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Research Article

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Dimensional Variation Analysis in Vehicle Design and Development: A World Class Quality Assurance Method

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Abstract

In Vehicle Development process, Dimensional Management is used as a preventive quality assurance method to ensure fulfilment of aesthetic and functional requirements to meet the world class quality standards. This makes it possible to eliminate potential issues at the initial stage of the product design and optimizing the geometrical robustness of the design. In this paper, we have demonstrated a Dimensional Variation Analysis (DVA) use case to understand the DVA simulation methodology for reducing dimensional variation as well as a study on the root cause variation by introducing the Fitment Failure Analysis (FFA) process. It is performed at system level and its effects are observed at vehicle level. We have also explained the geometrical tolerance effects arising from assembly to vehicle packaging points to meet vehicle layout and piping, wire, and tube packaging requirements in all affected vehicles as per DMU guidelines. An issue from Vehicle DMU review feedback of exhaust system assembly has been chosen to perform DVA simulation.

Keywords

Dimensional variation analysis, Fitment failure analysis, Dimensional management, Exhaust system

Introduction

Shortening launch time, the period from customer voice capturing to ramped up production, while simultaneously satisfying the world class quality requirements is a priority of the OEMs. It can be achieved by capturing all major issues from history base vehicle data, benchmark data, digital simulation, improving the IPTV value, B10 life, etc.

The DVA is a robust process to define and/or verify how the dimensional schema of the parts and their statistical variation affect the assembly variation. Using Siemens TeamCenter Visualization i.e., Vis-View (DVA) tool for statistical tolerance stack up analysis, designers are performing variation analysis on the JT model at design stage before parts are being matured for tolling signoff for production. DVA tolerance analysis tool is based on a process document where we as input have to give our part and each part has its features and the features have tolerances. These tolerances are coupled, and DVA can calculate the assembly build quality from these tolerances and features. The quality of the assembly is defined as functional measurement. Once the features and tolerances for all parts have been defined, assembly operations identify how these parts will assemble or interact with one another. The next step is to define the measurement for the critical dimensions to be controlled in this case study. Once the process model is defined, simulations that replicate the virtual build of the exhaust system are

run from the reports generated. The variation magnitudes and contributors may be viewed for each measurement model parameter. Tolerance values may be changed, and the simulations rerun to ascertain the impact of the change across the entire assembly. With the help of contributor's report, designers can determine where tolerance controls are needed and how tight the limits are to be set to assist process planning and tool design team. The DVA tool is incorporated in the product design and development to assist designers and manufacturing engineers so that they don't release or create defects at the initial stage of the product. World Class Quality (WCQ) requirements to ensure 100% vehicle geometry confirmation at the initial stage of the product below initiatives are inbuilt in DVA (DFQ) process.

Design for Quality (DFQ), 5th Design Analysis is introduced as design analysis document, and this consists of DVA results and interpretations. This is integrated in design release process.

- 5th D/DFQ will help in manufacturing and assembly teams in doing DFM (Design for Manufacturing) and DFA (Design for Assembly) feasibility study. DVA results and interpretations will identify gaps in part manufacturing tolerances and help to decide the right assembly sequence.
- DVA results and interpretations would also help in relaxing tighter tolerances where not required, thereby reducing manufacturing costs. Fixture costs could be optimized too as DVA results and interpretations would suggest alternate/better assembly process.
- DVA tool can be used by R & D stakeholders for tolerance analysis to meet supplier demands, consumer demands and analysis report preparation.

Concept

Usually, R & D engineers from automotive industries use DVA tool for system level statistical tolerance stack up variation analysis to identify problems in manufacturing, assembly processes at early stages of the product design. In this study, we have increased its usage up to vehicle level. For example, exhaust system layout packaging variation analysis which mostly depends on the pipe bends, flange welds position, pipe length w.r.t. exhaust pipe and exhaust gas process unit mounting position w.r.t. long member frame. These variations impact the following functionalities and aesthetic aspects at vehicle and aggregate level.

