# Analysis of GD&T tools to support the product development process

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A thesis in the field of Automotive Engineering for the Degree of Master of Engineering

Politecnico di Torino

March 2020

# Abstract

With the development of science and technology, as well as the arrival of the information age, the pace of the economic integration in the world is getting larger and larger. Also, the competition among enterprises is becoming increasingly fierce. Product quality and cost are becoming the challenges of an enterprise's development. Thus, controlling both the product quality and the cost has become the focus of enterprises.

GD&T (Geometric Dimensioning and Tolerancing) is the technical information that must be used throughout the product's life cycle, including design, manufacturing, assembly, and inspection. It uses standard symbols to define part features and the tolerance zones. It also defines a part on the basis of the functionalities of the part. GD&T can not only improve communications and have better product designs, but can also reduce costs. Thus, with the application of GD&T, companies and factories can get a bonus both in the cost point of view and the quality point of view.

In this thesis, we will have a look at the applications of the GD&T and GPS in the product development process. Also, we will investigate the functionalities of GD&T and GPS softwares for application, in which the VisVSA (Variational Statistical Analysis) software is used to help analyze the tolerances. In this thesis we choose the trolley and sliding guide assembly as the case study. In the automotive industry, sliding doors are usually used as rear doors in commercial vehicles which are characterized with large passenger compartment volume. The assembly of the sliding door is a vital issue for the quality and custom satisfaction of the vehicles equipped with sliding doors. In the aspect of the opening and closing movements of the sliding door, the assembly between the sliding door trolley and sliding guide has a deep influence on the sliding door motion smoothness and the closing force. The sliding door is moved by the trolleys rolling in the sliding guides. The lower sliding guide mainly plays the role of load bearing and trajectory guiding, which is in the primary part. The lower and middle sliding guides play the trajectory guiding role only and are in the secondary part.

In detail, first of all, the basic concepts related with the GD&T are introduced. Then we choose the trolley and sliding guide assembly as the case study in order to develop the tolerance analysis based on the dimensional chain method. Tolerance analysis is the process of calculating the cumulative tolerances of assemblies based on the known assembly tolerances or limit deviations. From the perspective of the dimensional chain theory, tolerance analysis is to solve the calculation problem, that is, the dimensions and tolerances of the component rings are known, and the dimension and tolerance of the closed ring are determined after the final assembly. The tolerance analysis based on the dimensional chain takes the critical dimension as the closed ring and the known dimensions as the component rings.

In addition, we will develop the tolerance synthesis and multi-object based assembly deviation optimization, with which we will understand how GD&T tools can support the product development process. The tolerance synthesis is the process of allocating tolerance values of known products to all parts according to certain criteria, with the knowledge of the final assembly tolerance. From the perspective of dimensional chain theory, tolerance allocation is a solution to the inverse calculation problem, that is, to decide the tolerances of each component ring economically and functionally based on the known closed ring tolerance and the basic dimensions of each component ring. Last but not least, we will verify the mathematical results with the tolerance analysis software to investigate the functionalities of VSA.

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# Chapter 1 Introduction of GD&T

## 1.1 Background of GD&T

With the development of science and technology as well as the arrival of the information age, the pace of economic integration in the world is getting larger and larger. Also, the competition among enterprises is becoming increasingly fierce. Facing this battlefield without smoke, companies must win with excellent product quality, low prices, and a keen response to the market. Product quality and cost are the lifeline of an enterprise's survival and development. Thus, controlling the quality and cost of the product has become the focus of each enterprise.

GD&T is the technical information that must be used throughout the product's life cycle, including design, manufacturing, assembly, and inspection. In addition, GD&T is a system based on two general purposes. On the one hand, it consists of a set of standard symbols in order to define part features and their tolerance zones. The symbols and their interpretation are documented by the American National Standards Institute Dimensioning Standard. On the other hand, GD&T is a philosophy of defining a part based on the functionalities of the part.

GD&T is beneficial in several aspects. The first advantage is to improve communications. With the application of GD&T, uniformity in drawing specifications and interpretation is provided. In other words, all the processes related to the product including design, production and inspection are done in the same language. Another benefit is to have better product designs. From the designers' point of view, it provides them a tool to express their ideas more clearly. From the design stage point of view, the philosophy of functional dimensioning establishes part tolerances based on the requirements of functionalities. Last but not least, the cost is the evident bonus due to the increased production tolerances. There are generally two ways that the tolerances are increased through the usage of GD&T. firstly, an additional tolerance for manufacturing is offered under certain conditions, saving the costs in production to a large extent. When the MMC modifier is used, it means that the stated tolerance applies when the feature-of-size is at its maximum material condition. When the actual feature-of-size departs from MMC, an increase in the stated tolerance, equal to the amount of the departure, is permitted. This extra tolerance is called the bonus tolerance. Secondly, assigning the tolerances on the basis of functional requirements usually results in a larger tolerance for manufacturing. It eliminates unnecessary tight demands caused by the approach of simply copying the existing tolerances or assigning tight tolerances. However, the disadvantages of GD&T can be lack of training available and large number of bad examples of GD&T on drawings, which leads to much confusion.

## 1.2 Tolerance design concepts

Tolerance design is mainly the method to study the effect of the accumulation of part errors on product performances and to economically distribute the tolerances. in general, tolerance design consists of two parts, that are the tolerance analysis and the tolerance synthesis.

Tolerance design has a great impact on product competitiveness. Product competitiveness is comprehensively reflected in various aspects such as time competitiveness, quality competitiveness, price competitiveness and innovation competitiveness. Products being competitive in the market means that they must be comprehensively competitive in these several aspects, not at the expense of any of them. If we simply put forward too high requirements on design tolerances in order to improve product quality, it will increase processing costs, reduce the rate of qualified products, delay product delivery and time to market, and affect time and price competitiveness. If the tolerance is designed and processed according to the economic accuracy of each part, which will also reduce the product quality and assembly success rate, and will also affect its comprehensive competitiveness.

How to reasonably design the tolerances in order to find a balance between the quality, the cost, and the assembly success rate, and to keep the product costs throughout the whole life cycle to a minimum under the premise of ensuring quality, is exactly the task to be completed by tolerance design.

### 1.2.1 Tolerance analysis

Tolerance analysis, also known as tolerance verification, is the process of calculating the cumulative tolerances of assemblies based on known assembly tolerances or limit deviations. If the calculation result fails to meet the design requirements, the tolerance of each part needs to be adjusted and recalculated.

From the perspective of the dimensional chain theory, tolerance analysis is to solve the calculation problem, that is, the dimensions and tolerances of the component rings are known, and the dimension and tolerance of the closed ring are determined after the final assembly. The purpose is to verify whether the basic dimension and the upper and lower deviations of each component ring on the drawing can meet the general functional requirements after processing. In other words, it is to verify the correctness of the design. If the final performance is not met, the tolerances of each component ring need to be modified again until the performance requirements are met.

The current research methods of tolerance analysis mainly include the extremum method, the probability statistical method, the statistical experiment method, etc.

The extremum method is when calculating the assembly tolerance under the assumption that all of the dimensions of parts are at the limit value at the same time. Then the product performance requirements are verified according to the limit value. The extremum method has a small amount of calculations and a quite simple theory. However, it rarely occurs the situation that all parts are at the extreme values at the same time, so the tolerance of the parts can only be increased to meet the design requirements, which leads to higher product costs.

The probability method assumes that the tolerances of each part follow a normal distribution, and that there is a linear relationship between assembly tolerances and part tolerances. Through this simplification, it is not only convenient to calculate but also close to the actual production, and at the same time allows the part to have a wider tolerance band, so this method is more commonly used than the extremum method.

The statistical experiment method is also called as the Monte Carlo method. It is a combination of numerical and statistical methods. It is mainly used when the assembly function is a non-linear expression. In order to ensure the correctness of the calculation, a large number of statistical samples are required to perform repeated operations. The convergence speed is affected by the number of statistical experiments. This method has been widely used in commercial software packages such as MOBILE and VSA.

### 1.2.2 Tolerance synthesis

Tolerance distribution, also known as tolerance synthesis, is a process of allocating tolerance values of known products to all parts according to certain criteria, with the knowledge of the final assembly tolerance. It is of great significance to reasonably and economically allocate the tolerances among all the parts of an assembly.

From the perspective of dimensional chain theory, tolerance allocation is a solution to the inverse calculation problem, that is, to decide the tolerance of each component ring economically and functionally based on the known closed ring tolerance and the basic dimensions of each component ring. Under the guarantee of product assembly technology requirements, the product design accuracy and manufacturing cost are weighed. Under the optimization model, the economic and reasonable tolerances and limit deviations of each component ring are determined. The purpose is to determine the tolerances and the upper and lower deviations of each component ring according to the overall technical requirements.

There are two problems to be solved for tolerance synthesis. One is to determine the tolerance $T_i$ of each component ring according to different methods. The second problem is how to determine the limit deviation of each component ring $A_i$ after the tolerance $T_i$ is obtained. In other words, tolerance design must not only determine the size of the tolerance zone, but also the location of the tolerance zone.

Due to the fact that the parameters that are related with tolerance synthesis are numerous, the tolerance synthesis is a problem with multi random variables, which makes it a problem to be optimized as well. Thus, the challenges are to establish practical objective functions and constraints, and to use various optimization algorithms to achieve optimal allocation of tolerances

## 1.3 General terms

In this part, some terms that are used in this thesis are introduced from the conceptual point of view for indication.

The feature is a general term applied to a physical portion of a part, such as a surface, a hole or a slot. The feature of size is one cylindrical or spherical surface or a set of parallel surfaces, each of which is associated with a size dimension. Location dimension is a dimension which locates the centerline or center plane of a part feature relative to another part feature, centerline, or center plane.

MMC is Maximum Material Condition, i.e. when a feature-of-size contains the most amount of material. LMC is Least Material Condition, i.e. when a feature-of-size contains the minimum amount of material. RFS is Regardless of Feature Size, i.e. when a geometric tolerance (or datum) applies independent of the feature size. Datum is the reference plane used for making part measurements.

There are thirteen geometric characteristic symbols used in the language of GD&T, which are divided into five separate categories.

1. Form: flatness/ straightness/ circularity/ cylindricity
2. Orientation: perpendicularity/ angularity/ parallelism
3. Location: position/ concentricity
4. Runout: circular runout/ total runout
5. Profile: profile of a line/ profile of a surface

## 1.4 Conclusions

In chapter 1, the basic concepts about GD&T (Geometrical Dimensioning and Tolerancing) are introduced. First of all, the background of GD&T is briefly given, including the importance of such a technology, the basic idea of GD&T, the advantages and the disadvantages of GD&T. We can know that GD&T is of great importance to the quality control and cost control processes. Thus, the application of GD&T to industrial products is necessary and useful. Secondly, the concepts about the tolerance design is described, in which two basic ideas are introduced, that are the tolerance analysis and the tolerance synthesis. We introduce the general methods used in the tolerance analysis and the usual problem to solve in the tolerance synthesis, which is related with the optimization issues. In general, the tolerance synthesis is the method to solve the tolerance of the closed ring with known component rings, while the tolerance synthesis is the method to find the optimal solutions of the tolerances of the component rings with the required closed ring. Last but not least, some general terms that are related with GD&T and that are referred in this thesis are introduced in the conceptual point of view.

# Chapter 2 Tolerance Analysis of the automobile sliding door trolley and sliding guide assembly

## 2.1 Introduction

In the automotive industry, sliding doors are usually used as rear doors in commercial vehicles which are characterized with large passenger compartment volume. The assembly of the sliding door is a vital issue for the quality and custom satisfaction of the vehicles equipped with sliding doors. In the aspect of the opening and closing movements of the sliding door, the assembly between the sliding door trolley and sliding guide has a deep influence on the sliding door motion smoothness and the closing force. The sliding door is moved by the trolleys rolling in the sliding guides. The lower sliding guide mainly plays the role of load bearing and trajectory guiding, which is in the primary part. The lower and middle sliding guides play the trajectory guiding role only and are in the secondary part.

After the sliding door is installed on the vehicle body, under the action of gravity, the outer and lower sides of the middle and lower sliding guides will closely touch the middle and lower trolleys, and an assembly gap or clearance with a certain size will appear on the inner and upper sides. It is significant to ensure the size and accuracy of this gap within an optimal range. Because the trajectory and positioning of the upper rail are simulated in accordance with the movement trajectory of the upper trolley, the two may not fit face to face after the sliding door is installed. However, in order to ensure that the sliding door can move smoothly, a gap of a certain size in the Y direction should exist. For this reason, it is also important to ensure the size and accuracy of the gap between upper trolley and upper rail in both the Y direction and Z direction.

During the closing process of the sliding door, if the assembly deviation between the trolley and the sliding guide is too large or inconsistent, it will easily cause the sliding door movement to be unstable, which is related with the smoothness of the movement. Furthermore, the unreasonable deviation will induce the friction increase of the relative motion of the assembly, leading to an increasing closing force. More serious problems will occur when the sliding door is stuck during movement, which will hinder the basic use of the sliding door.

Thus, in this chapter we will apply the GD&T tools to optimize the clearance tolerance between each trolley and sliding guide so that the assembly quality and the functional performances are optimized.

In detail, we analyzed the possible defects that we would meet during the assembling processes and the related factors such as geometric characteristics, positions and sizes. Then the assembly deviation model of sliding door during the movement process based on dimensional chain was established. Also the tolerance analysis software VisVSA was used to simulate and calculate the assembly deviation of the sliding door during the movement process to verify the rationality and correctness of the above-mentioned dimensional chain model, and then we considered the optimization of key factors affecting the assembly gap deviation, so that the uniformity of the gap deviation between the sliding guide and trolley was improved, and the motion smoothness of the sliding door was improved as well.

## 2.2 Assembling process and problems

### 2.2.1 Description of the assembling process

The sliding door assembly is the last assembling step of the body-in-white assembling process. The assembly deviation of the upstream assembly is accumulated layer by layer, which will eventually affect the matching accuracy of the sliding door. Therefore, the assembly deviation of the sliding door assembly will be affected by multiple factors, and each factor is complicated.

