18 Things You Should Know About SPC for Gears

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Statistical Process Control (SPC) and statistical methods in general are useful techniques for identifying and solving complex gear manufacturing consistency and performance problems. Complex problems are those that exist in spite of our best efforts and the application of state-of-the-art engineering knowledge.

Statistical methods approach these problems *results-backward* as opposed to *knowledge-forward*. For example, the knowledge-forward approach would seek consistencies in gear profile, lead, runout, etc., with the assumption that consistencies improve performance. The results-backward approach, on the other hand, will analyze the situations starting from assembly performance. It will then relate performance variation to specific gear characteristics.

In other words, we use our gear expertise in a knowledge-forward approach. When this fails to solve a problem, we should use the results-backward approach. Once critical gear characteristics are determined, we can begin attempting to achieve consistency.

Let us begin by describing six SPC fundamentals and six statistical applications for gear design and manufacturing. These will lead us to an effective sequence for applying statisical methods.

Six Fundamentals of SPC

SPC is only a subset of statistical methods helpful in analyzing complex problems. These methods can be a useful set of tools for carrying out investigations of our manufacturing processes. SPC can chart the output of any process to examine whether the process condition is stable, has an excessive variation or is off-target. Furthermore, SPC can offer clues to strategies for correcting these conditions. Additional statistical tools can help us establish relationships between problematic process conditions and suspect variables.

1. ***Multivariate (T^2) Charts*** are useful in understanding and controlling correlated performance characteristics. The performance characteristics of assemblies, such as noise, durability, ease of maneuverability, etc., are likely to be correlated. That means, for example, that trying to reduce the noise may result in losing maneuverability, or improvement of maneuverability may result in a reduced durability, and so on. The problems associated with correlated characteristics can only be defined with the use of a multivariate chart (see Fig. 1).

2. ***Multivariate (T^2) Charts*** are also useful in understanding and controlling input gear characteristics. Gear characteristics are most likely to be correlative because they are generated simultaneously. In practical terms, we can state that when characteristics are correlated, each individual characteristic can be within specification, and yet jointly they constitute a statistical instability.

3. ***Multi-vari Charts*** are useful in analyzing size as well as shape problems. For example, four teeth on a gear measured by conventional means may all individually be within specification, and yet differences among them may be the root cause of a problem. A proper way to define a problem that takes into account characteristics of each tooth individually as well as differences among the four teeth is a multi-vari chart (See Fig. 2).

Multi-vari and multivariate charts are different. Multi-vari charts analyze variations within a given characteristic, whereas multivariate charts analyze

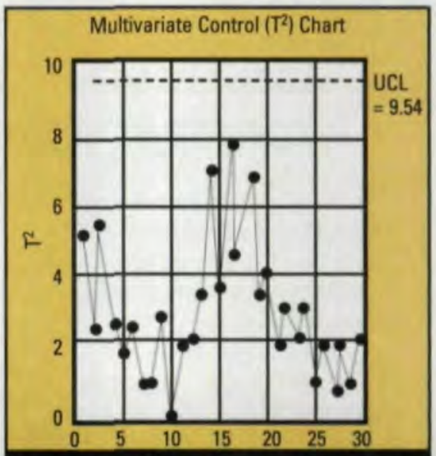

Fig. 1 — This T^2 chart combines 3 characteristics—tip, form and high point—in a single entity.

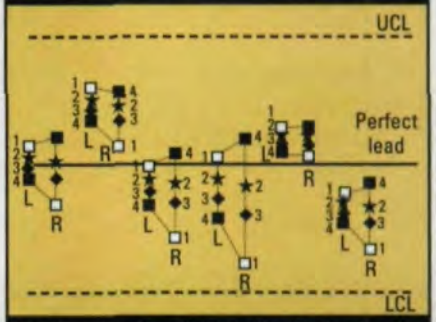

Fig. 2 — A multi-vari chart showing lead variation on 4 left and 4 right teeth simultaneously.

