# Characteristics of Repeatability Tests of Vehicle Body Assembly Fixtures and Considerations for Repeatability Tests

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***Abstract* — The dimensional repeatability of assembly fixtures plays a determinant role on the geometrical and dimensional quality of vehicle body assemblies. The fixture quality with good design should be tested and verified on the manufacturing floor. The sheet metal parts of vehicle bodies have compliance characteristics, which are different from those of conventional rigid parts. Addressing the non-rigid parts of vehicle body assembly, this paper reviews the fixture repeatability tests and their characteristics. The paper discusses the key factors, such as measurement point selection, passing criteria, sample size, pin-hole conditions, and possible part wear, of such repeatability tests. The paper also reviews the fixture repeatability tests using a laser tracker and a go/no-go gauge pin. Based on the study, the paper provides the recommendations for effective fixture repeatability tests of the vehicle body assemblies.**

***Keywords — Dimensional Quality; Assembly Fixture; Repeatability; Sheet Metal Parts***

## I. Introduction

### A. *Fixtures for Vehicle body Assembly*

A vehicle body consists of hundreds of sheet metal parts that have unique complex shapes and various sizes from 0.1 m to over 2 m. In addition, the thickness of sheet metal parts varies from 0.6 mm to 2.8 mm. Compared with rigid and machined parts, the sheet metal parts are very flexible or compliant in terms of shape.

In vehicle body manufacturing, sheet metal parts and subassemblies are assembled to form a vehicle body. The assembly fixtures ensure that the geometrical positions and shapes of sheet metal parts and subassemblies are accurate and precise during various assembly operations, such as welding, riveting, and gluing.

The positioning function of assembly fixtures for the parts and subassemblies is executed using locating pins and blocks. The pins insert into the precision holes and slots on the parts, while the blocks control the surfaces of the parts. Normally, the locating pins and blocks of a fixture are called PLPs (Principal Locating Points). One of the key elements of fixture dimensional quality is the precision of pins and blocks to locate the parts.

The uniqueness of sheet metal parts must be addressed in the assembly fixture design for vehicle body manufacturing. An "N-2-1" locating principle was proposed based on the conventional "3-2-1" locating rigid parts [1]. A reconfigurable modular fixture was developed subject to a discrete number of point forces [2]. The impact of fixture position on the dimensional quality of sheet metal parts was also studied, considering the part variation, tooling variation, and subassembly spring-back [3]. Addressing the non-rigid nature of sheet metal parts, fixture optimization for automotive dimensional quality is also an active research topic. For example, the optimization was applied on fixture layout [4], locator positions [5], unilateral fixture [6], and clamping sequence [7]. All the research contributed to the better understanding and quality improvement of new fixture design in the vehicle body manufacturing.

### B. *Significance of Fixture Dimensional Quality*

A fundamental quality requirement on assembly fixtures is its dimensional accuracy, which is the closeness of fixture units to their design intends in terms of position. The accuracy of a fixture unit can be ensured by appropriate design and fabrication. The verification of the dimensional accuracy of locating pins and blocks can be directly measured without product parts.

The positioning repeatability, in contrast, is about the measurements of position variation of the parts when they are positioned and secured in an assembly fixture. The dimensional quality of assembly fixtures with good design should be verified on the manufacturing floor. Therefore, the measurement process should simulate the situations of the parts in manufacturing operations. The corresponding test procedure is called a fixture repeatability (FR) test.

Regarding FR tests, some studies were on the fixtures for rigid parts [8]. However, little research published focuses on the assembly fixtures for non-rigid sheet metal parts. A recent study was on the repeatability of a single, 305×406 mm flat part in a laboratory environment [9], which may be a good starting point. More FR studies are needed for complex-shaped parts in the assembly manufacturing of vehicle bodies.

Therefore, this paper tries to study and review the dimensional quality of fixtures with focus on the repeatability tests, address their unique characteristics for sheet metal parts.

## II. CHARACTERISTICS OF FR TESTS

### A. *Prerequisites of FR Tests*

The objectives of fixture dimensional quality tests are to verify that a fixture unit is built to the design specifications and able to position parts accurately and repeatability. Before conducting a repeatability test, there are four requirements must be met.

The first one is the readiness of instrument and fixture. The preparation tasks include verified measurement instrument certification, levelness and flatness of fixture base, fixture fabrication and assembly, and fixture design data availability, etc.