The sliding door is connected to the vehicle body through three bracket trolleys positioned in the grooves of the three sliding guides to realize the connection to the vehicle body. The three trolleys roll or slide on the sliding guide so that the opening and closing of the door is ensured. The respective trolley rolls or slides together in the corresponding guide rail, and the sliding door slides along the guide rail to achieve opening and closing. The three rails on the vehicle body play different roles. The lower rail mainly plays the role of load bearing and guiding the path, while the middle rail and the upper rail mainly play the path guiding role. Thus, the assembly and positioning requirements of each rail are different according to the different roles that these sliding guides are playing. For example, in order to assign the sliding door with the tendency to close automatically, the middle rail is often at a slight angle of about 1 degree with respect to the lower rail. The track of the upper rail is generally determined after the determination of the tracks of the middle and lower rails based on the trajectory of the upper trolleys. Besides the above reasons, also take into account the appearance of the vehicle body, the trajectories of the three guide rails are normally not parallel to each other as shown in Fig. 1 below.

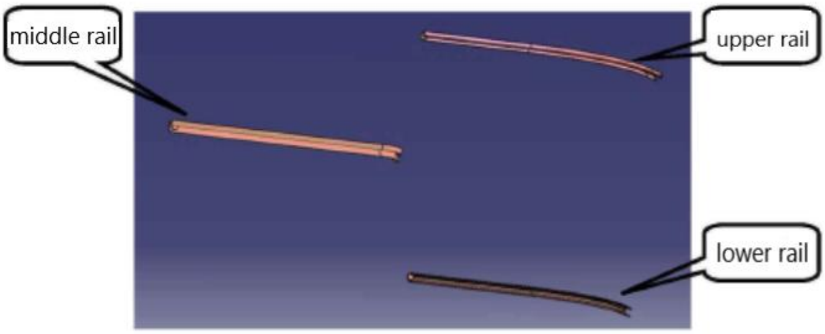



Fig. 1 Spatial postures of three sliding guides

In detail, the assembling process consists of three parts. First of all, the sliding door and the three sets of the trolleys are positioned and connected through the cooperation of the shaft and the hole. Secondly, each guide rail is connected with the vehicle body through front and rear welding points. Last but not least, the matching between the trolley and the sliding guide is a cylindrical surface. Regarding the matching relationship between the three guide rails and the corresponding trolleys, in order to make the model simpler and more effective, it is necessary to ignore some insignificant factors for the analysis. The accuracy of the assembly gap between the lower rail and the lower trolley is mainly related to the positioning of the guide rail, the dimensional and geometric tolerances of the guide and the trolley. The accuracy of the clearance between the middle rail and the middle trolley is affected by more factors, including the middle rail positioning tolerance, the clearance tolerance of the lower guide rail and the installation tolerance of the middle and lower trolley brackets. The tolerance of the clearance between the upper guide rail and the upper trolley is not only due to the principle of the sliding trajectory design of the sliding door, but also related to the two clearance accuracy mentioned above.

### 2.2.2 The assembling problems

The motion of the sliding doors on the vehicle body is the core problem of sliding door design and assembly, which is related to the functional requirements of sliding doors. The common assembling defects concerned with the matching between trolley and sliding guide that will occur in the assembly of sliding door can be divided into two aspects. One aspect is related with the motion smoothness. When the door sticks during opening and closing, which will result poor portability and smoothness. The other aspect is concerned with the closing force needed by the passenger when closing the door. Due to the high friction caused by unreasonable clearance between the sliding guide and trolley, the closing force is evidently enlarged and the push-pull feeling is not satisfying. The above problems will tend to be more serious with the increase of the life of the vehicles. Also, they are items that the customers experience frequently and pay more attention to. Therefore, it has become an important indicator for evaluating the design ability and manufacturing level of sliding door models for automobile manufacturers. It is thus one of the focuses of the research content of sliding doors.

The assembling process of the sliding guides and trolleys must not only ensure that the assembly of the three sets of guide rails and trolleys do not interfere in their own positions and sizes, but also ensure that the assembly of each guide rail and the corresponding trolley meets certain clearance accuracy requirements. In addition, the assembly must as well take into account the portability and smoothness of the sliding motion of the door. If the accuracy of the clearance between the sliding guides and the trolleys in the directions of the X and Y axes of the vehicle is not consistent during the movement of the sliding door, it may cause the sliding friction of the sliding door to increase, or even become stuck. As a result, the closing force of the door is increased, which will affect the smoothness and lightness of the closing-door action. Further it may affect the matching quality of the assembly between the door and vehicle body.

## 2.3 Selection of sliding door location scheme

### 2.3.1 Six-point locating principle

Any part or assembly in space needs six points to fully limit all of its six degrees of freedom. Typically, we apply the six-point locating principle to define the six points. The six-point locating principle is also known as 3-2-1 locating principle. It means that we select three locating points on the main datum plane to fix the three degrees of freedom of the part, then we select two locating points on the second datum plane to limit two degrees of freedom, and lastly select one locating point on the third datum plane to fix the last degree of freedom. It is mainly suitable for the assembly of rigid parts. Thus, we can apply this principle to determine the location scheme of the sliding door assembly if we can assume the assembly is a rigid part. The Fig.2 below has shown the 3-2-1 locating principle.

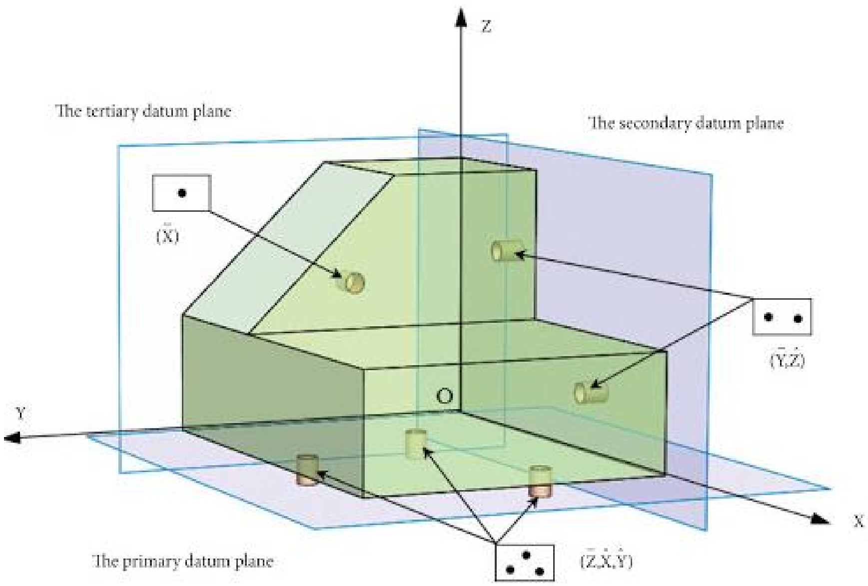



Fig. 2 3-2-1 locating principle

There are several rules that can be followed to arrange the six positioning reference points. The main datum plane needs to be arranged on the surface with the largest area or with special functional requirements. The second datum plane is arranged on the secondly largest surface of the part. The third datum plane is the surface with the smallest area. In addition, the distance between the locating points should be as large as possible. The locating points should be selected in a relatively stable area of the workpiece, that is, an area that will not change during the assembly or inspection process.

### 2.3.2 Sliding door locating points

This step is the preparation for the simulating model of the assembly deviation of the sliding door in the software. Before we get to the achievement of the six locating points of the sliding door, we should be aware of the main characteristics of the door assembly structure. In other words, we choose the locating points according to the important areas that fix the sliding door. It is helpful to analyze the characteristics and functionalities of the parts that constitute the assembly and to figure out the matching relationship between the parts. In this way we can achieve the choices of locating areas.

First of all, we have known that the sliding door mainly relies on the upper, middle, and lower trolleys embedded in the three sliding guide grooves to connect with the vehicle body. Secondly, a certain device is required to withstand the closing force of the sliding door, to ensure the correct orientation of the rear part of the door in the left and right direction after the sliding door is closed, and to lock and clamp the door. That's why the sliding door has a lock device near the middle of the rear side body, matching with the locking pin on the door. Lastly, in order to limit the movement position of the sliding door, also to prevent the door from colliding with the side panel under the action of external force, and to increase the ability to bear the longitudinal tensile force of the sliding door, a stopper is installed on the upper and lower sides of the front part of the vehicle body respectively.

As a result, we can choose the six locating points from the important areas mentioned above, that are, the connection positions between the three trolleys and sliding guides, the lock device position and the stopper positions. Considering that the stopper is made of rubber materials mainly to prevent the impact of the door on the door frame, which cannot be considered to be rigid. For this reason, it is usually not suitable to choose the stopper position as the locating point. While for the lock device, when the sliding door is closed, the lock will withstand the closing force in the vertical and horizontal directions, limiting the sliding door's movement in the Y direction to prevent the sliding door from automatically opening. There is no doubt that this position of lock device plays a crucial role.

We can fix all of the six degrees of freedom of the sliding door in the condition that the door is closed as followings. The degrees of freedom of the sliding door to translate along the Y and Z axes in the vehicle's SAE coordinate system are fixed by embedding the lower trolley in the lower sliding guide. The degrees of freedom to translate along the X axis and to rotate around the Y axis are fixed by embedding the middle trolley in the middle sliding guide. The degree of freedom to rotate around the X axis is fixed by embedding the upper trolley in the upper sliding guide. The degree of freedom to rotate around the Z axis is fixed by the lock device.

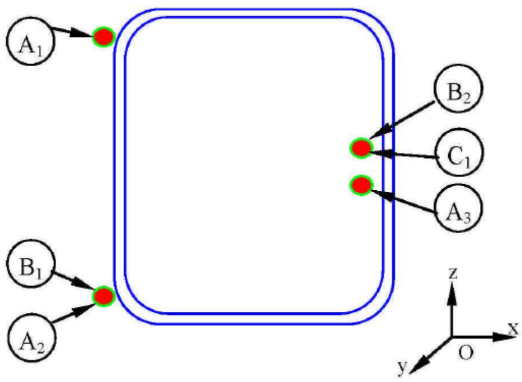



Fig. 3 Location scheme of the sliding door

According to the above analyses, the six locating points when the door is closed are chosen as: the geometric center of the upper trolley ($A_1$), the geometric center of the middle trolley ($B_2$ and $C_1$), the geometric center of the lower trolley ($A_2$ and $B_1$) and the geometric center of the lock device ($A_3$). The Fig. 3 above has presented the location scheme of the sliding door when it is closed. The locating references A, B, C are arranged according to the 3-2-1 principle. Among them, $A_1$ to $A_3$ control the size of the sliding door along the Y axis. $B_1$ and $B_2$ control the size of the sliding door along the Z axis. $C_1$ controls the size of the sliding door along the X axis.

We consider that the assembly of the sliding doors and trolleys, the assembly of the sliding guides and vehicle bodies, and the assembly of sliding guides and trolleys are rigid. Factors such as dimensional tolerances and geometric tolerances (form and position tolerances) of various parts are comprehensively examined. The deviation fluctuation range of the fitting clearance between the sliding guides and the trolleys in the Y and Z directions will be studied, which will be described in detail in the next part.

## 2.4 Tolerance analysis based on the dimensional chain model

From the assembly relationship between the sliding door and the vehicle body, it can be known that the gap deviation between each trolley on the door and the sliding guide on the vehicle body in the Y and Z directions is mainly related to the dimensional deviation of the trolley or the guide and the relative position deviation. Considering the assembly deviation as the closed ring of the dimensional chain, we can not only specify the level of the dimensional factors and geometric characteristics that affect the gap deviations, but also improve the calculation efficiency and accuracy by using relevant mathematical software. With the method of dimensional chain to model the assembly deviation of the sliding door in motion, we can also find the key factors that affect the uniformity of the gap deviation of the assembly, and explore the optimization of the assembly deviation.

### 2.4.1 Basic concepts

If we have known the tolerance or limit deviation of each part of the assembly, then we can calculate the cumulative tolerance of the assembly according to the assembling conditions in detail. The process described above is the tolerance analysis process. If the calculating results do not meet the design requirements, the tolerances of each part need to be adjusted and recalculated until the requirements are satisfied. At present, the tolerance analysis model based on dimensional chain is widely used in the field of mechanical design and manufacturing. From the dimensional chain point of view, tolerance analysis is to solve the calculation problem. In other words, it is to determine the size and tolerance of the closed ring after the final assembly, with the knowledge of the sizes and tolerances of the component rings in the dimensional chain.

The dimensional chain refers to the closed dimension group formed by end-to-end interconnected dimensions in a certain order during the part processing or assembly process. Each dimension of the dimensional chain is called the ring of the dimensional chain. Among them, the dimension whose accuracy is indirectly guaranteed at the end of assembly is called the closed ring, and the rest dimensions are called the component rings. The dimensional chain model is actually a tool to describe the dimensional relationships. The dimensional chain model can describe dimensional deviation, geometric feature deviation and dynamic adjustment at the same time. Common deviation calculation methods of the dimensional chains include the extremum value method, the statistical method, the Monte Carlo simulation method, etc.

The tolerance analysis based on the dimensional chain takes the critical dimension as the closed ring and the known dimensions as the component rings. The deviation of the critical dimension is calculated from the deviation of the known dimensions. This model is intuitive, simple, and suitable for situations where the connection relationship between parts is relatively simple.

Although the sliding door is mainly composed of flexible thin plates, the installation and matching of the sliding door principally involves the assembly of the trolleys and guide rails. In the case that the assembly is not involved in welding or is rarely affected by welding, the assembling process and motion of the sliding door are assumed to be rigid body assembly and motion. As a result, the modeling using dimensional chain is still reasonable and effective.

### 2.4.2 Description of the dimensional chain model with sliding door assembly

In order to eliminate or mitigate the motion problems of the sliding door assembly, we use the method of the dimensional chain modeling to establish the assembly deviation model, when the sliding door moves to the initial position (close to the fully open position of the sliding door), the intermediate position and the closed position (close to the closed position of the sliding door) respectively. These three positions can constitute the assembly deviation model of the sliding door during the movement process. In the modeling process based on the dimensional chain, factors such as the size tolerance and the geometric feature deviation of the part must be considered at the same time. This article combines the actual size tolerance data and the geometric feature tolerance data of the sliding door model of SAIC-GM. With the reference of the data, then we can calculate the assembly deviation of the sliding door. Also, we can analyze the variation trend of the clearance tolerances between the trolley and the sliding guide during the sliding door movement in order to find the key factors that affect the accuracy of the assembly clearance.