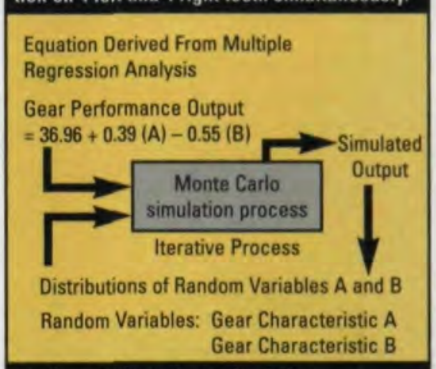

Fig. 3 — A Monte Carlo simulation.

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relation and variation between two or more characteristics.

4. *Multivariate Analysis* is useful in analyzing process instabilities and relating them to process variables. An instability is characterized by an abnormal condition on a control chart. To understand the source of unstable behavior, we generally analyze process variables. If process variables are stable, then we look for the explanation elsewhere. Multivariate analysis captures the missed opportunites in analyzing process variables that we have prematurely concluded to be noncontributory. For example, (A) incoming material condition, (B) workpiece speed and (C) tool feed may all appear to be within normal range when analyzing an instability visible on a control chart. Conventional wisdom leads us to look elsewhere for the root cause. A multivariate chart will offer additional help by analyzing T^2_{AB}, T^2_{AC}, T^2_{BC} and T^2_{ABC}. If this aid is not utilized, it is possible that the instability may remain a mystery.

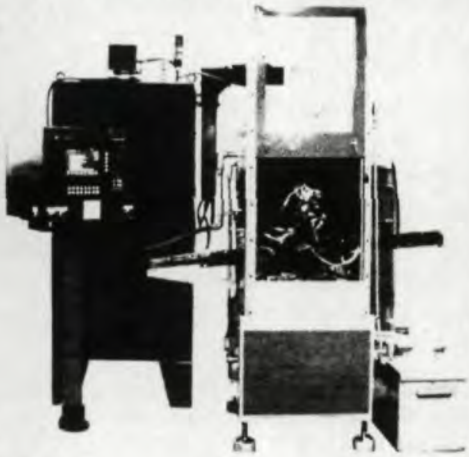
5. *Multiple Regression Analysis* is useful in establishing relationships between gear performance characteristics and gear characteristics. Neither worst-case tolerancing nor statistical tolerancing alone are sufficient to fully understand how gear characteristics affect the performance of assemblies containing gears. Such understanding can only be developed through probabilistic relationships based on actual data rather than any theoretical considerations. Multiple regression analysis helps develop this relationship.

6. *Monte Carlo Simulations* are computer-based, iterative statistical procedures wherein we determine targets and ranges of critical gear characteristics to match targets and ranges of performance. The inputs to the simulation processes are probabilistic equations and targets and ranges of gear characteristics. The output from the simulation processes are the target and range of performance (see Fig. 3).

Six Applications for SPC in Gear Manufacturing

1. Acceptable as well as unacceptable production of gears can best be characterized by using SPC. Gear characteristics that fall within specifications are not in themselves indications of the quality of the processes that produced them. For example, an acceptable gear profile is judged by a specified envelope. However, the process that created the envelope is a multivariate process; that is, three characteristics that make up the gear profile—tip, form and high point—are produced simultaneously. A correct judgment about the process condition responsible for these characteristics can only be made with a T^2 chart. Any decisions regarding process actions based on specifications tend to produce either overreactions or underreactions. While gear metrology is very advanced, it does not go far enough in integrating SPC for process actions.

2. Effects of design and production of gear characteristics on gear performance can best be characterized by using SPC. Gear characteristics are simultaneously



generated and therefore, we must judge their acceptability together, rather than discretely. The issue of joint acceptability does not get enough coverage either in standards or at gear design and manufacturing conferences.

3. Output performance characteristics of assemblies containing gears, such as durability, noise, ease of transmission under quickly changing inputs and smoothness of transmission, are correlated to one another. Knowledge of these correlations is critical to the SPC of assemblies. These correlations can be quantified using statistical methods.

4. Suspect gear characteristics that contribute to poor performance of assemblies are most likely correlated to one another. Knowledge of these correlations is critical to the SPC of gear manufacturing processes. These correlations can be quantified by using statistical methods.

