when air/fuel ratio, ignition timing, and some of the engine combustion parameters were held constant under steady operation: $y = \beta M$, where y is the IMEP and M is the fuel flow.

Wiper System

The function of a wiper system is to clear precipitation (rain, snow, etc.) and foreign material from a windshield to provide a clear zone of vision. An annoying phenomenon that affects the performance of a windshield wiper system is wiper chatter. Chatter occurs when the wiper blade does not take the proper set and "skips" across the windshield during operation, potentially causing deterioration in both acoustic and wiping quality.

The characteristics measured traditionally to improve the quality of a wiper system are chatter, clear vision, and uniformity of wiper pattern, quietness, and life. The ideal function in a study [7] was defined as "the actual time for a wiper to reach a fixed point on the windshield for a cycle should be the same as the theoretical time (ideal time) for which the system was designed," expressed as

$$y = \beta M,$$

where y is the actual time and M is the theoretical time (1/rpm of the motor).

Welding

In welding processes, traditional measurements include appearance, maximum strength or reject rate, and so on. A study conducted for a welding process [8] defined the ideal function as $y = \beta MM^*$, where y is the force, M the displacement, and M^* the length. In a study of spot welding conditions [9], the ideal function $y = \beta M$, where y is the current and M is the voltage, was used. This means that if the welding is performed ideally, the welded unit is as uniform as the material itself; therefore, the voltage–current relationship must be proportional.

Chemical Reactions

In the manufacture of chemical products, the determination of conditions favoring synthesis reactions greatly affects quality and cost. Traditionally, yield of product has been used as the quality characteristic. Such digital-type characteristics are not recommended in quality engineering. One of the most important issues in chemical reactions is to control reaction speed.

Figure 11.2 shows the case of a chemical reaction with side reactions. In the figure we have

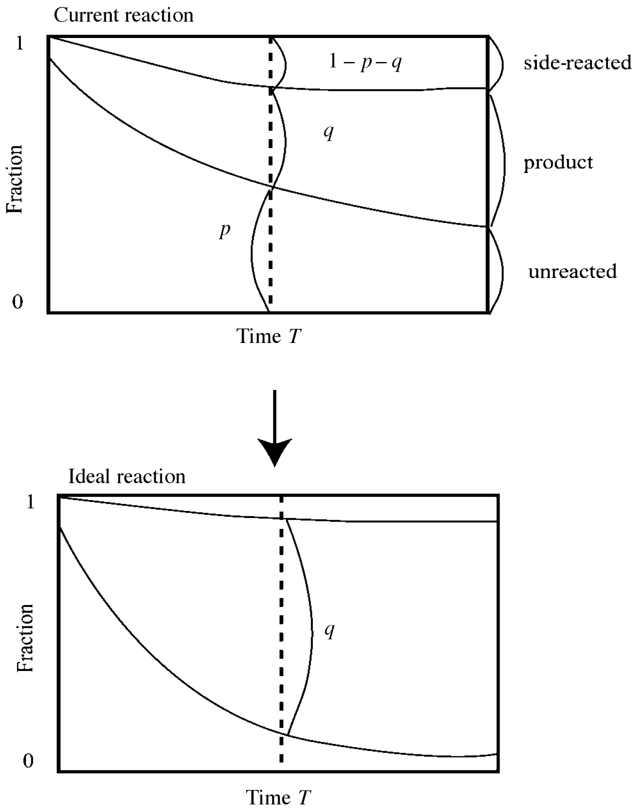

Figure 11.2 Dynamic operating window

p: fraction unreacted

q: fraction of reacted product

T: time

Letting

β_1: total reaction speed

β_2: side reaction speed

the fraction of total reaction is written as

$$p = e^{-\beta_1 T}$$

Setting

$$M_1 = \ln \frac{1}{p}$$

the function is written as

$$M_1 = \beta_1 T$$

When there are side reactions, the fraction of side-reacted products is written as

$$1 - p - q = e^{-\beta_2 T}$$

Setting

$$M_2 = \frac{1}{1 - p - q}$$

the fraction of side reactions is written as

$$M_2 = \beta_2 T$$

In a study by Toa Gosei Chemical Company [10], the equations above were used for calculation of the SN ratio. As a result, the reaction was increased 1.8-fold above the current condition, which means that the reaction time can be cut approximately in half.