In the process of dimensional chain modeling, the geometric features of parts are counted into the dimensional chain model as zero-size component rings. The increase or decrease characteristic of the component ring is determined by its actual impact on the closed ring. The so-called "zero size" indicates that the size of the ring is considered to be zero and the tolerance is that of the geometric characteristic of the part. For instance, the flatness of the inner plane of the sliding guide is 0.05, which will be counted as $0^{+0.05}_{-0.05}$mm.

Theoretically we can represent the assembly tolerance of the sliding door in movement process with the assembly deviation model in the three typical positions of the sliding door. However, it will involve a lot of spatial issues of the dimensional chains, which makes the modelling and calculation become quite complex. Out of the purpose of improving efficiency of calculation and convenience as well, the method of directly converting spatial dimension to linear dimension is applied. In other words, all of the component rings that make up the dimensional chain are projected to the axis of the closed ring, that is the Y axis or Z axis in the SAE reference system. Thus, the dimensional chain is transformed into the linear dimensional chain. Although this solution requires to calculate the spatial angle between the dimensions of each component ring and the axial direction, it simplifies the dimensional chain from complex spatial form to the simple linear form, making the modelling process easier to be described and understood, in addition to more convenient calculations.

In order to determine the increased or decreased characteristic of the component ring, we can apply the loop method. In a dimensional chain, firstly we assign the closed ring a direction. Then draw arrows for each component dimension surrounding the dimensional chain in this direction. Comparing the direction pointed by the component size arrow with that pointed by the closed ring arrow, the increased or decreased characteristic of the component ring can be determined accordingly. If it is opposite to the defined direction of the closed ring, then the component ring is the increasing ring. Otherwise it is the decreasing ring. The loop method is characterized by simplicity and immediacy. However, the determination process requires carefulness in the case of relative complex dimensional chain.

There are generally two basic solutions to solve the dimensional chain, which are the extremum method and the probability method. The extremum method calculates the extreme size and tolerance of the closed ring under the assumption that all the component rings are in the condition of the extreme size. The probability method is also known as the root mean square method. it solves the dimensional chain with the application of the probability theory. The respective formulations to express the tolerance of the closed ring in the dimensional chain are as followings.

The extremum method: $T_0 = \sum_{i=1}^{n} \left|\left(\xi_i^d T i^d\right)^2\right| + \sum_{j=1}^{m} \left(\xi_j^a T_j^a\right)^2$

The probability method: $T_0 = \sqrt{\sum_{i=1}^{n} \left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{m} \left(\xi_j^a T_j^a\right)^2}$

In which, $T_i$ is the dimensional tolerance of each component ring in the assembly function. $T_j$ is the geometric tolerance of each component ring in the assembly function. $\xi_i$ is the sensitivity factor of the dimensional tolerance. $\xi_j$ is the sensitivity factor of the geometric tolerance.

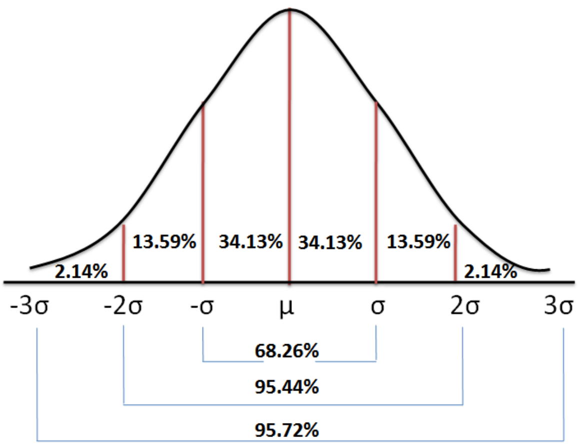



Fig. 4 Normal distribution for the dimensional tolerance

One thing worth to be mentioned is that in cases of mass production, the possible process size of the processed part is distributed according to a certain rule in general, which is usually the Gaussian distribution, also known as the normal distribution shown in the Fig. 4 above. It means that the possibility for the process size to achieve the extreme dimension is quite rare. According to the principle of probability multiplication, the probability of the return of the limit size of a closed ring is equal to the product of the probabilities of the limit size of each component ring. The larger the number of the component rings, the less the probability of all component rings being extremum. As a result, the extremum method is not suitable for cases of mass production with a relatively large number of component rings.

Considering that the sliding door assembly involves the mentioned situations, we will apply the root mean square method to calculate the gap tolerance between the sliding guide and trolley in each position. Under normal productive conditions, the process dimension or tolerance should follow the Gaussian distribution, also known as the normal distribution. Thus, the calculation of the closed ring tolerance of the assembly is based on the assumption that the dimensional tolerances of the component rings conform to the Gaussian distribution, which corresponds to the actual condition.

In the following paragraphs, the assembly dimensional chain model will be established respectively with respect to the initial position, middle and closed position of the sliding door. The variation tendency of the gap deviation during the movement will be studied and stressed as well.

### 2.4.3 Dimensional chain in the initial position

The initial position refers to the place where the sliding door is fully opened. The scheme of the sliding door in the initial position with the three sets of the sliding guides and the trolleys is shown in Fig. 5 in the next page. It can be shown that when the door is in the initial position, each trolley is generally on the far left of the corresponding sliding guide.

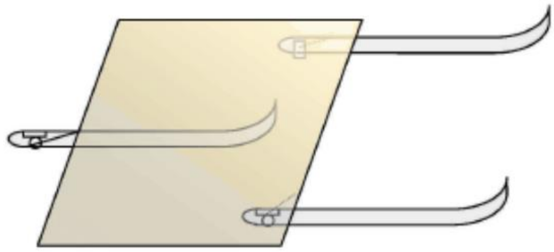


Fig. 5 Sliding door in initial position

#### 2.4.3.1 Clearance tolerance between lower rail and trolley

We will now calculate the clearance tolerance in the Y and Z directions respectively for the lower rail and trolley.

Firstly, we will see the details in the Y direction. The fitting state of the lower rail and lower trolly is represented on the left in Fig. 6 in the following. The dimensional chain and related GD&T are shown in Fig. 6 in the right side as well. The data of the dimensional tolerance and the geometrical tolerance of the sliding door refer to Tab. 1 and Tab. 2 below.

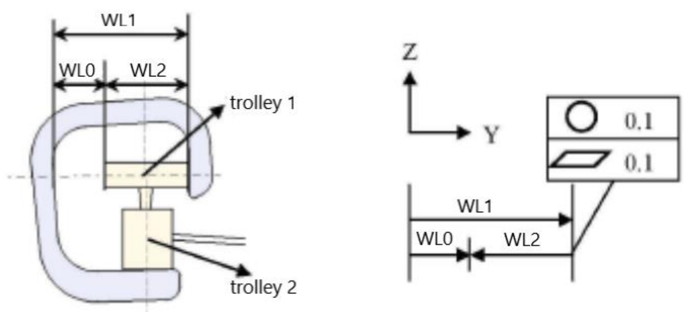



Fig. 6 Fitting state(left) and dimensional chain with GD&T(right) in Y axis (lower set)

Tab. 1 Dimensional data of the dimensional chain (lower set in Y)

| Dimension | Nominal Value/mm | Tolerance/mm | Indication |
|---|---|---|---|
| $W_{L1}$ | 23 | 0.4 | width of inner side of lower rail |
| $W_{L2}$ | 20 | 0.3 | diameter of lower trolley 1 |
| $W_{L0}$ | 3 | ? | clearance in Y axis of lower set |

Tab. 2 GD&T information (lower set in Y)

| Feature | Tolerance Type | Tolerance/mm |
|---|---|---|
| flatness $d_1$ between trolley 1 and sliding guide | flatness | 0.1 |
| circularity $d_2$ of lower trolley 1 | cylindricity | 0.1 |

According to the above, the dimensional chain of the lower sliding rail and lower trolly set in the Y direction can derive the following equation.

$$W_{L0} = W_{L1} - W_{L2} + d_1 + d_2$$

Applying the root mean square method, we can achieve the tolerance of the closed ring dimension in the Y direction $TW_{L0}$.

$$TW_{L0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.3^2) + (0.1^2 + 0.1^2)} = 0.5196$$

Secondly the clearance tolerance in the Z direction is calculated in a similar way. The fitting state of the lower rail and lower trolly is represented on the left in Fig. 7 in the following. The dimensional chain and related GD&T are shown in Fig. 7. in the right side as well. The data of the dimensional tolerance and the geometrical tolerance of the sliding door refer to Tab. 3 and Tab. 4 in the next page.

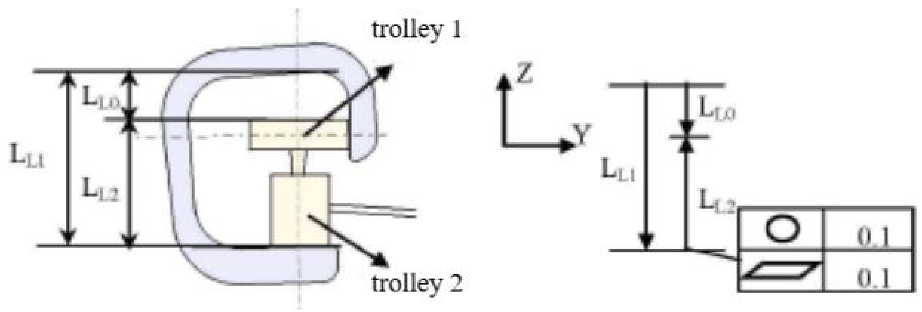



Fig. 7 Fitting state(left) and dimensional chain with GD&T(right) in Z axis (lower set)

Tab. 3 Dimensional data of the dimensional chain (lower set in Z)

| Dimension | Nominal Value/mm | Tolerance/mm | Indication |
|---|---|---|---|
| $L_{L1}$ | 32 | 0.4 | height of inner side of lower rail |
| $L_{L2}$ | 27 | 0.4 | Z distance between trolley 1& 2 |
| $L_{L0}$ | 5 | ? | clearance in Z axis of lower set |

Tab. 4 GD&T information (lower set in Z)

| Feature | Tolerance Type | Tolerance/mm |
|---|---|---|
| flatness $d_1$ between trolley 2 and sliding guide | flatness | 0.1 |
| circularity $d_2$ of lower trolley 2 | cylindricity | 0.1 |

Similarly, the dimensional chain of the lower sliding rail and lower trolly set in the Z direction can derive the following equation.

$$L_{L0} = L_{L1} - L_{L2} + d_1 + d_2$$

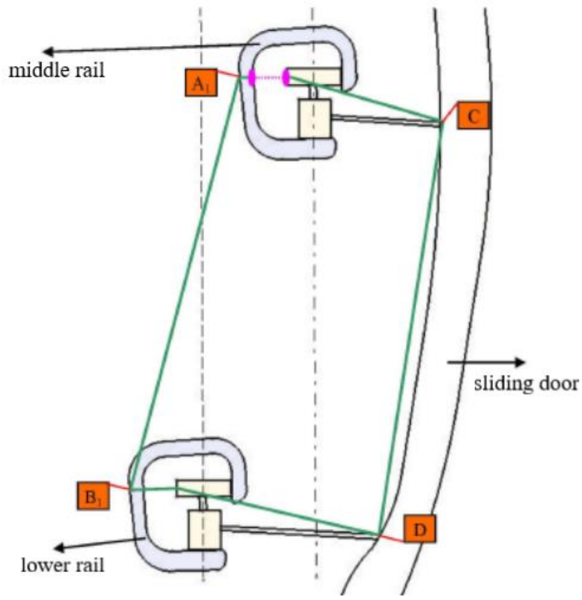
Applying the root mean square method, we can achieve the tolerance of the closed ring dimension in the Z direction $TL_{L0}$.

$$TL_{L0} = \sqrt{\sum_{i=1}^{2} \left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2} \left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.4^2) + (0.1^2 + 0.1^2)} = 0.5831$$

#### 2.4.3.2 Clearance tolerance between middle rail and trolley

The principle for the calculation of the clearance tolerance of the middle set is similar to the above for the lower set of rail and trolley, while the dimensional chain model is different. The deviation of the clearance between the middle rail and the middle trolley is also affected by the deviation of the clearance between the lower rail and the lower trolley. For this reason, the dimensional chain should consider the dimensions related with the lower set as well.

Firstly, in the Y direction, the fitting state of the upper set of the sliding guide and trolly projected in the YZ plane is represented on the left in Fig. 8 below. The dimensional chain and related GD&T are shown in Fig. 8. in the right side as well. The data of the dimensional chain and the related GD&T information can refer to Tab. 5 and Tab. 6 respectively.