The second is the dimensional accuracy assurance of fixture locating elements, which is to make sure that the sizes and positions of fixture locators (PLPs) are accurate. The fixture dimensional accuracy is evaluated by measuring the sizes and positions of PLPs. The evaluation process is simple – just to verify whether the PLPs meet the design specifications. The passing criteria of dimensional accuracy varies from an automaker to another. Normally, the pin locations should be < ± 0.25 mm to the designed positions. For a locating block, its surface should be < ± 0.25 mm to the design nominal.

If the measurement data show that a pin or a block is off location, then the pin or block needs to be adjusted by changing shims. According to the NAAMS standards [10], the shims are commonly available in 0.25 mm increments starting at 0.25 mm ±0.03 of thickness. After a shim adjustment, the affected fixture units should be measured again to verify.

The third requirement is about the parts and their working conditions in the fixture units. Various items should be checked. A readiness checklist, refer to Table 1, can be used as a guidance [11].

The fourth test prerequisite is the repeatability verification of the measurement instrument itself on site. The verification can be conducted by measuring parts 25-30 times when they stay in the fixture. Such a test may be called a static test as the parts and fixture units are stationary. A good result from a static test should be around 0.05 mm in six standard deviations (or 6σ) of the measurement data.

TABLE I. READINESS CHECKLIST FOR FR TESTS

| Process and Fixture | Yes | No | N/A |
|---|---|---|---|
| Entire station tooling is properly functional. | | | |
| All clamps are properly functional. | | | |
| Clamps work in the designed sequence. | | | |
| No interference between parts and fixture. | | | |
| **Product and Dimensional** | **Yes** | **No** | **N/A** |
| Parts are with the latest change level. | | | |
| Holes on parts meet design tolerance. | | | |
| GD&T datum scheme is verified. | | | |
| There is no visible damage on parts. | | | |
| **Test Preparation** | **Yes** | **No** | **N/A** |
| Measurement target placement is agreed. | | | |
| Test passing criteria is agreed. | | | |
| Measurement setup (benchmarks, etc.) is verified. | | | |
| Test instrument has passed a static test. | | | |
| If it is the 2nd test, corrective action is completed. | | | |

### B. *Process of FR Test*

After the four conditions are met, it is ready to verify the dimensional repeatability and consistency of fixture functions. Different from the dimensional accuracy assurance, an FR test must be conducted with sheet metal parts to simulate the production operations in manufacturing environment. In other words, the parts will be measured every time after being loaded and positioned again. To avoid introducing the variation of reproducibility, the part loading and unloading should be performed by one worker in the same manner. The overall FR test flow is designed as Fig. 1 shows [11].

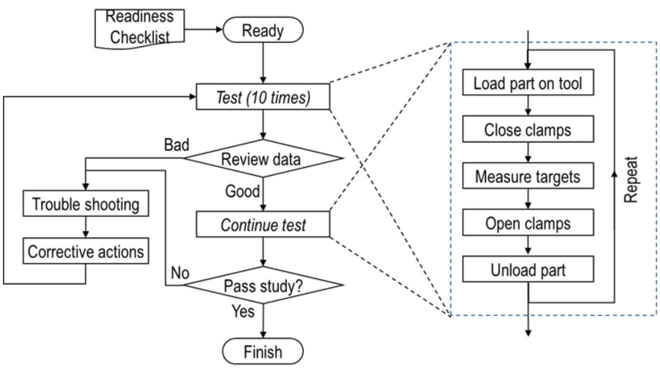


Fig. 1. A process of FR tests.

During an FR test, it is important to monitor the measurement data. After the first ten times of measurements, it is advisable to have a quick review on the data. If the results of the first ten measurements of an FR test are significantly higher than the predefined passing criterion, the test should be stopped to find the root cause as the continuation of the test likely fails to meet the passing criterion. One useful way is to check whether a data trend exists. A gradual move in a data set, like an example in Fig. 2, indicates part location loosing over time [11].

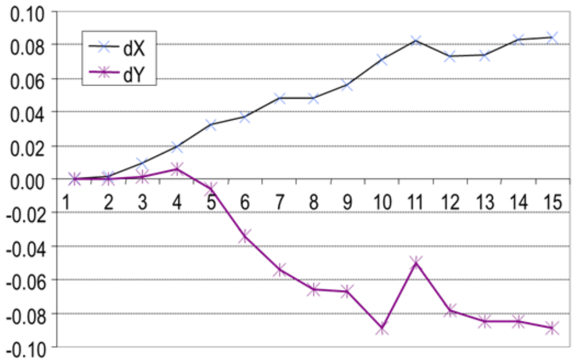


Fig. 2. Data trend example in an FR test.