- Flexi bellow life (should not be assembled in pre-stressed condition)
- Packaging (chassis and bus body level)
- Exhaust system failure, ultimately vehicles goes on breakdown

In figure 1, Exhaust system fitment dimensions are shown, all of these dimensions need to be controlled at vehicle level. Assembly/aggregates fitment dimensions w.r.t. vehicle VCS and packaging requirements need to be maintained within the tolerance zone. DVA study will provide optimum tolerance values at the design stage for upcoming manufacturing

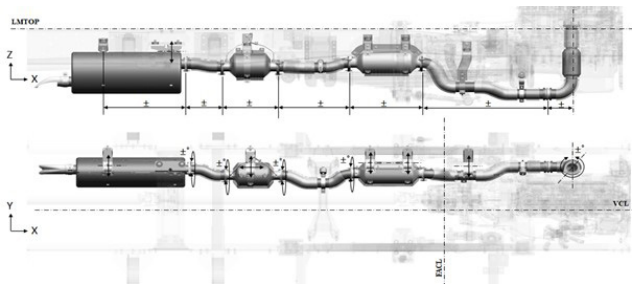


Figure 1: Exhaust system fitments dimensions.

vehicles and these dimensions need to be added on aggregates' fitment drawings. Fitment drawing tolerances will be helpful to quality team for verification of the aggregate's fitment dimensions which are critical to be maintained at vehicle level. Unavailability of optimum tolerance values on fitment/assembly drawing will reduce clarity on defect of component or process to quality team. Currently, in info-fitment drawing or assembly drawing having torque value for fasteners, BOM, Position of the aggregate's dimensions are shown as reference or in open dimension. Due to reference and open dimensions, technicians do the assembly as per assembly drawing or SOP procedures due to which hose and pipes, wiring harness, metal pipe, brake bunch, flexi bellow, etc. are assembled in pre-stressed conditions which leads to deterioration of intended vehicle/aggregate performance.

The FFA is a new concept of DVA on physical assembly of components. The FFA process is used to identify system, sub-system, and assembly fitment (bolted, welded structures) impacts on the functionalities of aggregates and vehicle performance. The purpose of a FFA is to assess risk of a product design by considering all potential fitment failures like fitment issue at assembly line and fitment issue at supplier end due to stacking of excess tolerance and same can be used for DVA model creation and make it more accurate.

The FFA identifies the risks associated due to these

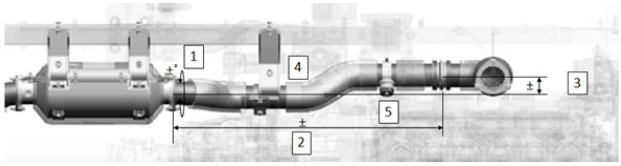


Figure 2: Exhaust system layout.

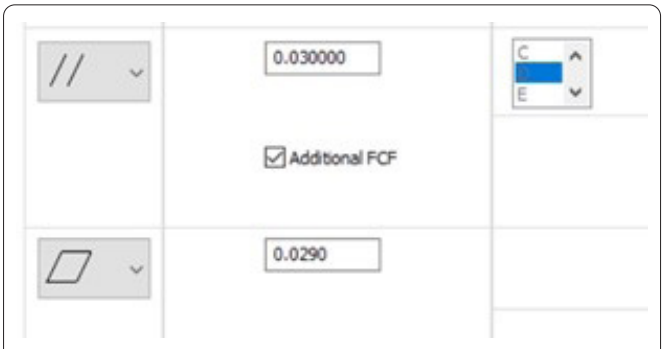


Figure 3: Tolerance zone size.

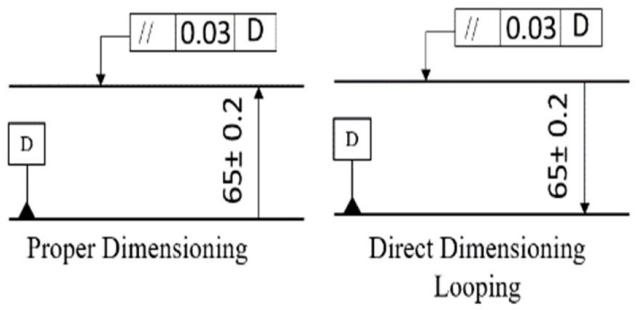


Figure 4: Dimensioning strategy.

potential fitment failures, their excess/lower tolerance values, improper controlling of critical dimensions assuming the product is compliant with design specifications. These factors could belong to the OEM, the supplier or improper usage at end-user which will eventually lead to potentially unfulfilled certification and technical requirements.

Some key points which make it different from tolerance stack up analysis and product structure tree of DFMEA are: Tolerance stack-up analysis is a design term for tolerance stack up in worst case scenario whereas FFA is concerned about real world tolerances and fitment variation analysis. Product structure tree is basically a hierarchical system structure for aggregates or assemblies whereas FFA is a hierarchical system structure for aggregates or assemblies with dimensions and their tolerances and its impact on the functionalities of aggregates and vehicle. Initially, we analyzed system level variation through DVA and later, we added system surrounding aggregates for getting the vehicle level effects of the exhaust system components' variations. The variations can be due to part geometry variations, welded structure, improper tolerancing, etc.