5. Manufacturing precision of gear characteristics is uneconomical until statistical relationships between gear characteristics and assembly performance are first established. In one example, a lead variation was found to be almost 95% out of specification, and yet assemblies containing the gears with such excessive variation only suffered 5% reject rate. If we rush to solve the lead variation problem at great ex-pense, there is no guarantee that the 5% assembly reject rate will go down. How a 95% out of spec gear characteristic can cause only a 5% assembly fallout can be explained only through statistical relationships.

6. Without the use of statistical methods, it is almost impossible to separate the effects of machining and heat treating on manufacturing variation. Without such clear separation, fully resolving variation problems is impossible.

Recommended Sequence for Deploying SPC & Statistical Methods

1. Establish a statistical relationship between assembly performance and gear characteristics. Then select eight assemblies with acceptable performance and eight assemblies with borderline or unacceptable performance. It may not be easy to find 16 assemblies if you are in the prototype stage. In that case, select the following alternate route to generating 16 assemblies. Take two assemblies. Any gear assemblies will have a minimum of four parts. By swapping these four parts between two assemblies, you can generate 16 assemblies for purposes of statistical analysis. Use multiple regression to analyze the data and generate an equation between performance characteristics and gear characteristics.

2. Use Monte Carlo simulations to establish targets and ranges of gear characteristics to match performance targets and ranges.

3. Investigate whether any correlations exist among critical gear characteristics. Use correlation analysis.

4. If correlations are high, use a multivariate (T^2) chart to monitor the output.

5. If correlations are low, use either average and range (X-R) charts (Fig. 4) or

individuals and moving range ($\bar{X}$-MR) charts (Fig. 5) for monitoring each individual gear characteristic. To select either set of charts, first determine whether a process output is homogeneous or heterogeneous. Do this by taking a group of five consecutive pieces and examining its range. If the range is one-half of the specification range or lower, the process output is homogeneous. Otherwise it is heterogeneous. If the process is homogeneous, use X-MR charts for monitoring process output. If the process is heterogeneous, use $\bar{X}$-R charts.

6. Because differences among teeth are contributing factors to ultimate gear performance, a multi-vari chart must accompany all the other charts to understand and control tooth-to-tooth variation within a gear.

The above described sequence is an investigative use of SPC. If any problems are uncovered as a result of this exercise, we can begin the solution process. If no problems are uncovered, we may choose to use SPC from this point on in the process for monitoring output. Inappropriate variations can then serve as a warning of incipient problem conditions.

Statistical tools may come to the rescue when you are confronted with puzzling gear problems. SPC, a results-backward approach, is a complement to the more traditional knowledge-forward approaches to gear problem solving. Once you develop expertise in the use of these methods, you will find they also accelerate and improve the productivity of your knowledge-forward approaches as well. ⚙

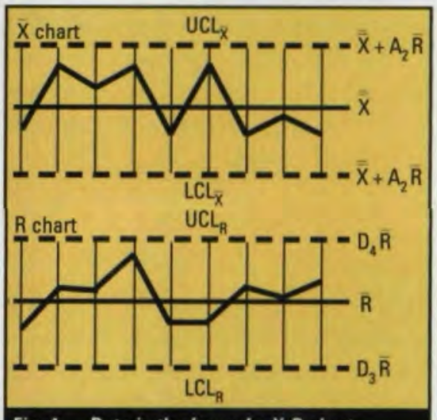


Fig. 4 — Data in the form of a X-R chart.

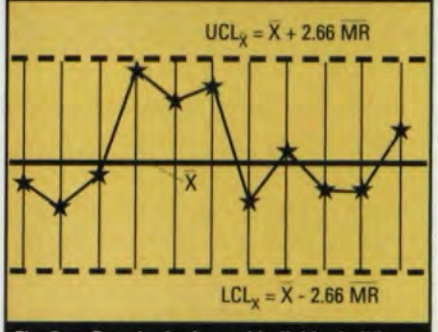


Fig. 5 — Data in the form of individuals (X).

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