Grinding Process

The dry developer used for electrophotographic copiers and printers consists of toner and carrier. The particle size of the developer is one of the physical properties that has a strong influence on image quality.

Size distribution typically was analyzed as classified data. Quite often, yield was used for analysis. In a study of developing a technique for improving uniformity and adjusting particle size conducted by the Minolta Camera Company [11], the ideal function was $y = \beta/M$, where y is the particle size and M is the grinding energy. In a later study [12], conducted by the same company, a different ideal function was used. Since particles are ground by high-pressure air, the collision of particles in the grinding process is similar to the collision between molecules in chemical reactions.

In this case, the portion with a particle size larger than the upper specification limit was treated as unreacted, and the portion with a particle size smaller than the lower specification limit was treated as overreacted. The ideal functions, similar to the chemical reaction (i.e., the total reaction and side reactions) were used to optimize the grinding process.

Noise Reduction for an Intercooler [13]

Intercoolers are used with turbochargers to increase the output power of car engines. The output power of an engine is determined by the amount of mixed gas that is sucked into the engine cylinder. The more gas sucked in, the higher the feeding efficiency by compressing the mixed air and consequently, raising the air pressure above the atmospheric pressure.

When the airflow resistance inside the cooler is high, the cooling efficiency is reduced and noise is often noted. Before this study, the problem-solving approach has been to detect causes by measuring audible noise level, but without success. From the viewpoint of the product function, it is required that the airflow resistance be low and the flow rate be uniform. The engine output power varies with driving speed. The airflow changes as the accelerator is pushed down. Therefore, it is ideal that the airflow rate in the intercooler be proportional to the amount of air. As the rpm rate of the turbocharger varies under different driving conditions, it is also ideal for the airflow rate to vary proportional to the rpm rate of the turbocharger. The ideal function was defined as $y = \beta MM^*$, where y is the airflow speed of the intercooler, M the amount of airflow, and M^* the rpm rate of the turbocharger.

Wave Soldering [14]

In the manufacture of high-density printed circuit boards, quality characteristics such as bridge or nonsoldering have been used to improve quality. The yields of these characteristics were studied. In the early stage of quality engineering, nondynamic characteristics such as smaller-the-better and larger-the-better SN ratios were used. These two characteristics were combined to be the *nondynamic operating window SN ratio*.

In this study, voltage and current relationships were used as the ideal function. The relationship between current and cross-sectional area was also studied. Thus, there were two signal factors. To maximize the SN ratio of the voltage–current relationship is to optimize the product function. To maximize the SN ratio of the current and cross-sectional area is to optimize manufacturability. In this way, product- and manufacturing-related functions can be studied simultaneously using only one index: an SN ratio with double signals. It is truly a *simultaneous engineering* or *concurrent engineering* approach, as shown by $y = \beta MM^*$, where y is the current, M the voltage, and M^* the cross-sectional area.

Development of an Exchange-Coupled Direct-Overwrite Magnetooptical Disk [15]

Magnetooptical disks are used as computer memory components. In early versions of the products, information already recorded had to be erased before rerecording, taking a long time. To save on recording time, developers tried to develop direct-overwrite MO disks. However, disks consisted of multiple complicated layers. After years of work, there was little success.

Using the quality engineering approach, the ideal function was defined as follows: "The length of magnetic mark is proportionally transformed to the time of light emitted from the laser." In the past, interactions between control factors had been studied. By use of the SN ratio based on the ideal function as defined, the time required for development was greatly reduced.

Equalizer Design [16]

One of the most important quality items for amplifiers is that the gain of frequency is flat. However, it is not quite flat for amplifiers with a wide frequency range. To make the response flat, a circuit called an *equalizer* is connected to compensate for the declining gain.