Methodology

The Variation Analysis determines variation in critical dimensions (measures) of the product design. There is a move to blend control of dimensional variation into product design and development process at initial stage of product by introducing DFQ process in the design release process and introducing FFA process info-fitment drawings. A dimensional variation analysis model is created in JT environment which includes and follows GD&T and assembly sequence. It predicts the number of variations within the assembly and its effect in vehicle DMU surrounding aggregates and displays the key contributors to that variation at defined production volume.

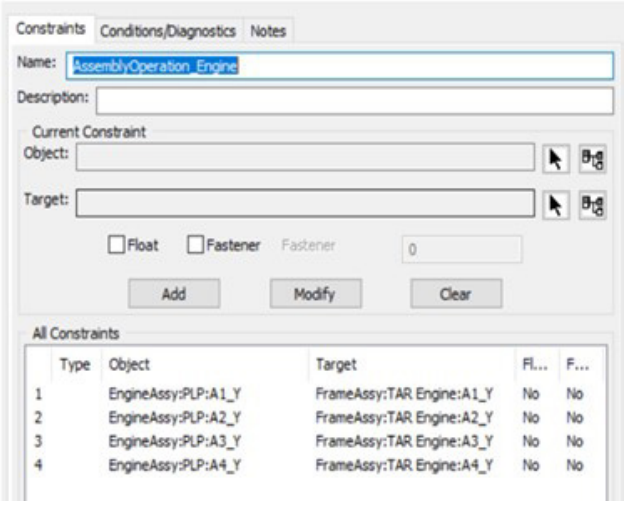


Figure 5: Assembly and measurement operation process.

There are three main types of the results that can be obtained directly from a DVA model these are:

- Monte Carlo simulation.
- High-Low-Median sensitivity analysis.
- Run Extreme simulation.

All three analysis provide different information for assessing product quality.

Monte Carlo simulation

A Monte Carlo simulation predicts what percentage of builds/samples/vehicle will fail to meet critical quality characteristics, which is defined as measurement in DVA model. A Monte Carlo simulation will tell if the results of a measurement are "good" or "bad". It works by simulating thousands of builds using virtual parts and collecting data for each build. The simulation randomly varies tolerances within specified ranges to all parts, assemblies the parts as defined in the build sequence and the takes measurements for desired outputs.

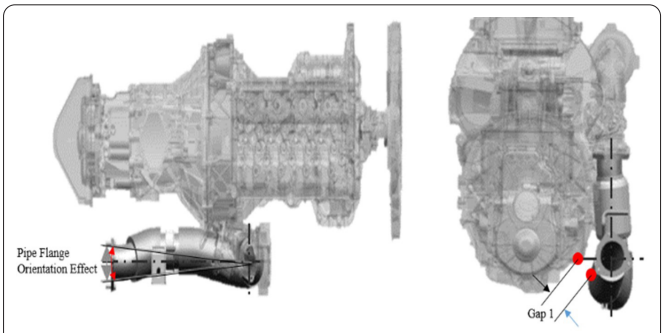


Figure 6: Measurement addition in DVA model.

High-Low-Median sensitivity analysis

A "High-Low-Median" (HLM) sensitivity determines which tolerances have the largest contribution per measurement. It works by varying an individual tolerance to a High, Low, and Median position, while holding the rest of the tolerances within a model at their nominal values. This process is repeated for all toleranced features. When a specific tolerance is varied and results in a larger value for a given measurement, the measurement is considered to be more sensitive to that particular tolerance. Each contributor percentage is calculated based on corresponding measurement values at High, Low, Median, and Nominal. HLM Sensitivity lists the contributors to variation in descending order. Changing a tolerance at the top of the list will have a greater impact on the measurement than changing a tolerance at the bottom of the list.