If a significant spike or outlier shows up in a data run chart, it is likely due to an interference between the parts and/or between a part and a component of the fixture. Carefully checking the part relationship with all fixture components can often find the root cause, such as a proximity sensor touching a part.

After an FR test, the final step is to review the test results and complete the test document. An example of FR test result is shown in Fig. 3 [11]. For this example, fourteen points on parts were measured in the FR test. Most of them have two or three directions measured. The variation, in terms of 6σ, of all the measurement points is less than 0.25 mm.

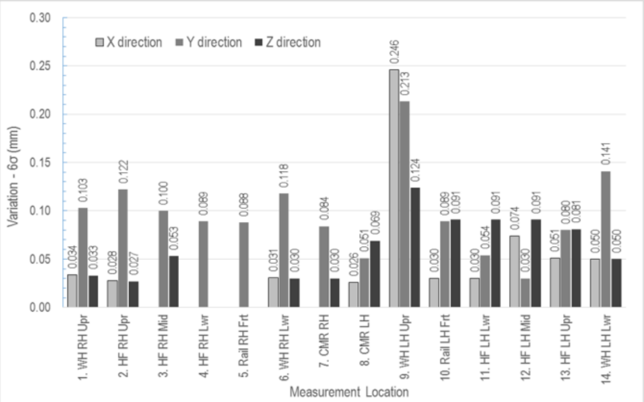


Fig. 3. An example results of an FR test

### C. Equipment for FR Tests

Laser trackers, an example shown in Fig. 4 a) [12], are widely used for dimensional quality tests because of the accuracy and functionality of laser trackers. Their manufacturers include FARO and Leica. The main specifications of their laser trackers are listed in Table 2 [12, 14]. Other instruments for an FR test may be a portable CMM (Coordinate Measurement Machine) or a theodolite [13].

TABLE II. SPECIFICATIONS OF LASER TRACKERS

| Item | Leica LTD 640 | Faro Xi |
|---|---|---|
| Accuracy of coordinate | ±10 μm/m | 18.1 μm/m + 3 |
| Accuracy (DMI) | ±10 μm/m ± 0.5 | 1.8 μm + 0.4 |
| Repeatability (DMI) | ±2 μm/m | ±1 μm |
| Resolution (DMI) | 1.26 μm | 0.158 μm |
| Work range (distance) | 40 m | 35 m |
| Work range (elevation) | ±45° | -50 – +75° |

The operating principle of a laser tracker is to steer a laser beam between the instrument home and a measurement target. When adjusting and measuring two gimbal angles, the position of the target is calculated from the two angles and the distance. A target of a laser tracker is a sphere-mounted retroreflector (SMR). It comprises an apex of the mirrors coinciding with the center of curvature of a precision ball, shown in Fig. 4 b).

a)

b)

Fig. 4. Laser tracker and SMR for FR tests.

The laser tracker measures a radial distance based on distance measuring interferometry (DMI) mode. SMR must first be locked by the tracker to establish its initial location and then glued on the target position. Once the SMR initial location is established, the laser track can calculate the exact location changes of an SMR during a test.

### D. Alternative Repeatability Test

A FR test can be conducted without expensive laser measurement instruments. A simple way may be called “witness hole” or “drill panel study”. Its process starts with drilling holes on sheet metal parts when they are in their designed positions in an assembly fixture. After the parts are unloaded, reloaded, and positioned again, the holes on the parts should be well lined up, which indicates the individual parts held by the fixture on the same positions repeatedly. That can be verified using a stab gauge pin, as shown in Fig. 5 [11].

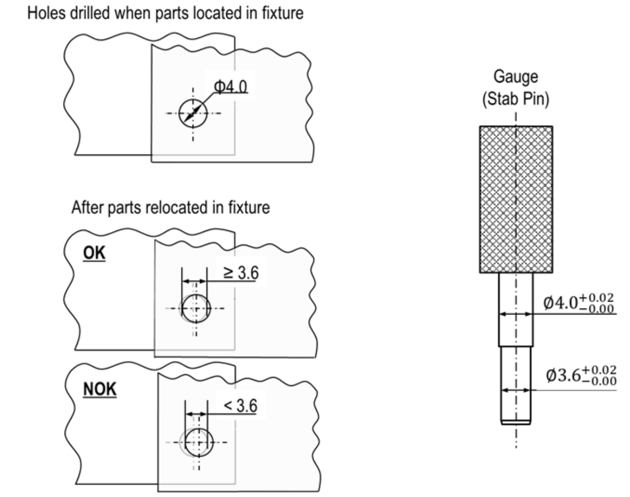


Fig. 5. Simple FR test using stab gauge pin

The passing criteria should be pre-established, say the location change of parts should be less than 0.20 mm. Then, the passing diameter of a stab pin is 3.6 mm for the holes of 4.0 mm diameter. In case that the 3.6-mm stab pin cannot be inserted into a hole, the relative locations of the parts change more than 0.20 mm after they repositioned. Similar to using a laser tracker, multiple witness holes at various locations are need for a FR test and the parts need be reloaded and measured multiple times.