Using two-stage optimization, the robustness of the equalizer was optimized; the control factors that least affect SN ratio but were highly sensitive were used to tune them so that the gain became flat. The ideal function is that the output voltage (complex number) is proportional to the input voltage.

Fabrication of a Transparent Conducting Thin Film [17]

Transparent conducting flat films are used as flat displaying devices for computers. This type of film is used because of its high conductivity and good pattern quality following etching.

In manufacturing, an electron-beam-heating vacuum deposition process was used. Traditionally, resistance and transparency were used for quality measurement. In this study, the ideal function was defined as $y = \beta MM^*$, where y is the current, M the film thickness, and M^* the voltage. The result showed that the standard deviation was reduced by the fraction 1.83, and conductivity was increased 1.16-fold.

Low-Pass Filter Design [18]

In the design of ac circuits, root mean squares have traditionally been used. By using complex numbers in parameter design, the variability of both the amplitude and phase of the output can be reduced. Therefore, a system whose input and output are expressed by sine waves should use complex numbers.

In the study, amplitude was varied under a fixed frequency, and the proportionality between the input and the output in complex numbers was measured to optimize the stability. After optimization, a 3.8-dB gain was confirmed.

Development of a Power MOSFET [19]

A power MOSFET is used as a reliable switching device in automobile electronics. It is required that the *on* resistance be low so that the unit may be miniaturized. Traditionally, quality characteristics such as film thickness or bonding strength were measured. In this study, the ideal function was defined as $y = \beta M$, where y is the voltage drop and M is the current. From the results, the standard deviation was reduced by a factor of 8, and the resistance was reduced by a factor of 7.

Design of a Voltage-Controlled Oscillator [20]

Voltage-controlled oscillators are used in wireless communication systems. The performance of those oscillators is affected by environmental conditions and the variability of component parts in printed circuit boards. Traditionally, quality characteristics such as transmitting frequency or output power were used for evaluation. In this study, the function $y = \beta MM^*$, where y is the output (complex number), M the dc voltage, and M^* the ac voltage, was used. A 7.27-dB gain was obtained after tuning.

Optimization of an Electrical Encapsulant [21]

An encapsulant is used to isolate the elements in a night-vision image intensifier. In the past, cycle testing was used to evaluate reliability. In this study, the following ideal function, $y = \beta M/M^*$, where y is the current leakage, M the applied voltage, and M^* the electrode spacing, was used. The SN ratio of the encapsulation system was improved by 3.8 dB compared to the standard conditions, and the slope was reduced to 80%.

Ink Formulation [22]

In the development of ink used in digital printers, characteristics such as permeability, stability, flow value, and flexibility have commonly been used. But the results of the use of these characteristics were not always reproducible.

In a digital printer, a document is scanned and the image is converted to electric signals. The signals are then converted to heat energy to punch holes on the resin film, which forms the image on paper. The ideal function for the ink development is that the dot area of the master is proportional to the dot area printed.

11.6. Classification of SN Ratios

Continuous Variables and Classified Attributes

There are two types of data: continuous variables and classified attributes. Voltage, current, dimension, and strength belong to the *continuous variables* category. In quality engineering, *classified attributes* are divided into two groups: *two-class* classified attributes and *three-or-more-class* classified attributes. The SN ratio equations are different for different types.

From the quality engineering viewpoint, it is recommended that one avoid using attribute data, for the followings reasons. First, attribute data are less informative. For example, if a passing score in school is 60, students having scores of 60 and 100 are classified equally as having passed, whereas a student with a grade of 59 is classified as having failed. There is a big difference between the two students who passed, but little difference between a student with a score of 60 and one with a score of 59.

Second, attribute type data are inefficient. In athletic competition, it is difficult to draw a conclusion from the result of two teams playing only one game. We do not conclude that the winning team is going to have a 100% chance to beat the defeated team. In tennis, for example, a champion is commonly declared after one player and wins two of three sets or three of five sets.