Run Extreme simulation

The worst-case tolerance analysis is to determine the effect of the smallest and largest assembly dimensions on the

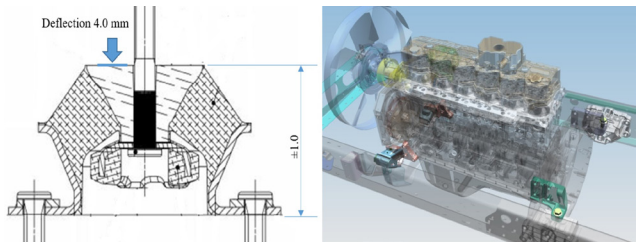


Figure 7: Rubber mounts.

product performance [3]. It is used to analyze the conditions when the value of dimension reach maximum or minimum. It is rarely used in engineering because results are usually too much pessimistic. This approach is applicable when:

1. The volume of production is very small.
2. 100% acceptance is required.
3. The number of constituent dimensions in assembly is very small.

Case study

Exhaust system layout is very important to meet the vehicle and regularity norms requirements hence it should be packaged in vehicle DMU as per vehicle platform requirements. Especially exhaust pipes and flex bellow position and orientation directly impact the exhaust system durability and performance. In the below case study, we have taken variation in exhaust pipes manufacturing and assembly process.

Problem statement

"Difficulties in assembling process of the exhaust flexi pipe with engine ETV valve flange due to variation observed in pipe bends and flange orientation".

Following component and assembly variations need to be considered in DVA model:

- **Flange Orientation Variation:** This will reduce the exhaust pipe surroundings gap.
- **Pipe Length Variation:** This will transfer the load in X direction, flexi bellow may accommodate this lateral load up to allowable limit.
- **Pipe Bend Variation:** This will reduce the exhaust pipe surroundings gap.
- **(4 and 5). Pipe Locator:** This will assist in align the pipe in Y direction.

DVA model creation process

DVA model creation process is comprised of:

- Part/Assembly CAD model creation and identification
- DVA model assembly creation
- Features creation on CAD model
- Tolerance allocation
- Assembly operation creation
- Measurement

Part/Assy CAD model creation and identification

In this step, we need to identify all surrounding/affecting components/assemblies which affect the objective of the gap variations analysis in dynamic and static conditions of the vehicle. An assembly can be considered as a single part if their child part's tolerances are not affecting the analysis result. All of these components' tolerances will reflect in the HML (Contributors) report. For accurate and quick DVA model creation, appropriate components/assemblies (mainly effected components) selection is an important activity as it can cause delay in DVA model creation and confusion in contributors.

DVA model assembly creation

In this step, DVA model assembly creation sequence should be in-lined with actual manufacturing/assembling process. As per the assembly sequence, tolerance values vary from the first component to the end for variation analysis. Hence, by doing the iterations of changing the assembly sequence, we can identify the assembly sequence in which maximum or minimum variation will happen. This will help in DFA signoff process and in identifying the best suited assembly sequence w.r.t product functionality.

Features creation on CAD model

In this step, features (Hole, Pin, Surface, etc.) need to be created on component's model. These features will be used as datum and positioning system. Proper tolerance allocation on features will directly impact the DVA result. Hence, it should be defined properly.

Tolerance allocation

In this step, tolerance (Size and feature control frame) needs to be defined on component's features (Hole, Pin, Surface, etc.) by referring the component's drawing. While allocating the tolerances on feature geometry, measurement affected tolerances need to be considered. For example, if we need to find the gap variation between EGP flange and Exhaust Pipe flange, tolerance to be allocated along the length of the pipe and EGP. So, while allocating the tolerances on the feature, we need to study the objective of the DVA and based on this, we should allocate the dimensions and tolerance on the DVA model. Hence, it is not necessary that all the dimensions/tolerances in released drawing are fed in the DVA model. While defining the feature control frame following points need to be insure:

- The zone size of the orientation tolerance (squareness/perpendicularity, parallelism, and angularity) must be less than that of the location tolerance (symmetry, concentricity, and position).
- Reference features should not be in a direct dimension loop.
- Concentricity cannot be applied to the second segment.

Assembly operation and measurement

In this step, components need to be assembled with each other by adding assembly operation. Defined component's features (Hole, Pin, Surface, etc.) should be considered as

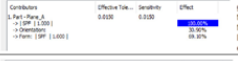
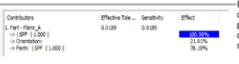
Primary, Secondary, and Tertiary datum's in assembly operation process. Features are defined under target and object constraints category. Base/fix components should be considered under target and moving/placing components should be considered under object. Once the assembly operations are completed, measurement needs to be added in DVA model. Based on the measurement requirements, we can add multiple measurement nodes under the DVA model. If we want to know the variation between two components out of 10 assembly components, then we need to add assembly operation after the second component. In the same manner, we can add measurement nodes as per the requirement. Measurement points are placed on the part geometry and tolerances are then added. The directions (x, y, z) of measurement and tolerance need to be correlated.