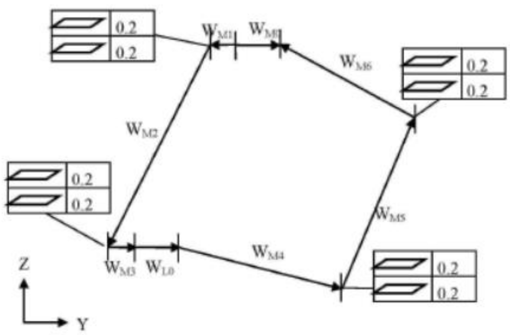




Fig. 8 Fitting state(left) and dimensional chain with GD&T(right) in Y axis (middle set)

Tab. 5 Dimensional data of the dimensional chain (middle set in Y)

| Dimension | Nominal Value/mm | Tolerance/mm | Indication | Angle w.r.t closed ring |
|---|---|---|---|---|
| $W_{M1}$ | 1.5 | 0.1 | wall thickness of middle rail | 0° |
| $W_{M2}$ | 1535.319 | 0.4 | distance between point $A_1$ and $B_1$ | 89.25° |
| $W_{M3}$ | 1.5 | 0.1 | wall thickness of lower rail | 0° |
| $W_{L0}$ | 3 | 0.5196 | clearance in Y axis of lower set | 0° |
| $W_{M4}$ | 32.5 | 0.4 | distance between measure point of lower trolley and point D | 14.6° |
| $W_{M5}$ | 1489.75 | 0.4 | distance between point C and D | 88.67° |
| $W_{M6}$ | 35.8 | 0.4 | distance between measure point of middle trolley and point C | 15° |
| $W_{M0}$ | 3 | ? | clearance in Y axis of middle set | 0° |

Tab. 6 GD&T information (middle set in Y)

| Feature | Tolerance Type | Tolerance/mm |
|---|---|---|
| flatness $d_1$ between middle trolley and middle rail | flatness | 0.2 |
| flatness $d_2$ of middle rail | flatness | 0.2 |
| flatness $d_3$ between lower trolley and lower rail | flatness | 0.2 |
| flatness $d_4$ of lower rail | flatness | 0.2 |
| flatness $d_5$ of mounting surface of lower bracket | flatness | 0.2 |
| flatness $d_6$ of mounting surface of lower bracket on door | flatness | 0.2 |
| flatness $d_7$ of mounting surface of middle bracket | flatness | 0.2 |
| flatness $d_8$ of mounting surface of middle bracket on door | flatness | 0.2 |

We can see from the figure above that the assembly deviation between the lower rail and trolley $W_{L0}$ becomes a component ring in the dimensional chain for the middle set. The dimensional chain for the middle cooperation of rail and trolley is thus expressed in a way different from the lower assembly. That is,

$$W_{M0} = -W_{M1} - W_{M2}cos89.25° + W_{M3} + W_{L0} + W_{M4}cos14.6° + W_{M5}cos88.67° - W_{M6}cos15° + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8$$

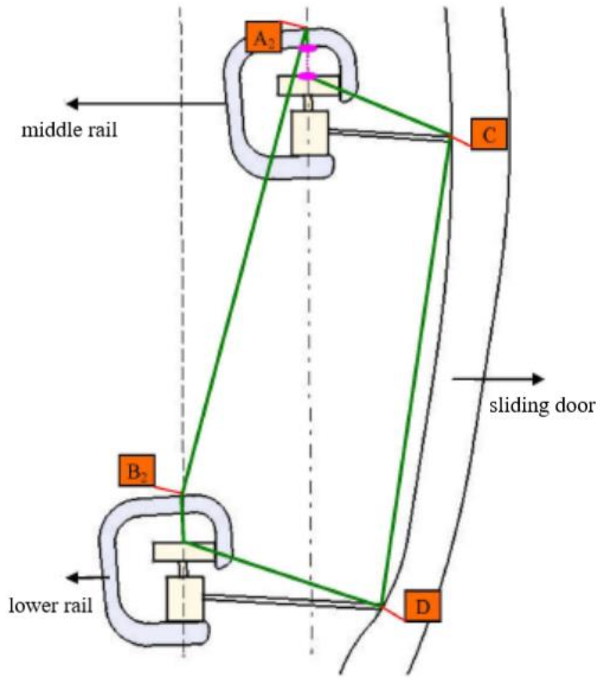
The tolerance of $TW_{M0}$ can be derived using the root mean square method accordingly.

$$TW_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.0131^2 + 0.9677^2 + 0.0232^2 + 0.9659^2) \times 0.4^2 + 0.5196^2] + (0.2^2 \times 8)}$$

$$= 0.9535$$

Secondly the clearance tolerance in the Z direction is calculated in a similar way. The fitting state of the middle rail and trolly set is represented on the left in Fig. 9 below. The dimensional chain and the related GD&T information are shown in Fig. 9. in the right side as well. The dimensional data of the dimensional chain and the applied GD&T information refer to Tab. 7 and Tab. 8 in the following page respectively.



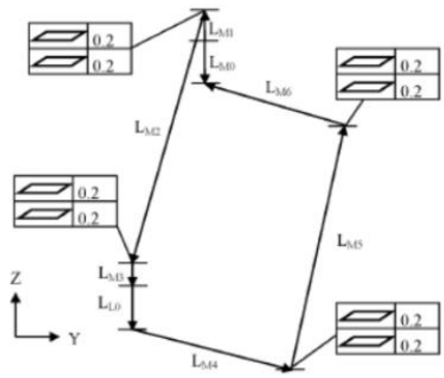




Fig. 9 Fitting state(left) and dimensional chain with GD&T(right) in Z axis (middle set)

Tab. 7 Dimensional data of the dimensional chain (middle set in Z)

| Dimension | Nominal Value/mm | Tolerance/mm | Indication | Angle w.r.t closed ring |
|---|---|---|---|---|
| $L_{M1}$ | 1.5 | 0.1 | wall thickness of middle rail | 0° |
| $L_{M2}$ | 1533.562 | 0.4 | distance between point $A_2$ and $B_2$ | 89.31° |
| $L_{M3}$ | 1.5 | 0.1 | wall thickness of lower rail | 0° |
| $L_{L0}$ | 5 | 0.5831 | clearance in Z axis of lower set | 0° |
| $L_{M4}$ | 28.6 | 0.4 | distance between measure point of lower trolley and point D | 19.83° |
| $L_{M5}$ | 1489.75 | 0.4 | distance between point C and D | 88.67° |
| $L_{M6}$ | 29.4 | 0.4 | distance between measure point of middle trolley and point C | 20.45° |
| $L_{M0}$ | 5 | ? | clearance in Z axis of middle set | 0° |

Tab. 8 GD&T information (middle set in Z)

| Feature | Tolerance Type | Tolerance/mm |
|---|---|---|
| flatness $d_1$ between middle trolley and middle rail | flatness | 0.2 |
| flatness $d_2$ of middle rail | flatness | 0.2 |
| flatness $d_3$ between lower trolley and lower rail | flatness | 0.2 |
| flatness $d_4$ of lower rail | flatness | 0.2 |
| $d_5$ of mounting hole of lower bracket | position | 0.4 |
| $d_6$ of mounting hole of lower bracket on door | position | 0.4 |
| $d_7$ of mounting hole of middle bracket | position | 0.4 |
| $d_8$ of mounting hole of middle bracket on door | position | 0.4 |

The dimensional chain of the middle sliding rail and middle trolly set in the Z direction can derive the following equation similarly.

$$L_{M0} = -L_{M1} + L_{M2}cos89.31° + L_{M3} + L_{L0} + L_{M4}cos19.83° - L_{M5}cos88.67° - L_{M6}cos20.45° + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8$$

Applying the root mean square method, we can achieve the tolerance of the closed ring dimension in the Z direction $TL_{M0}$.

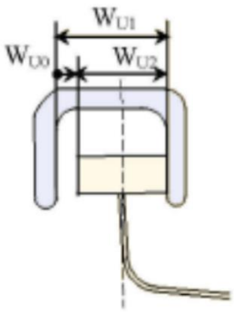
$$TL_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.012^2 + 0.9407^2 + 0.0232^2 + 0.937^2) \times 0.4^2 + 0.5831^2] + (0.2^2 \times 4 + 0.4^2 \times 4)} = 1.2009$$

### 2.4.3.3 Clearance tolerance between upper rail and trolley

When designing the upper rail trajectory, the trajectory of the upper trolley is determined generally after the trajectory design and spatial arrangement of the middle and lower rails are completed according to the closing motion simulation of the sliding door. The upper guide rail is of a specific linear trajectory. Therefore, the deviation of the fit clearance between the upper rail and the upper trolley is not only affected by the installation positioning, geometric dimensions, shape and position tolerances of the upper rail and the upper trolley, but also related to the clearances between the middle and lower rail-trolley sets.

As we have done in the above two cases, at first, we will talk about the dimensional chain in the Y direction. The fitting state of the upper set of the sliding guide and trolly projected in the YZ plane is represented on the left in Fig. 10. The dimensional chain is shown in Fig 10. in the right side as well. The data of the dimensional chain can refer to Tab. 9 in the next page.



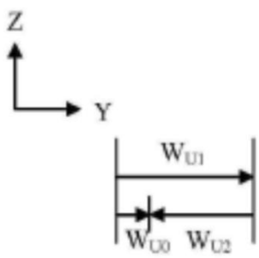




Fig. 10 Fitting state(left) and dimensional chain with GD&T(right) in Y axis (upper set)

Tab. 9 Dimensional data of the dimensional chain (upper set in Y)

| Dimension | Nominal Value/mm | Tolerance/mm | Indication |
|---|---|---|---|
| $W_{U1}$ | 23 | 0.4 | width of inner side of upper rail |
| $W_{U2}$ | 20 | 0.3 | diameter of upper trolley |
| $W_{U0}$ | 3 | ? | clearance in Y axis of upper set |

As mentioned above, when considering the clearance between the upper rail and the upper trolley, due to the influence of the other two clearances, the upper trolley and the upper rail do not necessarily have a contact fit. Therefore, the geometric tolerances of the upper rail and the upper trolley ($d_1$ and $d_2$) are not considered for the time being. As a result, for the dimensional chain of the upper set, the following equation can be obtained in the Y direction.

$$W_{U0} = W_{U1} - W_{U2}$$

Applying the root mean square method, we can achieve the tolerance of the closed ring dimension in the Y direction $TW_{U0}$.

$$TW_{U0} = \sqrt{\sum_{i=1}^{2} \left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2} \left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.3^2) + (0)} = 0.5$$

However, the expression above is not appropriate enough. Instead, there are two important factors to be taken into account. One thing is that the tolerance between the mounting surface of the upper trolley bracket and the sliding door is the surface-to-surface fit, and their tolerance values are 0.2. Another thing is that the two clearances of the lower and middle sets in the Y axis will affect that of the upper set. Simplifying the second issue as the triangular micromovement, the displacement caused by the micromovement can be considered as the quantity of the influence of the two sets, which is $\Delta x_3 = \Delta x_1 + (\Delta x_2 - \Delta x_1) \times \frac{AC}{AB} = 1.3347$.

With consideration of the two factors, we can modify the equation of clearance tolerance of upper set as

$$TW_{U0} = \sqrt{0.5^2 + 0.2^2 + 0.2^2 + 1.3347^2} = 1.4531$$

Secondly the clearance tolerance in the Z direction is calculated in a similar way. We can also consider the influence of the lower and middle sets after the calculation of the closed ring. The fitting state of the upper rail and upper trolly is represented in the left in Fig. 11below. The dimensional chain and related GD&T information are shown in Fig. 11. in the right side as well. The data of the dimensional tolerance and the applied geometrical tolerance of the sliding door can refer to Tab. 10 and Tab. 11 in the following respectively.

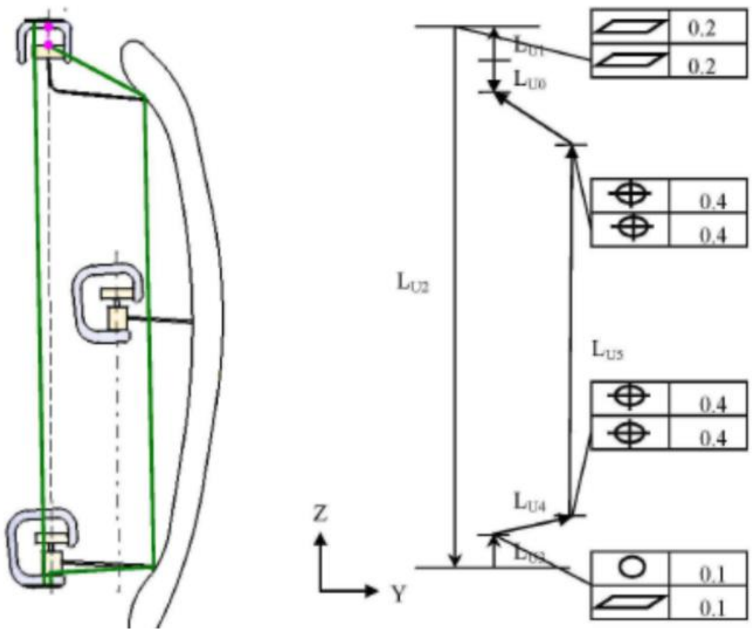



Fig. 11 Fitting state(left) and dimensional chain with GD&T(right) in Z axis

Tab. 10 Dimensional data of the dimensional chain (upper set in Z)

| **Dimension** | **Nominal Value/mm** | **Tolerance/mm** | **Indication** | **Angle w.r.t closed ring** |
|---|---|---|---|---|
| $L_{U1}$ | 1.5 | 0.1 | wall thickness of upper rail | 180° |
| $L_{U2}$ | 1597.581 | 1 | distance in Z axis between upper and lower rail | 0° |
| $L_{U3}$ | 1.5 | 0.1 | wall thickness of lower rail | 180° |
| $L_{U4}$ | 25 | 0.4 | length of lower trolley bracket | 94° |
| $L_{U5}$ | 1563.23 | 0.3 | distance between upper and lower trolley brackets | 180° |
| $L_{U6}$ | 25 | 0.4 | length of upper trolley bracket | 114° |
| $L_{U0}$ | 5 | ? | clearance in Z axis of upper set | 0° |

Tab. 11 GD&T information (upper set in Z)

| Feature | Tolerance Type | Tolerance/mm |
|---|---|---|
| flatness $d_1$ between upper trolley and upper rail | flatness | 0.2 |
| flatness $d_2$ of upper rail | flatness | 0.2 |
| flatness $d_3$ between lower trolley and lower rail | flatness | 0.1 |
| flatness $d_4$ of lower rail | flatness | 0.1 |
| $d_5$ of mounting hole of lower bracket | position | 0.4 |
| $d_6$ of mounting hole of lower bracket on door | position | 0.4 |
| $d_7$ of mounting hole of upper bracket | position | 0.4 |
| $d_8$ of mounting hole of upper bracket on door | position | 0.4 |

We can obtain the dimensional chain of the upper set in the Z direction.

$$L_{U0} = L_{U2} - L_{U1} - L_{U3} - L_{U4}cos94° - L_{U5} - L_{U6}cos114° - d_1 - d_2 - d_3 - d_4 - d_5 - d_6 - d_7 - d_8$$

Assuming that a certain angle is caused by the movement of the other two sets of sliding guide and trolley, the effect of the middle and lower sets upon the upper one can be represented by a component ring $d_9$ in the dimensional chain.

$$d_9 = AC - AC' \cos\theta = 0.0009$$

In addition, considering the parallelism tolerance of the upper rail relative to the lower rail with the amount of 0.4. Thus, the tolerance for $L_{U0}$ is

$$TL_{U0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{(0.1^2 + 1^2 + 0.1^2 + 0.0698^2 \times 0.4^2 + 0.3^2 + 0.4067^2 \times 0.4^2) + (0.2^2 \times 2 + 0.1^2 \times 2 + 0.4^2 \times 4) + 0.4^2 + 0.0009^2} = 1.4273$$

### 2.4.4 Dimensional chain in the middle position

The state of the sliding door in the middle position is shown in Fig. 12 below. When the sliding door moves to the middle position of the guide rail, in addition to the factors considered in the initial position when calculating the clearance tolerance between each guide rail and the trolley, two important factors need to be considered. First of all, in order to reduce the closing force, there is a slight angle of 1.5° between the middle and lower rails, causing the tolerance of the inclination of the middle rail to the lower rail to be 0.1°. Additionally, the parallelism tolerance of the upper rail relative to the lower rail is 0.4 mm. The process of the calculations is almost the same as the initial position. Thus, we will not cover it in detail, while the data can be found in the following.