This inexpensive way for FR tests is proven effective [15] in production environment. However, the conclusion from such a test is just pass or not pass, without quantitative unrepeatability.

## III. Considerations for FR Tests

Aforementioned, the majority of vehicle body parts are made of sheet metal workpieces with thin thickness. With few exceptions, vehicle body parts cannot be consider rigid. This is obvious for the large parts during assembly operations when assembly forces apply. Due to the compliant nature of parts, the FR tests for vehicle body parts must be under special considerations.

### A. *Quantity of Measurement Points*

The selection of measurement points should be based on the characteristics of non-rigid sheet metal parts. If a panel were rigid, it would be sufficient to have two measurement points on the panel. Because of the non-rigid nature of the sheet metal parts, multiple points should be placed on the parts.

To assess the location and its variation, a guideline is needed on the minimum quality of measurement points. Normally, at least three measurement points (targets) should be placed on a part, except for very small ones (length < 150 mm) having two points. Additional points are needed for larger parts or subassemblies. As an example, there are eight measurement points placed on a body side panel (Fig. 6) [11]. In general, a mid-sized part needs about five points and large one (length > 1.5 m) needs eight points to fully represent the dimensional precision of a part because of its compliant nature.

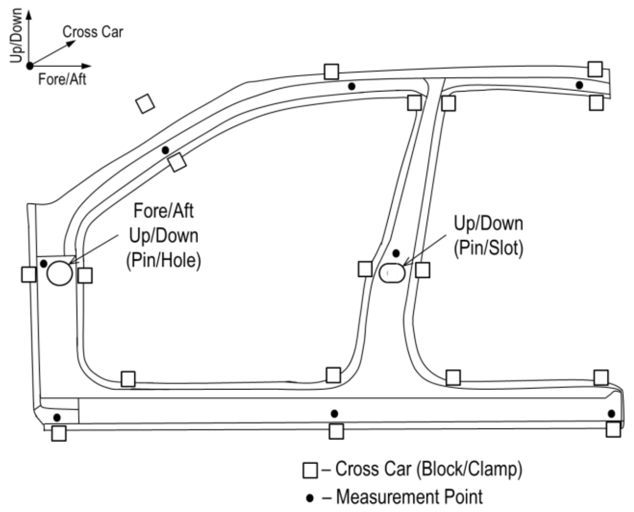


Fig. 6. An example of measurement points of an FR test.

### B. *Locations of Measurement Points*

The location selection of the measurement points is an important preparation task for an FR test. First, the measurement points should be on the locations where high dimensional quality required. For example, the dimensions of door openings of a vehicle body are critical to the door fit quality, in terms of gap and flushness between doors and a body, as well as door closing effort. Some joint areas between different parts can be another example that needs high dimensional quality.

The requirements for such critical features are normally specified in product design to ensure the automotive functionality and quality. These features are focal points in the assembly process planning and fixture design. Generally, the locators are designed to control the critical points of part dimensional quality. Therefore, most of the measurement points should be placed on or near the critical features, as shown in Fig. 6.

For an analysis reference purpose, a few measurement points should also be placed on the fixture base, fixture structure, and movable fixture units if applicable. The measurements on the fixture can be used later for a correlation analysis between parts and fixture to find out the source of part variation. Figure 7 shows an example of measurement targets in an FR study [11]. Measurement target “A” is glued on a sheet metal part; “B” is on a fixture.

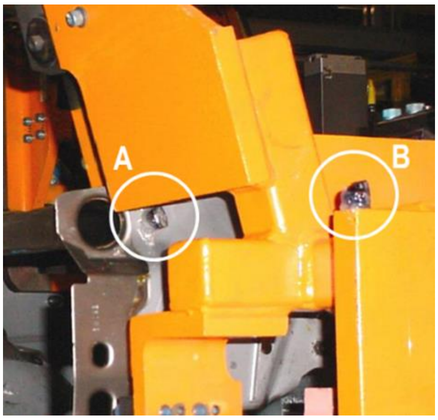


Fig. 7. Acual measurement targets in an FR test.