The third, and most serious, problem encountered when using attribute data is the possibility of developing interactions. In one study of a welding process, yield was studied. Yield looks like a continuous variable, but it is the fraction represented by the number of nondefective pieces divided by the total number of pieces. A nondefective piece may be counted as 1 and a defective as 0. For example, a one-factor-at-a-time experiment was conducted to compare two control factors, A and B.

$$A_1B_1\text{:}\quad \text{yield} = 40\%$$

$$A_2B_1\quad \text{yield} = 70\%$$

$$A_1B_1\quad \text{yield} = 40\%$$

$$A_1B_2\quad \text{yield} = 80\%$$

From the results, one might conclude that the best condition would be A_2B_2 and the yield might be over 90%. But one might be surprised if a confirmatory experiment under condition A_2B_2 resulted in less than 40%. This shows the existence of an interaction between A and B. Let's assume the following levels of A and B:

A_1: low current

A_2: high current

B_1: short welding time

B_2: long welding time

Condition A_1B_1 was low current and short welding time; therefore, too little energy was put into the system, and the result was: no weld. Conditions A_2B_1 and A_1B_2 have more energy going in and the yields are higher. But under condition A_2B_2, high current and long welding time, the yield was low because too much energy was put into the system and the result was: burnthrough. It is seen that if 0–1 data were used, the two extremely opposite conditions are considered equally bad. It is also seen that the superiority and inferiority of factor A is inconsistent, depending on the condition of another factor, B, and vice versa. The interactions between control factors indicate inconsistency of conclusions. We should avoid using 0–1 data. But in some cases, continuous data are unavailable because of a lack of technology. In such cases it is necessary to convert the data so that interactions may be avoided.

Following is an example of data collection. In the case of welding, samples are collected from each welding condition. From each sample, load and deformation are considered as the input and output, respectively. The SN ratio is calculated from the relationship above. There will be SN ratios for A_1B_1, A_2B_1, A_1B_2, and A_2B_2. The effect of A is compared by the average SN ratios of (A_1B_1, A_1B_2) and (A_2B_1,

A_2B_2), and the effect of B is compared by the averages of (A_1B_1, A_2B_1) and (A_1B_2, A_2B_2).

Classification Based on Intention

There are two types of SN ratios, based on intention: passive and active. The SN ratio used in measurement is called *passive*. An object, the input signal, is measured, and from the result, the true value of the input signal is estimated. That is why the SN ratio is called passive. For the passive type we have:

- *Input:* true value to be measured
- *Output:* measured value

In the *active* type, a signal is put into a system to change the output:

- *Input:* intention
- *Output:* result

For example, a steering wheel is turned to change the direction of a car. The output is changed by intention, so it is an active output. In control systems or product/process design, the parameters for tuning are of the active type. The difference is in the way that the signal factor is considered. Although the intentions are different, the equations and calculation of the SN ratio used are the same.

Fixed and Multiple Targets

Dynamic SN ratios are used to study either multiple targets or a certain range of targets, whereas nondynamic SN ratios are used to study a single target. The former includes three aspects: linearity, sensitivity, and variability. The latter includes two aspects: sensitivity and variability.

In earlier stages of quality engineering, nondynamic characteristics were commonly used. There are three types of nondynamic characteristics: nominal-the-best, smaller-the-better, and larger-the-better. *Nominal-the-best characteristics* are used to hit the target after reducing variability. The output is ideally equal to the target. *Smaller-the-better characteristics* are used to reduce both average and variability. The output is ideally equal to zero. *Larger-the-better characteristics* are used to maximize average and minimize variability. Ideally, the output is equal to infinity.

Dynamic SN ratios are more powerful and efficient; therefore, it is recommended that one use them as much as possible.

Classification Based on Input and Output

As described earlier, quality characteristics are classified as continuous variables, and discrete or classified attributes, the latter also being referred to as digital. SN ratios are classified into the following four cases:

Case	Input	Output
1	Continuous variables	Continuous variables
2	Continuous variables	Digital
3	Digital	Continuous variables
4	Digital	Digital

Case 1 is the type that occurs most frequently. Driving a car, for example, the steering wheel angle change is the input and the turning radius is the output.