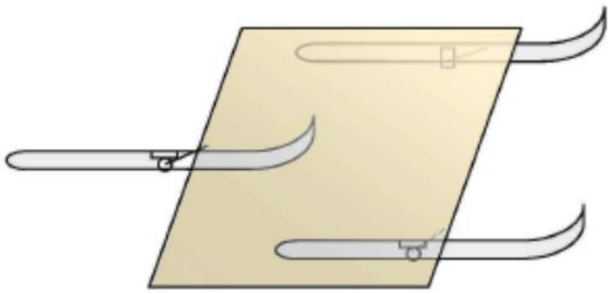


Fig. 12 Sliding door in the middle position

#### 2.4.4.1 Clearance tolerance of the lower set

The calculation of the tolerance of the gap between the lower trolley and the lower sliding guide in the middle position is assumed to be the same as that in the initial position.

(1) in the Y direction

According to the root mean square method, the tolerance $TW_{L0}$ in the middle position of the sliding door can be calculated as following.

$$TW_{L0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.3^2) + (0.1^2 + 0.1^2)} = 0.5196$$

(2) in the Z direction

According to the root mean square method, the tolerance $TL_{L0}$ in the middle position of the sliding door can be calculated as following.

$$TL_{L0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.4^2) + (0.1^2 + 0.1^2)} = 0.5831$$

**2.4.4.2 Clearance tolerance of the middle set**

(1) in the Y direction

According to the root mean square method, the tolerance $TW_{M0}$ in the middle position of the sliding door can be calculated as following.

$$TW_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.0131^2 + 0.9677^2 + 0.0232^2 + 0.9659^2) \times 0.4^2 + 0.5196^2] + (0.2^2 \times 8)}$$

$$= 0.9535$$

(2) in the Z direction

Along the Z axis, the factor of the inclination tolerance of the middle rail with relative to the lower rail should be taken into account when calculating the clearance tolerance. Remind that angle between the middle and lower rails is 1.5° and the inclination angle tolerance is 0.1°. The effect of the inclination tolerance on the geometrical relationship of the lower and middle rails is represented in the Fig. 13 in the following.

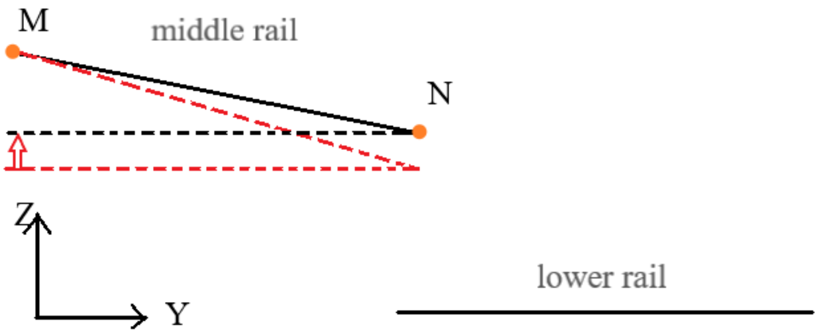


Fig. 13 Inclination tolerance of middle rail w.r.t lower rail

The tolerance of inclination angle can be transferred to the linear tolerance $d_9$, which can be calculated according to the geometrical relationships.

$$d_9 = \frac{1}{2}\left[MNsin\left(1.5° + \frac{0.1°}{2}\right) - MNsin\left(1.5° - \frac{0.1°}{2}\right)\right]$$
$$= \frac{1}{2} \times 1014.101 \times (0.02705 - 0.02530) = 0.8847$$

According to the root mean square method, the tolerance $TL_{M0}$ along the Z axis in the middle position of the sliding door can be calculated as following.

$$TL_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.012^2 + 0.9407^2 + 0.0232^2 + 0.937^2) \times 0.4^2 + 0.5831^2] + (0.2^2 \times 4 + 0.4^2 \times 4) + 0.8847^2} = 1.4916$$

#### 2.4.4.3 Clearance tolerance of the upper set

(1) in the Y direction

The calculation for the upper set in the Y direction when the sliding door is in the middle position is assumed to be the same as that in the initial position. According to the root mean square method, the tolerance $TW_{U0}$ in the middle position of the sliding door can be calculated as following.

$$TW_{U0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{0.5^2 + 0.2^2 + 0.2^2 + 1.3347^2} = 1.4531$$

(2) in the Z direction

Along the Z axis, the factor of the parallelism tolerance of the upper rail relative to the lower rail which is 0.4 mm should be taken into account when calculating the clearance tolerance. The effect of this factor can be added to the component ring $d_9$ which represents the effect of the middle and lower sets upon the upper one. Different from the calculation in the initial position of $d_9$ which equals to 0.0009, $d_9$ changes to 0.0014 considering the geometrical change due to the parallelism tolerance.

Thus, according to the root mean square method, the tolerance $TL_{U0}$ of the upper set along the Z axis in the middle position of the sliding door can be calculated as following.

$$TL_{U0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{(0.1^2 + 1^2 + 0.1^2 + 0.0698^2 \times 0.4^2 + 0.3^2 + 0.4067^2 \times 0.4^2) + (0.2^2 \times 2 + 0.1^2 \times 2 + 0.4^2 \times 4) + 0.4^2 + 0.0014^2} = 1.4273$$

### 2.4.5 Dimensional chain in the closed position

The state of the sliding door in the closed position is shown in Fig. 14 in the following. When the sliding door is moved to the closed position of the guide rail, in addition to the factors considered in the middle position, there are two other factors to consider when calculating the clearance tolerance between each guide rail and the trolley. In one aspect, the three guide rail closures consist of a segment of arc, which results in two geometric tolerances. The roundness tolerance caused by the arc and the position tolerance caused by the center of the arc are set to be 0.4mm and 0.2mm respectively. In the other aspect, the middle trolley and bracket are connected by a hinge. When the sliding door rotates to match the closing movement, the pin shaft has position tolerance and aperture tolerance, which are set to 0.4mm and 0.4mm, respectively. Similarly, the detailed equations to calculate the clearance tolerance will not be included here, while the data can be seen in the following chapter.

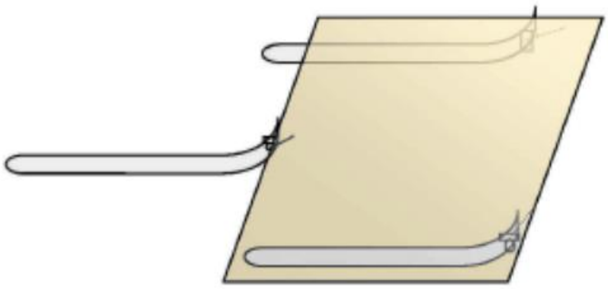


Fig. 14 Sliding door in the closed position

#### 2.4.5.1 Clearance tolerance of the lower set

(1) in the Y direction

Taking into account the fact that the roundness tolerance caused by the arc and the position tolerance caused by the center of the arc are 0.4mm and 0.2mm respectively, we consider the effect on the tolerance as a value equals to the root mean square of the two tolerances.

$$\Delta T = \sqrt{\Delta t_1^2 + \Delta t_2^2} = \sqrt{0.4^2 + 0.2^2} = 0.4472$$

Thus, according to the root mean square method, the tolerance $TW_{L0}$ of the lower set along the Y axis in the closed position of the sliding door can be calculated as following.

$$TW_{L0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.3^2) + (0.1^2 + 0.1^2 + 0.4472^2)}$$

$$= 0.6856$$

(2) in the Z direction

According to the root mean square method, the tolerance $TL_{L0}$ along the Z axis in the closed position of the sliding door can be calculated as following, which is the same as that in the initial condition.

$$TL_{L0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{(0.4^2 + 0.4^2) + (0.1^2 + 0.1^2)} = 0.5831$$

**2.4.5.1 Clearance tolerance of the middle set**

(1) in the Y direction

Considering the two factors mentioned above, we can calculate the tolerance $TW_{M0}$ along the Y axis in the closed position of the sliding door can be calculated as following.

$$TW_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.0131^2 + 0.9677^2 + 0.0232^2 + 0.9659^2) \times 0.4^2 + 0.6856^2] + (0.2^2 \times 8 + 0.4472^2 + 0.4^2 + 0.4^2)} = 1.2764$$

(2) in the Z direction

Similar to the consideration in the middle position, the effect of the inclination tolerance of the middle rail with relative to the lower rail is added.

$$d_9 = \left[MNsin\left(1.5° + \frac{0.1°}{2}\right) - MNsin\left(1.5° - \frac{0.1°}{2}\right)\right]$$
$$= 1014.101 \times (0.02705 - 0.02530) = 1.7693$$

According to the root mean square method, the tolerance $TL_{M0}$ along the Z axis in the closed position of the sliding door can be calculated as following.

$$TL_{M0} = \sqrt{\sum_{i=1}^{7}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{8}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{[(1^2 \times 2) \times 0.1^2 + (0.012^2 + 0.9407^2 + 0.0232^2 + 0.937^2) \times 0.4^2 + 0.5831^2] + (0.2^2 \times 4 + 0.4^2 \times 4) + 1.7693^2} = 2.1384$$

### 2.4.5.1 Clearance tolerance of the upper set

(1) in the Y direction

In addition to the factors considered in the initial position, adding the effect of the tolerance caused by the closing arc, the tolerance $TW_{U0}$ in the closed position of the sliding door can be calculated as following.

$$TW_{U0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2} = \sqrt{0.5^2 + 0.2^2 + 0.2^2 + 1.7955^2 + 0.4472^2}$$

$$= 1.9375$$

(2) in the Z direction

Considering the parallelism tolerance of the upper rail with reference to the lower rail, the tolerance $TL_{U0}$ of the upper set along the Z axis in the closed position of the sliding door can be calculated as following.

$$TL_{U0} = \sqrt{\sum_{i=1}^{2}\left(\xi_i^d T_i^d\right)^2 + \sum_{j=1}^{2}\left(\xi_j^a T_j^a\right)^2}$$

$$= \sqrt{(0.1^2 + 1^2 + 0.1^2 + 0.0698^2 \times 0.4^2 + 0.3^2 + 0.4067^2 \times 0.4^2) + (0.2^2 \times 2 + 0.1^2 \times 2 + 0.4^2 \times 4) + 0.4^2 + 0.0028^2} = 1.4273$$

### 2.4.6 Results analysis

After analyzing the factors that affect the dimensional tolerances and geometric characteristics of the guide rails and trolleys when the sliding door moves to the initial position, the middle position and the closed position, the dimensions of the dimension chain are used to directly convert the spatial dimensions to linear ones. Based on the modeling method and root mean square calculation method, the dimensional chain assembly deviation model of the sliding door motion process was finally obtained. Combined with a sliding door model of SAIC, the actual results of the clearance tolerances were calculated.

The calculation results of the clearance tolerances of each position and direction during the sliding door movement are shown in the Tab. 12 below, and the change trend of the clearance tolerance is shown in Fig. 15 and Fig. 16 in the next page.