### *C. Measurement Directions of Points*

Furthermore, to get satisfactory information of location and its variation, it is often the case that more than one direction (of Fore/Aft - X, Cross Car - Y, and/or Up/Down - Z) of a point are measured. Determination of two or three directions to measure relays on the significance of the directions of a point. For instance, the pin/hole of the body side panel is a principal datum controlling two directions, or Fore/Aft and Up/Down. Therefore, the measurement point nearby the pin/hole should be measured in all three directions. In contrast, the front lower point of the body side panel (the left lower point in Fig. 6) can be measured in Cross Car and Up/Down directions. In case of uncertainty, all three directions should be measured. The data in an unimportant or less meaningful direction can be disregarded later.

### *D. Passing Criteria and Locating Gap*

The passing criterion of a FR test are normally < 0.25 mm in 6σ. The main consideration for the criterion is the fit condition between a locating pin and a hole on a part, which is designed as a clearance fit. There is an inherent gap (Fig. 8) between a pin and a hole, which slightly reduces the precision of part location.

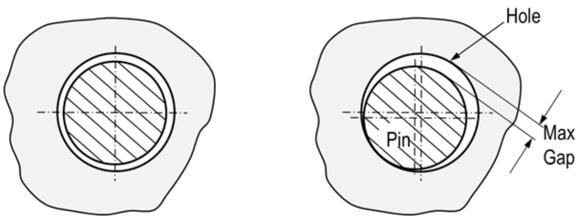


Fig. 8. Situations of gap between a locating pin and a hole.

By the NAAMS standards, the size of a pin is its nominal dimension ±0.05 mm and the size of a hole is nominal $-0.15^{+0.00}_{-0.02}$ mm. Then, the resultant clearance (or gap) can be anywhere between 0.10 and 0.22 mm. The gap median is 0.16 mm. Therefore, considering other sources of variation, such as a small movement of the fixture as a whole, it is reasonable that the criterion of FR tests is at 0.25 mm in 6σ.

However, in rare cases when the smallest pin applies to the largest hole, the maximum gap between the pin and the hole is 0.22 mm, which still meets the NAAMS standard. With this possibly largest gap, it can be difficult to get an FR test less than 0.25 mm in 6σ, as the gap alone is 0.22 mm. Therefore, 0.30 mm in 6σ of FR results may be acceptable provided that the maximum 0.22 mm gap measured from the actual sizes of a pin and a hole.

### *E. Sample Size of Repeatability Test*

In general, an FR test, like GR&R (gauge repeatability and reproducibility), needs to run multiple times, say 25 times, to be statistically reliable. However, the locating holes on thin sheet metal parts may be worn out because of multiple loading and unloading actions, as the holes are not designed for that many times of usage. In such situations, over 20 times measurements without the wearing of hole may not be practical. Therefore, the sample size may be reduced to fifteen or even to ten, if meeting two conditions. One is the thickness of parts is less than 1.0 mm; the other wearing is visible or proved by a slow trend in the measurement data. In no circumstances, the sample size should be less than five.

When the measurement times or sample size of data is less than 15, an FR test result should be evaluated based on the range of data on every point and direction, instead of six standard deviation (6σ). The passing criterion may keep the same as 0.25 mm. In other words, the ranges of all measurement points of an FR test should be < 0.25 mm in terms of range.

## IV. Closing Remarks

This paper examines the dimensional repeatability assurance of vehicle body assembly fixture, addressing the compliant characteristics of sheet metal parts of vehicle bodies. The paper discusses the test conditions, process flows, and main steps of fixture repeatability tests for sheet metal parts. The paper also reviews the FR test process using a laser tracker and a go/no-go gauge pin.

The paper investigates the key factors in the FR tests and makes recommendations. The recommended quantity of measurement points is three for a small part, while more points needed on mid-sized and large parts. The locations of measurement points should be placed on the critical features and areas of parts and subassemblies, normally near the fixture locators designed on the critical features. In addition, the normal passing criteria of FR tests is 0.25 mm in terms of six standard deviations with sample size of 25 or more. Addressing the locating pin-hole fitting conditions and part wearing out, the passing criteria and sample size of the FR tests may be compromised.

The good understanding and guideline of FR tests and the major considerations for the non-rigid vehicle body parts can be beneficial for the effective FR tests and their standardization in the automotive industry. Please refer to [11] for the additional information of the fixture development, locating principles, dimensional accuracy and repeatability, and quality assurance certifications for vehicle assembly manufacturing.

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