Result Interpretation

The Contribution analysis report provides a ranked list of measurement contributing factors. Each contributor contains floating locators, translation, rotation, orientation, form, location, etc. of the assemblies. It may vary based on the feature control frame characteristics. These factors will contribute to measurement (gap/flash, point to point, angle, etc.) variation. Normally floating locators % will be raise due to gap available between male and female parts (nut and bolt, slot and pin, hole and shaft, etc.). Translation and rotation % will be affected due to tolerances on components geometric feature. Contributor's constraints impact on measurement variation is categorised by effective tolerance, sensitivity, and effect. In case study, we found that exhaust pipes, catcon and silencer flange orientation variation are playing major roles in reducing surrounding/peripheral gap in vehicle DMU. In above DVA report it is clearly showing that % of rotation and translation is high. The rotation is increasing due to welded flange angular variation and translating raising due to excess slot length. For solution point of view DVA result is recommending for controlling the flange orientation & slot length reduction.

In table 1, we have explored the effect of profile tolerance on DVA model. This will help the user in proper selection of profile tolerance and converting some of geometrical features into the profile tolerance, which cannot be put in DVA model e.g., rubber mounts stiffness effects on DVA simulation. For considering the rubber mounts deflection effects on DVA simulation, we need to consider deflection value and height variation of mounts in profile tolerance. If the engine mount rubber deflection is 4 mm and its height variation is ±1, then cumulative profile zone/nominal tolerance will be 5 mm (4 + 1).

Table 1: Significance of profile tolerance in DVA model.

Sr No.	Distance (in mm)	Tolerance	Profile Tol.	Low/High	Range	HLM	Observations
1	0.0	± 1.0	0	-0.0376/0.0314	0.0691	0	Without form tolerance
2	0.0	± 1.0	1	-0.0584/0.0368	0.0952		As Profile Tolerance is a property of individual surface, hence, profile tolerence without orientation tolerence results in high variations.
3	0.0	± 1.0	1	-0.0409/0.0199	0.0608		Orientation tolerence should be given along with position tolerance for better control and fitment. Form tolerence should not exceed position tolerence.
4	0.0	± 1.0	1 / 0.1 Zone Shift	-0.0581/0.0369	0.095		Only zone shift have similar variation to zone shift with nominal shift. Zone shift impact is more incase of unsymmetric tolerances.
5	0.0	± 1.0	1 / 0.1 Zone Shift with Nominal Shift	-0.0581/0.0369	0.095		For Rubber mounting parts: deflection value to be placed as profile tolerance and extreme deflection to be placed as zone shift with nominal shift.
6	0.0	± 1.0	1 / -0.1 Zone Shift with Nominal Shift	-0.0587/0.0367	0.0954		A nominal shift without a zone shift is not possible. There is no effect of Negitive profile tolerance

Conclusion

The DVA for assembly plays an important role in product design and manufacturing and helps to establish co-relation between physical and virtual assessment. Identifying areas which need improvement and provide recommendations for the same after consulting with CFT which can help engineers carry out tolerance analysis, tolerance optimization and fault diagnosis. The DVA helps the designer to reallocate the tolerances in very complex packaging environment without affecting the functionality as well as manufacturability. The DFM signoff can be done based on reallocated tolerances. In the case study we found following outcomes for the tolerance allocation and design analysis signoff process area

- Component and assembly level (vehicle level packaging constraints) tolerance to be specified separately on their drawings.
- The DFM sign-off process to be done by DVA result and recommendations. Tolerance given in component detail drawing should be finalised after DVA analysis. Correspondence to the finalised tolerance manufacturing process should be selected. It can also provide input for producing low-cost manufacturing process by optimizing the tolerance value.
- The DFA sign-off process to be done by DVA result and recommendations. Assembly sequence of components/sub-assembly should be decided based on DVA analysis, assembly sequence can be changed to achieve better results. DVA analysis can help to decide optimum assembly sequence for achieving desired gap and clearances. It can also help to analyse the impact of any change in current assembly sequence.

Acknowledgments

This study is carried out in scope and role of dimensional variation analysis (DVA) process in product design and development life cycle optimization at initial stage of the product design. A case study has been conducted for field and design issue resolution through DVA simulation. During the simulation research work the authors sincerely thank Mr. Satish Kumar for GD&T explanation and its roles in exhaust system components manufacturing.

Conflict of Interest

None.

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