Tab. 12 Mathematical results of clearance tolerance of trolley-rail sets (in mm)

| clearance of closed ring | initial position | middle position | closed position | avg. value |
|---|---|---|---|---|
| $TW_{L0}$ (Y) | 0.5196 | 0.5196 | 0.6856 | 0.5749 |
| $TW_{L0}$ (Z) | 0.5831 | 0.5831 | 0.5831 | 0.5831 |
| $TW_{M0}$ (Y) | 0.9535 | 0.9535 | 1.2764 | 1.0611 |
| $TW_{M0}$ (Z) | 1.2009 | 1.4916 | 2.1384 | 1.6103 |
| $TW_{U0}$ (Y) | 1.4531 | 1.4531 | 1.9375 | 1.6146 |
| $TW_{U0}$ (Z) | 1.4273 | 1.4273 | 1.4273 | 1.4273 |

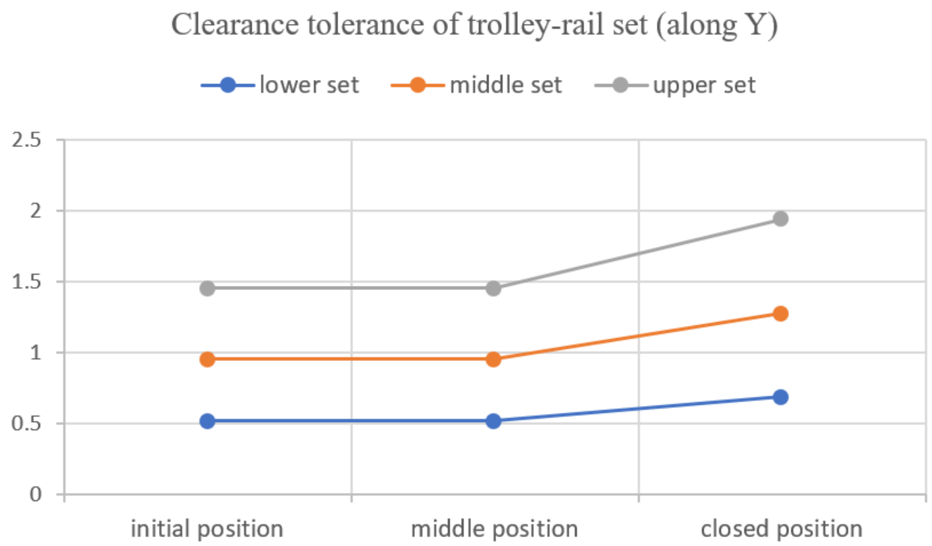



Fig. 15 Clearance tolerance tendency of different sets (along Y)

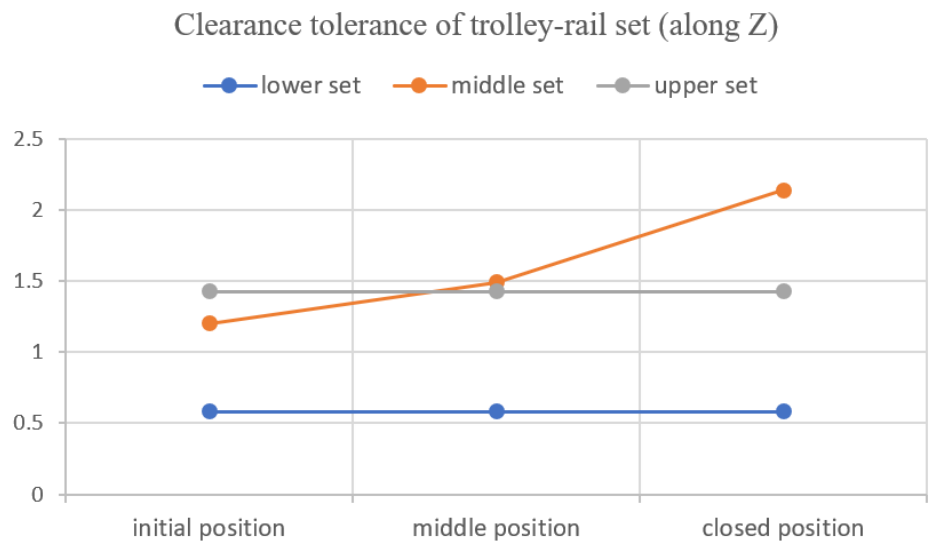



Fig. 16 Clearance tolerance tendency of different sets (along Z)

From the lower rail to the upper rail, the fluctuation range of the gap between the assembly gap and the trolley is basically larger and larger, because the design and installation of the sliding door is based on the following rail and trolley assembly. First of all, it must ensure its accuracy. In addition, the lower rail must play the dual role of bearing and guiding, and the middle rail and the upper rail play the guiding role.

During the sliding door's movement from the initial position to the closed position, the fluctuation range of the deviation gradually becomes larger. This is because during the movement of the sliding door of the car from the maximum opening to the full closing, the number of factors affecting the gap deviation gradually increases, and the degree of influence gradually increases;

With the gradual increase in the fluctuation range of the gap between the sliding door and the guide rail, problems such as insufficient constraints or interference during sliding door closing will occur.

The non-uniformity of the fluctuation range of the assembly gap deviation during the sliding door movement affects the sliding door closing smoothness and coordination of the movement, even the closing force is increased.

## 2.5 Conclusions

In chapter 2, we had the tolerance analysis of the case study of the sliding door trolley and the sliding guide assembly. First of all, we analyzed the general assembly processes and assembly problems. Then we chose the location scheme of the sliding door applying the 3-2-1 location principle. This is a step to learn the functionalities and schemes of the sliding door better and more deeply, which also is a preparation for the application of software. After that, we apply the dimensional chain model to study the gap tolerance of the assembly of the trolley and rail. We assume that the door is located in the initial position, the middle position and the closed position (with the closure increasing) respectively. Thus, we studied the upper, middle and lower trolly-rail assembly gap tolerance in these three positions separately and respectively in the Y axis and Z axis. Lastly, we gave the results study and conclusions on the mathematical results. We can find the fluctuation range of different sets and the changing tendencies when the door is closing.

# Chapter 3 Tolerance synthesis and assembly deviation optimization

## 3.1 Introduction

The assembly deviation of the sliding door rollers and the body guide rails is related to the coordination and smoothness of the entire closed door movement process, which directly affects the performance of the sliding door, which makes it possible to distribute and control the sliding door movement process and the body assembly deviation. It seems crucial. During the whole movement process, the quality of the sliding door and body assembly quality is mainly reflected in: the uniformity of the assembly gap deviation in each direction of each rail during the sliding door movement. During the movement, the better the uniformity of the assembly gap deviation, the higher the matching quality, and vice versa, the worse the matching quality. Therefore, the evaluation and improvement of the sliding smoothness and coordination of the sliding door on the vehicle body are actually the evaluation and improvement of the uniformity of the gap deviation between the rollers of the sliding door and the body guide rail.

This chapter will analyze and find the key factors that affect the accuracy of the assembly gap during sliding door movement based on the model and calculation results of the assembly deviation of the sliding door movement, and combine this key factor variable to the assembly deviation of sliding door movement. The multi-objective-based process optimization was carried out in order to achieve a certain degree of uniformity in the sliding gap between the sliding door and the body assembly gap during the entire movement. Controlling the deviation of the assembly gap during the sliding door movement within a reasonable range can not only improve the smoothness and coordination of the sliding door movement, but also reduce the closing force of the sliding door.

## 3.2 Key factors affecting uniformity of assembly deviation

During the movement of the sliding door, the deviation of the assembly gap between the guide rails and the rollers in the direction does not change much. It is only because the three guide rails have a curved arc near the closed position. The deviation of the assembly gap at this position has increased slightly.

The variation trend of the gap deviation in the direction of each guide rail: The gap deviation of the upper and lower guide rails and the roller is relatively gentle. Only the gap deviation between the middle rail and the middle roller gradually increases, and the tolerance value has increased by nearly two times from to. It can be seen from the three dimensional chain formulas that the gap between the middle rail and the middle roller in the direction is a closed loop at each position. The main reason that the deviation of the mounting gap gradually increases is the inclination of the middle rail relative to the lower rail. tolerance. Due to the expansion effect of the inclination in the direction, even if the inclination tolerance of the middle rail is not too large, the tolerance will be gradually enlarged as the sliding door moves. Therefore, it can be said that the inclination tolerance of the middle rail relative to the lower rail is a key characteristic factor affecting the deviation of the assembly gap in the direction of the middle rail and the middle roller.

From a longitudinal perspective, the gap deviation in the same direction at the same location increases from bottom to top, and this difference is determined by the different assembly status and role of each rail. Moreover, the gap deviations in the same direction at the same position affect each other.

(1) In the vicinity of the sliding door closed position, the gap deviation between the curved part of the three guide rails and the roller in the Y direction, the main influencing factor is the composite geometric characteristic tolerance of the curved part of the three guide rails.

(2) During the whole movement, the gap deviation between the middle guide rail and the middle roller in the Z direction is mainly affected by the inclination tolerance of the middle guide rail with respect to the lower guide rail.

So far, two key characteristic factors affecting the uniformity of the assembly deviation of the sliding door during the movement are determined: the tolerance of the combined geometric characteristics of the curved arc portions of the guide rails near the closed position and the inclination tolerance of the middle guide rail with respect to the lower guide rail.

## 3.3 Optimization of the assembly deviation

In the same position and same direction, since the gap deviation of each middle rail is affected by the gap deviation of the lower rail, the gap deviation of the upper rail is simultaneously affected by the gap tolerance of the middle and lower rails in the direction, and the direction is affected by the gap deviation of the middle rail influences. Therefore, the process optimization of sliding door assembly process optimization belongs to multi-objective optimization, and each gap deviation has a relationship with each other.

Multi-objective optimization is an important branch of mathematical planning. It is the optimization problem of more than one numerical objective function in a given area. It has a wide range of applications in engineering design, economic planning, plan management and other fields. In recent years, traditional multi-objective optimization methods have been greatly developed, and modern technologies such as genetic algorithms, fuzzy optimization, and neural networks have also been applied to multi-objective optimization, which has made great progress in multi-objective optimization methods. The essence of traditional multi-objective optimization method is to transform each objective function in multi-objective optimization into a single-objective function through processing or mathematical transformation, and then use single-objective optimization technology to solve.

For the purpose of this article, the assembly deviation process optimization of the sliding door movement process is based on the optimization of the gap tolerance uniformity of the guide rails and rollers in the two directions during the sliding door movement process. The objective problem is transformed into a single objective problem for processing, which is suitable for selecting the evaluation function method in the traditional multi-objective solution method. The main feature of the evaluation function method is that it can construct a function that can calculate specific data according to each sub-objective function or factor, instead of multi-objective optimization.

Combining the concept of variance and the related analysis above, this article uses the sum of the variances of the assembly gap deviation values when the sliding door moves to various positions to evaluate the uniformity of the assembly gap during the sliding door movement, in the Y direction and Z direction Construct objective functions separately.

$$f_Y(t) = f_L(TW_{L0}) + f_M(TW_{M0}) + f_U(TW_{U0})$$
$$f_Z(\alpha) = f_L(TL_{L0}) + f_M(TL_{M0}) + f_U(TL_{U0})$$
$$t \in (0.2\ , 0.5), \alpha \in (0.05°\ , 0.1°)$$
$$f_Z(\alpha) \leq 0.04,\ f_Y(t) \leq 0.04$$

Solving t and α satisfying the constraint conditions can make the assembly deviation in the two directions of the sliding door reach a certain uniformity requirement (so that the maximum value of the uniformity evaluation function of the two assembly gap deviations does not exceed 0.04).

Through the above analysis, the optimization target, optimization function, constraint conditions and other factors of the assembly deviation of the sliding door movement process have been clarified. Although the two optimization functions listed in the previous section are long and complicated, the functional relationship is quite simple. Application software or other mathematical analysis software can easily analyze the changing relationship between the variables t and α and the objective functions $f_Y$ and $f_Z$.

According to the calculation result of the software, when t = 0.2785, $f_Y$ = 0.04, that is, when the shape and position tolerance of the curved arc part of each guide rail is 0.2785, the maximum value of the uniformity evaluation function of the assembly gap deviation in the direction of the sliding door movement process is not the maximum.

More than 0.04.

According to the calculation result of the software, when $\alpha = 0.066°$, $f_Z = 0.04$, that is, when the tolerance of the inclination of the middle rail to the lower rail is 0.066 °, the value of the uniformity evaluation function of the assembly gap deviation in the direction of the sliding door movement is not more than 0.04.

Compared with the evaluation function before optimization, the value of the evaluation function of the gap deviation uniformity of the sliding door after optimization was reduced by 50.86% and 73.92%, respectively, which can be seen in the Tab. 13 below.

Tab. 13 optimization results

| variable / target function | before optimization | after optimization | comparison |
|---|---|---|---|
| t | 0.4472 | 0.2785 | |
| α | 0.1° | 0.066° | |
| $f_Y$ | 0.0814 | 0.04 | decrease 50.86% |
| $f_Z$ | 0.1534 | 0.04 | decrease 73.92% |

## 3.4 Conclusions

In chapter 3 we analyzed and found the key factors that affect the accuracy of the assembly gap during sliding door movement based on the model and calculation results of the assembly deviation of the sliding door movement, and combined this key factor variable to the assembly deviation of sliding door movement. The two key characteristic factors affecting the uniformity of the assembly deviation of the sliding door during the movement are the tolerance of the combined geometric characteristics of the curved arc portions of the guide rails near the closed position and the inclination tolerance of the middle guide rail with respect to the lower guide rail.

The multi-objective-based process optimization was carried out in order to achieve a certain degree of uniformity in the sliding gap between the sliding door and the body assembly gap during the entire movement. Controlling the deviation of the assembly gap during the sliding door movement within a reasonable range can not only improve the smoothness and coordination of the sliding door movement, but also reduce the closing force of the sliding door.

# Chapter 4 Verifications of Variational Statistical Analysis VSA software

## 4.1 Introduction of the software VSA

Manufacturers have spent millions of dollars each year on product quality issues, such as incorrect assembly of parts, scrap and rework. Deviations can cause a significant portion of expensive and time-consuming build issues and engineering changes. With the dimensional solutions from the geometrical solutions, you can create 3D digital prototypes to simulate production build processes and predict the build issues, all of which can be done before cutting an individual tool. In recent years, various types of computer aided software for tolerance analysis have been applied widely in industries such as aviation, automobile and electronic technology, which promotes the rapid development of the designing and manufacturing technologies in various industries as a result.

Tab. 14 variational analysis softwares in market

<table>
<tr><td>software</td><td>ADCATS</td><td>EAVS</td><td>3DCS</td><td>VSA</td></tr>
<tr><td>company</td><td>Brigham Young University</td><td>GM</td><td>3DCS</td><td>UG</td></tr>
<tr><td>year</td><td>1992</td><td>1997</td><td>1998</td><td>1998</td></tr>
<tr><td>method</td><td>dimensional chain</td><td colspan="3">Monte Carlo</td></tr>
<tr><td>characteristic</td><td>rigid parts</td><td>sheet parts</td><td colspan="2">rigid parts / graphical interfaces</td></tr>
</table>

The common variational analysis softwares in the market and some comparisons among them are described in Tab. 14 above. As far, the most often used softwares for vehicle development are principally 3DCS and VisVSA. Both of them are based on the Monte Carlo method to accomplish the simulations and calculations. VisVSA software is a tolerance analysis software developed by UG company based on the assumption of rigid body parts in 1998. It is now part of the Siemens UGS Team Center Visualization suite of software for visual tolerance analysis of products. By combining three-dimensional visualization, two-dimensional viewing, dynamic component analysis and collaboration tools, its VisMockup component can interact with complex visual databases and two-dimensional rendering at the initial interface. VSA is based on Monte Carlo simulation to realize the dimensional tolerance analysis of the part assembly. The specific entities and features of the tolerance are interactively obtained from the CAD system, and the features change within a specific tolerance range.