Case 2 occurs in digital functions, such as an on–off system using temperature as the signal. For case 3, such as a transmitter in a communication system, the input is digital (mark and space) and the output is voltage. Case 4 occurs often in such chemical processes as separation, purification, and filtration.

Other Ways of Classifying SN Ratios

SN ratios can be classified based on the number of signal factors: single signal factors, double signal factors, multiple signal factors, and no signal factors. SN ratios with single signal factors occur most frequently. These without signal factors are of the nondynamic type. In Chapter 12, we illustrate the most important and frequently applied case: the SN ratio for continuous variables.

References

1. K. Ueno et al., 1992. NC machining technology development. Presented at the American Supplier Institute Symposium.
2. Kazuyoshi Ichikawa et al., 2000. Technology development and productivity improvement of a machining process through the measurement of energy consumed during on and off mode. Presented at the American Supplier Institute Symposium.
3. K. Ueno et al., 1992. Stabilization of injection molding process for carbon fiber reinforced plastic. Presented at the American Supplier Institute Symposium.
4. A. Obara et al., 1997. A measurement of casting materials for aerocraft using quality engineering approaches. *Quality Engineering Forum*, Vol. 5, No. 5.
5. J. S. Colunga et al., 1993. Robustness of fuel delivery systems. Presented at the American Supplier Institute Symposium.
6. Waheed D. Alashe et al., 1994. Engine idle quality robustness using Taguchi methods. Presented at the American Supplier Institute Symposium.
7. M. Deng, et al., 1996. Reduction of chatter in a wiper system. Presented at the American Supplier Institute Symposium.
8. Mitsugi Fukahori, 1995. Parameter design of laser welding for lap edge joint piece. *Journal of Quality Engineering Forum*, Vol. 3, No. 2.
9. Shinichi Kazashi et al., 1996. Optimization of spot welding conditions by generic function. *Journal of Quality Engineering Forum*, Vol. 4, No. 2.
10. Yoshikazu Mori et al., 1995. Optimization of the synthesis conditions of a chemical reaction. *Journal of Quality Engineering Forum*, Vol. 3, No. 1.
11. Hiroshi Shibano et al., 1994. Establishment of particle size adjusting technique for a fine grinding process for developer. *Journal of Quality Engineering Forum*, Vol. 2, No. 3.
12. Hiroshi Shibano et al., 1997. Establishment of control technique for particle size in roles of fine grinding process for developer. *Journal of Quality Engineering Forum*, Vol. 5, No. 1.
13. Hisahiko Sano et al., 1997. Air flow noise reduction of inter-cooler system. Presented at the Quality Engineering Forum Symposium.
14. S. Kazashi et al., 1993. Optimization of a wave soldering. *Journal of Quality Engineering*, Vol. 1, No. 3.
15. Tetsuo Hosokawa et al., 1994. Application of QE for development of exchange-coupled direct-overwrite MO disk. *Journal of Quality Engineering Forum*, Vol. 2, No. 2.

16. Yoshishige Kanemoto, 1994. Robust design and tuning for an equalizer. *Journal of Quality Engineering Forum*, Vol. 2, No. 5.
17. Yoshiharu Nakamura et al., 1995. Fabrication of transparent conducting thin films. *Journal of Quality Engineering Forum*, Vol. 3, No. 1.
18. Satoshi Takahashi, 1995. Parameter design of a low pass filter using complex numbers. *Journal of Quality Engineering Forum*, Vol. 3, No. 4.
19. K. Makabe et al., 1996. Technology development of drain electrode process for power MOSFET. *Journal of Quality Engineering Forum*, Vol. 4, No. 2.
20. Fumikazu Harazono, 1995. Robust design of voltage controlled oscillator. *Journal of Quality Engineering Forum*, Vol. 3, No. 4.
21. Lapthe Flora et al., 1995. Optimization of electrical encapsulant. Presented at the American Supplier Institute Symposium.
22. Takeshi Nojima et al., 1996. Optimization of ink prescription. *Journal of Quality Engineering Forum*, Vol. 4, No. 1.