In this article the software VisVSA is introduced in order to simulate and analyze the assembly deviation of the sliding door, as well as simulating calculations compared with the mathematical method discussed in the above chapter. In this way, we can verify the rationality of the modelling and the methods. Also, we can have a look at how tolerance analysis software has improved the tolerance design process.

## 4.2 Modelling processes of VSA

This section analyzes and calculates the assembly gap deviation range of the guide rails and trolleys in the Y and Z directions, which is also known as the value of the deviation 6σ. We will use the software to establish the assembly deviation model at the initial position, the intermediate position, and the closed position that represent the sliding door movement process. After the simulation calculation is completed, the deviation distribution result can be obtained by point-to-point measurement.

Tolerance analysis software VisVSA (can not only realize the modeling and analysis of a single component installation and positioning scheme, but also consider the virtual assembly modeling of different assembly sequences of multiple parts. In addition, the software can also consider the impact of dimensional tolerances and geometrical tolerances on key dimensions, including the contribution rate and sensitivity of each component ring to the key dimension. This is a very useful tool for studying the various assembly deviations of parts and assemblies. The principle operation procedures for tolerance analysis of VSA software is shown in Fig 17 in the next page.

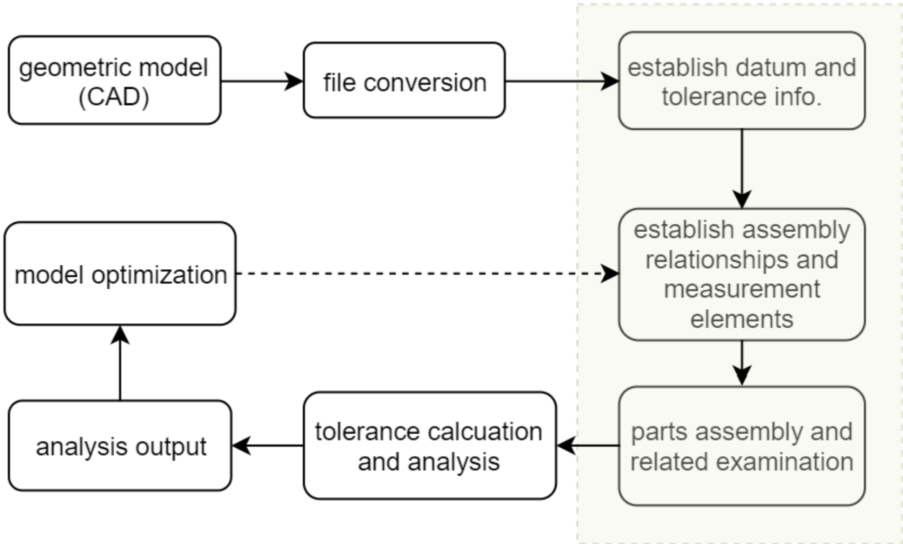
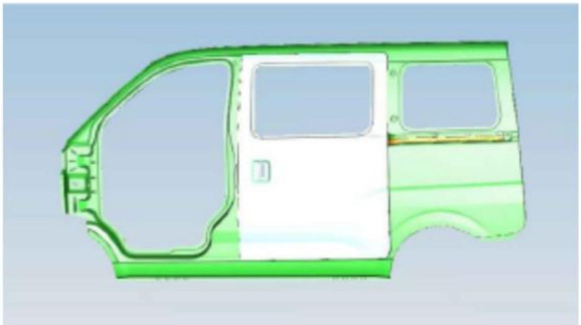



Fig. 17 VSA operation procedures

It is not possible for VisVSA (Visualization Variation Simulation Analysis) to create a 3D model. It is needed to convert the 3D model in CAD file into a recognizable file through the tools provided by itself. Then import the functions to create a functional characteristic relationship and assembly sequences for simulation.

In order to verify the validity and correctness of the assembly deviation model of the sliding door movement process based on the dimensional chain, in this chapter we will use the software to establish the assembly deviation model of the sliding door to obtain the simulation results and compare it with the former.

Before modelling in the tolerance analysis software, we need to finish the 3D model in CAD. We can see from the Fig. 18 below the assembly of the sliding door and the vehicle body. The model is composed of four sub-components, which are the side body, the sliding guides, the trolleys and the sliding door. The actual assembly sequence of the sliding door is following the rule, that is, the three guide rails are mounted on the vehicle body, three trolleys are mounted on the sliding door, and finally, the sliding door on which the trolleys are mounted is mounted on the rails on the vehicle body.



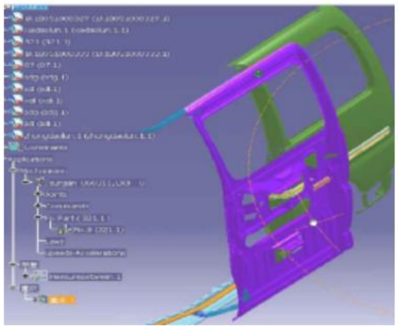


Fig. 18 Assembly of the sliding door and body

Principally, the procedures to simulate the assembly deviation are described as followings. Firstly, we define the features of points, faces, holes, pins, etc. on the part model and set the necessary feature tolerances. Secondly, define the assembly operations to determine the positioning of the parts. Thirdly, define the measurement, which is the determination of the critical dimension to be controlled. Finally, calculate the necessary simulation parameters and read the calculation results. The detailed steps are as followings.

(1) Feature extraction

Features of holes, shafts and faces are selected on the sliding doors. Features of holes, shafts, faces, and points are selected on the trolley. Take holes, faces and points on the guide rail. Find the holes, faces, and points on the side body that correspond to the three rails. Finally, according to the matching relationship between the roller and the guide rail, the positioning scheme of the sliding door on the vehicle body is determined so as to extract the corresponding positioning points and measurement points.

(2) Assembly operation

Taking into account the dimensional tolerances and geometric feature tolerances of each component, the three guide rails are assembled on the vehicle body in turn. Then, the bracket roller is used as an integral part, and the assembly process is completed according to the selected installation positioning holes and positioning points. Finally, the sliding door equipped with the bracket roller is mounted on the body rail as a whole. The positioning and coordination of the above three steps are the assembly operations required in the assembly deviation modeling of sliding doors.

Consider different factors in different positions to complete the assembly operation of the three positions representing the entire movement process of the sliding door.

(3) Measurement operation

After the assembly process of the sliding door and the vehicle body is completed, according to the operation requirements of the software, point features are extracted near the inside of each guide rail and roller that needs to measure the gap deviation. When setting point-to-point measurement operations, in order to ensure accuracy, pay attention to the consistency of the normal direction, that is, to maintain the consistency of each group of measurement operations with the Y and Z directions. The distance between the points is used to simulate the matching gap between the guide rail and the roller in both directions, and the size of the gap and the deviation 6σ can be thus calculated. The setting points and gaps are represented in Fig. 19.

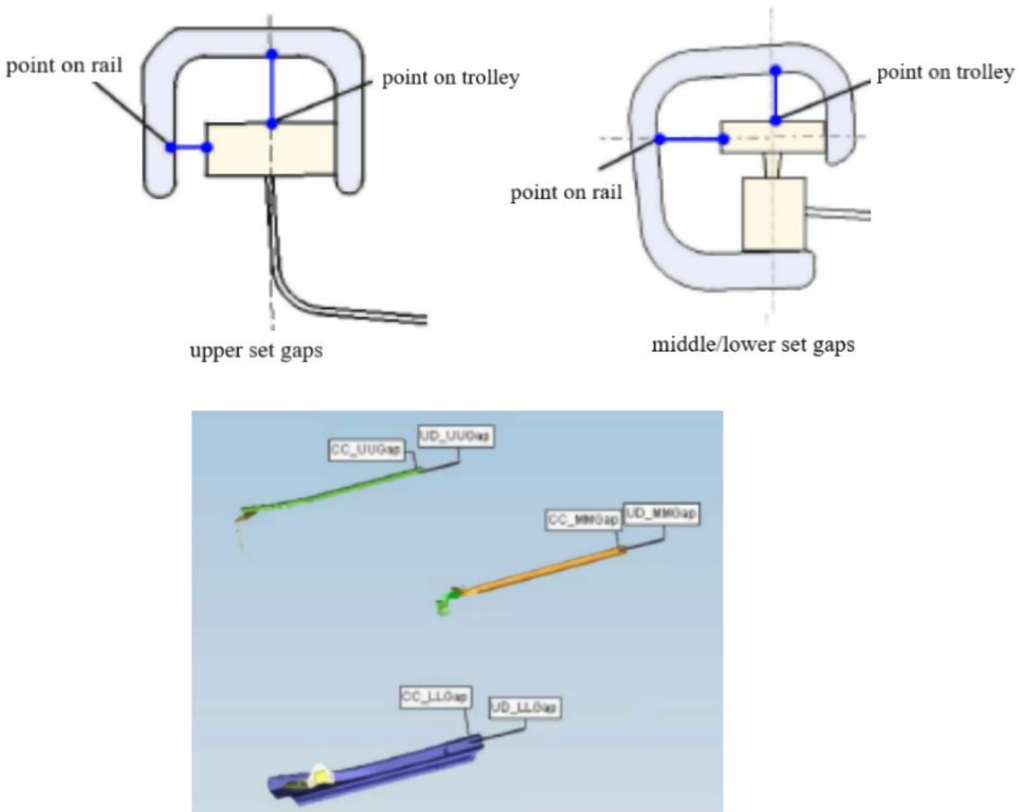



Fig. 19 Setting points and gaps

(4) the Monte Carlo sampling value is set to be 5000. The tolerance setting can refer to Tab. 15.

Tab. 15 tolerance setting table

| tolerance | symbol | value |
|---|---|---|
| profile of a surface of the measuring point | ⌓ | 0.025 |
| flatness of rail inner side | ▱ | 0.1 |
| circularity of trolley | ○ | 0.1 |
| diametral tolerance of trolley | | 0.3 |
| tolerance of interval between rail inner sides | | 0.4 |
| tolerance of distance between rails | | 0.4 |
| tolerance of distance between trolley brackets | | 0.4 |
| tolerance of rail wall thickness | | 0.1 |
| flatness of rail outer side | ▱ | 0.2 |
| flatness of rail track on door | ▱ | 0.2 |
| flatness of  trolley bracket | ▱ | 0.2 |
| flatness of trolley bracket on door side | ▱ | 0.2 |
| position of location hole on bracket | ⌖ | 0.4 |
| position of location hole on bracket on door | ⌖ | 0.4 |
| angularity of middle rail w.r.t lower rail | ∠ | 0.1° |
| parallelism of upper rail w.r.t lower rail | // | 0.4 |
| position of rail closing arc center | ⌖ | 0.4 |
| profile of the rail closing arc | ⌒ | 0.4 |

(5) Simulation calculation results

This step will be explained in the following part.

## 4.3 Comparison of mathematical and VSA simulated results

Tolerance analysis software is used to model the assembly deviation of the sliding door of the car. The final simulation results are shown in the table. The Fig. 20 and Fig. 21 in the next page show the display interface of the VSA software in which the sliding gap door is in the closed position as an example, indicating the outcome view on the 3D windows and the 6σ value of calculation result simulated by VSA. The simulation results of the assembly gaps are calculated by software, which is shown in the Tab. 16 in the following.

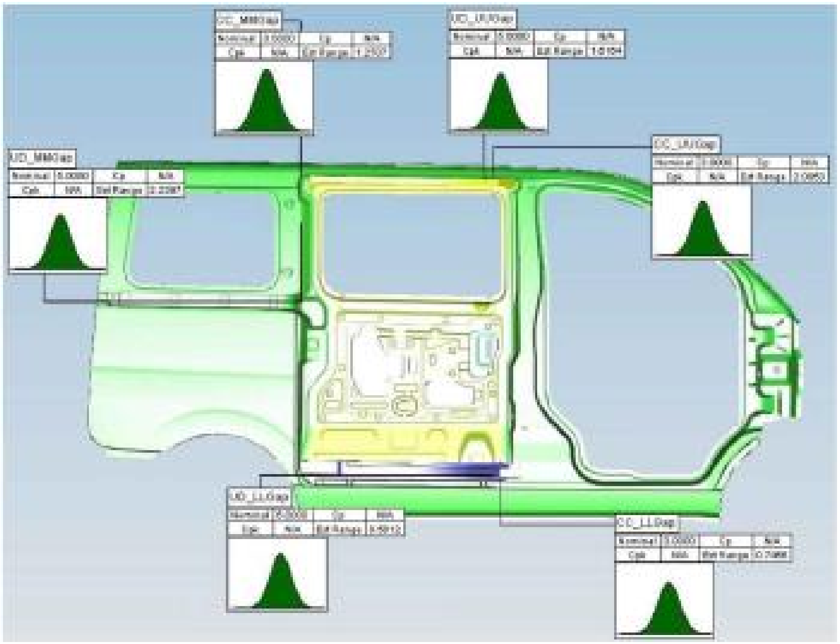



Fig. 20 outcome view on the 3D windows of VSA software

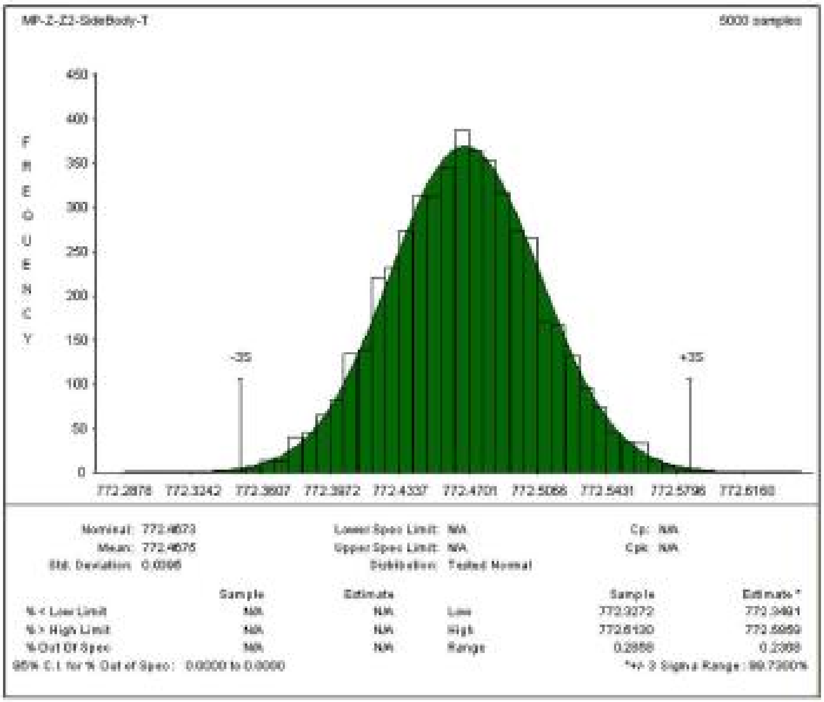



Fig. 21 6σ value of calculation result simulated by VSA

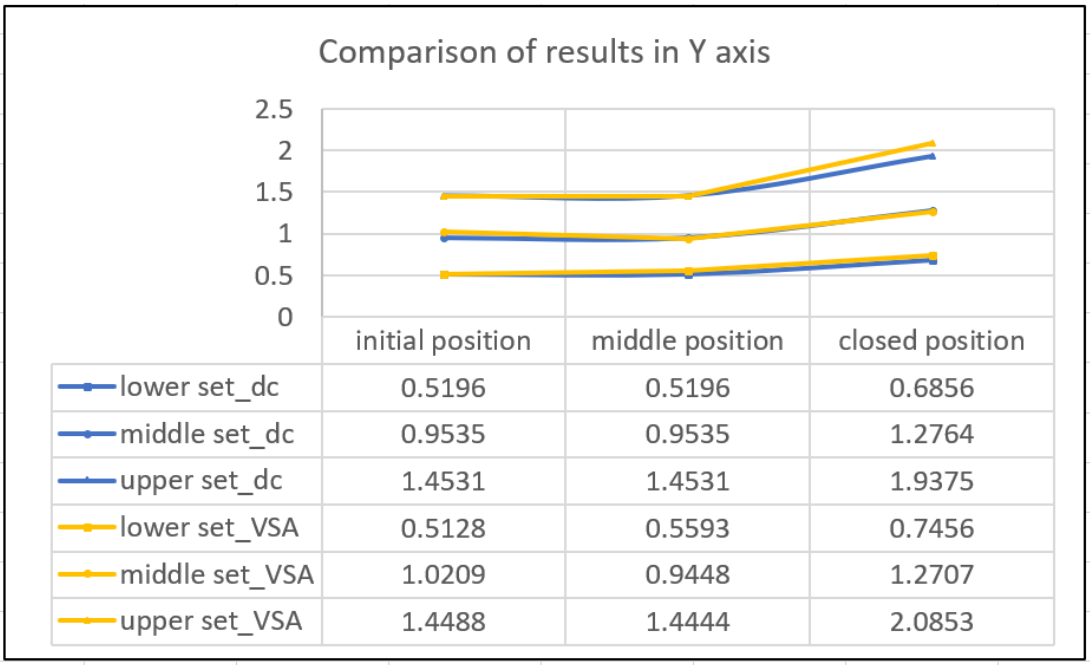
Tab. 16 simulation results of assembly gaps by VSA

| clearance of closed ring | initial position | middle position | closed position | avg. value |
|---|---|---|---|---|
| $TW_{L0}$ (Y) | 0.5128 | 0.5593 | 0.7456 | 0.6059 |
| $TW_{L0}$ (Z) | 0.5478 | 0.8186 | 0.5812 | 0.6492 |
| $TW_{M0}$ (Y) | 1.0209 | 0.9448 | 1.2707 | 1.0788 |
| $TW_{M0}$ (Z) | 1.2187 | 1.4332 | 2.2397 | 1.6305 |
| $TW_{U0}$ (Y) | 1.4488 | 1.4444 | 2.0853 | 1.6595 |
| $TW_{U0}$ (Z) | 1.3666 | 1.3425 | 1.6164 | 1.4418 |

So far, this section has established the assembly gap deviation model of the sliding door during the movement process of the sliding door through two modeling methods, namely the dimensional chain and simulation, and both have obtained the calculation results. In the following, the Tab. 17 shows the comparison of the specific data of the calculation results of the fluctuation range of the assembly gap deviation in each direction of the sliding door movement process.

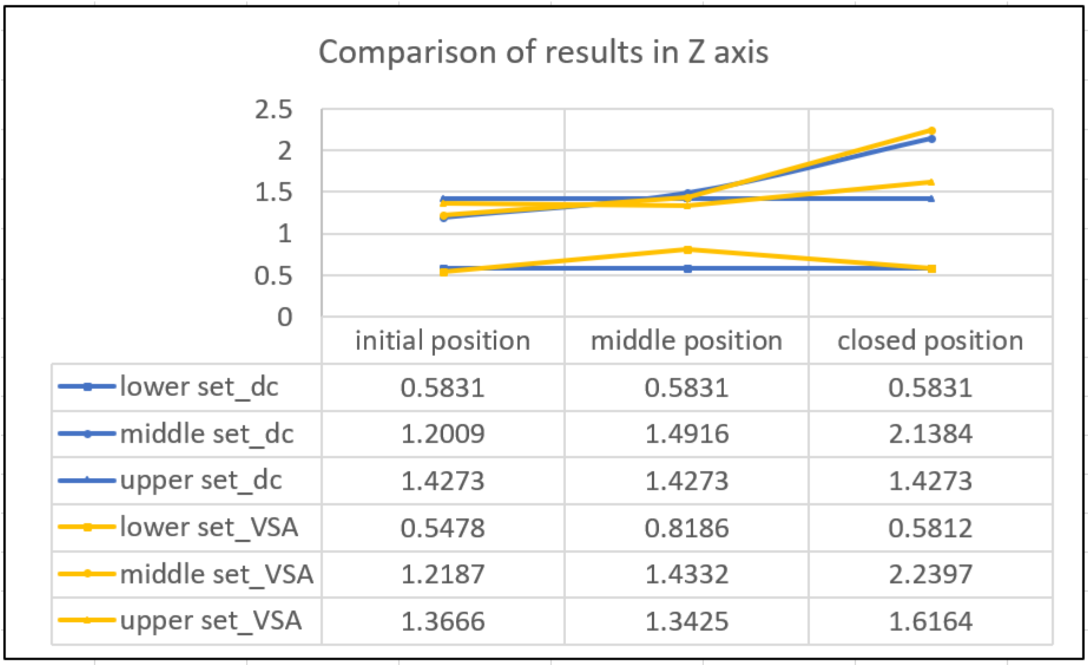
Tab. 17 comparison of results of two modelling

| position | clearance | dimensional chain | Vis_VSA |
|---|---|---|---|
| initial | $TW_{L0}$ (Y) | 0.5196 | 0.5128 |
| | $TW_{L0}$ (Z) | 0.5831 | 0.5478 |
| | $TW_{M0}$ (Y) | 0.9535 | 1.0209 |
| | $TW_{M0}$ (Z) | 1.2009 | 1.2187 |
| | $TW_{U0}$ (Y) | 1.4531 | 1.4488 |
| | $TW_{U0}$ (Z) | 1.4273 | 1.3666 |
| middle | $TW_{L0}$ (Y) | 0.5196 | 0.5593 |
| | $TW_{L0}$ (Z) | 0.5831 | 0.8186 |
| | $TW_{M0}$ (Y) | 0.9535 | 0.9448 |
| | $TW_{M0}$ (Z) | 1.4916 | 1.4332 |
| | $TW_{U0}$ (Y) | 1.4531 | 1.4444 |
| | $TW_{U0}$ (Z) | 1.4273 | 1.3425 |
| closed | $TW_{L0}$ (Y) | 0.6856 | 0.7456 |
| | $TW_{L0}$ (Z) | 0.5831 | 0.5812 |
| | $TW_{M0}$ (Y) | 1.2764 | 1.2707 |
| | $TW_{M0}$ (Z) | 2.1384 | 2.2397 |
| | $TW_{U0}$ (Y) | 1.9375 | 2.0853 |
| | $TW_{U0}$ (Z) | 1.4273 | 1.6164 |




| | initial position | middle position | closed position |
|---|---|---|---|
| lower set_dc | 0.5196 | 0.5196 | 0.6856 |
| middle set_dc | 0.9535 | 0.9535 | 1.2764 |
| upper set_dc | 1.4531 | 1.4531 | 1.9375 |
| lower set_VSA | 0.5128 | 0.5593 | 0.7456 |
| middle set_VSA | 1.0209 | 0.9448 | 1.2707 |
| upper set_VSA | 1.4488 | 1.4444 | 2.0853 |

Fig. 22 comparison of results in Y axis




| | initial position | middle position | closed position |
|---|---|---|---|
| lower set_dc | 0.5831 | 0.5831 | 0.5831 |
| middle set_dc | 1.2009 | 1.4916 | 2.1384 |
| upper set_dc | 1.4273 | 1.4273 | 1.4273 |
| lower set_VSA | 0.5478 | 0.8186 | 0.5812 |
| middle set_VSA | 1.2187 | 1.4332 | 2.2397 |
| upper set_VSA | 1.3666 | 1.3425 | 1.6164 |

Fig. 23 comparison of results in Z axis

We can compare the results in the Y axis and in the Z axis respectively, as shown in Fig.22 and Fig. 23. The calculation results of the assembly deviation modeling based on the dimensional chain of the sliding door movement process are basically consistent with the simulation results of the software-based sliding door assembly process simulation deviation, and the change trend of the assembly gap deviation 6σ value is also basically the same. This illustrates the validity and correctness of the assembly deviation modeling method based on the dimensional chain sliding door movement process described above. From the perspective of the modeling process, the assembly deviation modeling method based on the dimensional chain sliding door movement process takes into account both efficiency and calculation accuracy, and has its own advantages compared with the simulation modeling method. In a word, the assembly deviation modeling method of sliding door movement process based on dimensional chain can be used to analyze the deviation distribution of sliding door and body parts assembly. This provides a reference for the design, assembly and manufacture of sliding doors.

## 4.4 Conclusions

In chapter 4, we had an introduction of the VSA (Variational Statistical Analysis) software. The five general steps of the modelling processes of VSA are introduced. Also, we compared the mathematical results achieved in chapter 2 with the software simulated results. We can find that these two kinds of results are generally coincide.

# Chapter 5 Summary and Outlook

In chapter 1, the basic concepts about GD&T (Geometrical Dimensioning and Tolerancing) are introduced. First of all, the background of GD&T is briefly given, including the importance of such a technology, the basic idea of GD&T, the advantages and the disadvantages of GD&T. We can know that GD&T is of great importance to the quality control and cost control processes. Thus, the application of GD&T to industrial products is necessary and useful. Secondly, the concepts about the tolerance design is described, in which two basic ideas are introduced, that are the tolerance analysis and the tolerance synthesis. We introduce the general methods used in the tolerance analysis and the usual problem to solve in the tolerance synthesis, which is related with the optimization issues. In general, the tolerance synthesis is the method to solve the tolerance of the closed ring with known component rings, while the tolerance synthesis is the method to find the optimal solutions of the tolerances of the component rings with the required closed ring. Last but not least, some general terms that are related with GD&T and that are referred in this thesis are introduced in the conceptual point of view.

To deploy the case study, we choose the sliding door and sliding guide assembly as case study in this thesis. In chapter 2, we had the tolerance analysis of the case study of the sliding door trolley and the sliding guide assembly. First of all, we analyzed the general assembly processes and assembly problems. Then we chose the location scheme of the sliding door applying the 3-2-1 location principle. This is a step to learn the functionalities and schemes of the sliding door better and more deeply, which also is a preparation for the application of software. After that, we apply the dimensional chain model to study the gap tolerance of the assembly of the trolley and rail. We assume that the door is located in the initial position, the middle position and the closed position (with the closure increasing) respectively. Thus, we studied the upper, middle and lower trolly-rail assembly gap tolerance in these three positions separately and respectively in the Y axis and Z axis. Lastly, we gave the results study and conclusions on the mathematical results. We can find the fluctuation range of different sets and the changing tendencies when the door is closing.

The sliding door assembly is located at the most downstream of the body assembly process. Its matching quality with the vehicle body has the most direct impact on the comprehensive performances of the vehicle's tightness, wind noise and the coordination and smoothness of the closing door movement, as well as the appearance of the model.

This article focuses on the matching problems and motion problems that often occur in the assembly of sliding doors and bodyworks of cars. Based on the analysis of the connection and matching characteristics of the sliding door with the body side wall when the sliding door is closed, the positioning scheme of the sliding door with the body side wall when the sliding door is closed is selected, and the assembly deviation model is established. Based on the connection with the guide rail in the process and the characteristics of the movement, the assembly deviation model of the sliding door movement process based on the dimensional chain is established. Finally, according to the uniformity requirements of the assembly gap deviation during the sliding door movement process, the objective function of assembly deviation process optimization is combined with related mathematical analysis tools to optimize the key characteristic factors that affect the uniformity of gap deviation.

In chapter 3 we analyzed and found the key factors that affect the accuracy of the assembly gap during sliding door movement based on the model and calculation results of the assembly deviation of the sliding door movement, and combined this key factor variable to the assembly deviation of sliding door movement. The two key characteristic factors affecting the uniformity of the assembly deviation of the sliding door during the movement are the tolerance of the combined geometric characteristics of the curved arc portions of the guide rails near the closed position and the inclination tolerance of the middle guide rail with respect to the lower guide rail.

The multi-objective-based process optimization was carried out in order to achieve a certain degree of uniformity in the sliding gap between the sliding door and the body assembly gap during the entire movement. Controlling the deviation of the assembly gap during the sliding door movement within a reasonable range can not only improve the smoothness and coordination of the sliding door movement, but also reduce the closing force of the sliding door.

In chapter 4, we had an introduction of the VSA (Variational Statistical Analysis) software. The five general steps of the modelling processes of VSA are introduced. Also, we compared the mathematical results achieved in chapter 2 with the software simulated results. We can find that these two kinds of results are generally coincide.

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