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Virtual prediction of clutch disc misalignment in powertrain assembly across its design tolerance range

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Abstract- Clutch-disc alignment plays a critical role in the NVH performance, durability, and shift quality of automotive drivetrains. Even minor angular or lateral misalignments between the clutch disc, flywheel, and transmission input shaft can generate harmful dynamic loads, accelerated spline wear, and undesirable vibration signatures. Traditional alignment evaluation relies heavily on physical prototyping and end-of-line inspection, which are often reactive, cost-intensive, and limited in their ability to isolate root causes during early design stages. This paper presents a virtual methodology for defining, predicting, and validating clutch-disc misalignment criteria using Dimensional variation analysis (DVA) as a design-for-quality tool. The approach establishes quantifiable misalignment thresholds based on dynamic system behavior, correlates them with component tolerances, and evaluates their influence on clutch engagement quality and torsional response. A comprehensive DVA-based workflow is proposed for early-phase design optimization, enabling engineers to identify misalignment-induced excitation modes, assess factor sensitivities, and ensure robust manufacturability across platform variants. The results demonstrate how virtual misalignment analysis significantly mitigates prototype iterations, improves alignment robustness, and enhances system quality for diverse automotive applications.

Keywords: Misalignment, end of line, dimensional variation analysis

I. BACKGROUND

Clutch systems continue to play a key role in automotive powertrain operation by regulating torque transfer between the engine and transmission and by influencing vehicle drivability and overall refinement. Within the clutch subsystem, the clutch disc is particularly sensitive to geometric variation introduced during manufacturing and assembly. Misalignment between the disc, flywheel, pressure plate, and transmission input shaft can generate off-axis loads that contribute to vibration, elevated spline stress, judder, noise concerns, and reduced durability. As vehicle platforms migrate toward lighter engine architectures, greater modularity, and more stringent NVH targets, the allowable range of alignment variation has become progressively smaller.

Conventional alignment assessments rely on bench run-out measurements, input-shaft alignment checks, and end-of-line functional tests. While these evaluations remain essential, they occur late in the product development cycle and provide limited data regarding the dynamic effects of misalignment during real operating conditions. Correcting alignment deviations at this stage can require significant redesign or manufacturing adjustments, increasing cost and timing risk. These limitations have accelerated the need for virtual methods that can define alignment requirements earlier in the design process and support design-for-quality across multiple vehicle derivatives.

Dimensional variation analysis (DVA) provides a structured virtual approach for examining the sensitivity of clutch-disc behavior to geometric and assembly variation. By representing the mechanical interactions between the clutch components and the torsional drivetrain system, DVA enables prediction of misalignment-induced excitation modes, dynamic loads, and engagement disturbances prior to prototype testing. When integrated with tolerance stack-ups and manufacturing variability data, DVA supports the development of alignment acceptance criteria, assists in optimizing disc geometry, and enables evaluation of system robustness across worst-case tolerance conditions.

This paper examines the mechanisms through which misalignment influences clutch-disc performance, establishes quantifiable criteria for alignment evaluation, and proposes a DVA-based method for virtual design validation. The objective is to present a repeatable process that improves alignment robustness, reduces prototype iterations, and supports the design needs of modern automotive powertrain architectures.

II. PROBLEM DEFINITION

The system under consideration is a typical automotive powertrain used in passenger vehicles, comprising the engine crankshaft, flywheel, clutch disc assembly, and transmission input shaft. These components form the primary torque-transfer interface between the engine and transmission. Proper geometric alignment across this interface is essential to ensure consistent clutch engagement, acceptable NVH behaviour, and long-term durability.

In this system, the clutch disc operates between the flywheel and pressure plate while simultaneously engaging with the transmission input shaft through a splined connection. Any deviation in the relative position or orientation of these components—such as angular offset, lateral shift, or run-out—can introduce off-axis loading on the disc and spline. Such misalignment can lead to abnormal NVH responses, including vibration, noise, clutch judder, and increased spline wear, ultimately degrading clutch performance and reducing system reliability.
Direct physical measurement of misalignment effects at the engine–transmission interface is challenging because the assembly is enclosed and not fully accessible once built. As a result, traditional inspection methods capture only part of the geometric picture and provide limited insight into dynamic behaviour under real operating conditions. To overcome these limitations, a virtual simulation approach is required. By evaluating worst-case geometric conditions and tolerance extremes through virtual modelling, the misalignment mechanisms can be quantified, enabling early identification of risk conditions and supporting design-for-quality decisions before prototype hardware is available.

III. VIRTUAL METHODOLOGY

The virtual analysis methodology developed for this study integrates Dimensional Variation Analysis (DVA) with statistical simulation to evaluate the influence of geometric deviations on clutch-disc alignment. The workflow combines actual CAD geometry, production-intent tolerance information, and assembly variation modelling to replicate real manufacturing and installation conditions. The analysis is done considering following assumptions that all the part variations are within the allowable range of tolerance, DVA results do not count for part flexibility, thermal expansion, welding deformation and other uncalculated factors and results are based on 5000 Monte Carlo simulation. Simulation done with interference build acceptance.

Model Preparation and Data Integration
The DVA process begins with importing the complete clutch and transmission interface CAD data into the Teamcenter Visualization environment. All components are represented at the child-part level to ensure that local geometric features, functional surfaces, and mounting interfaces are accurately captured. The model incorporates the same geometric tolerances, GD&T callouts, and material specifications defined in the engineering drawings, allowing the virtual representation to reflect production-intent dimensional behavior.

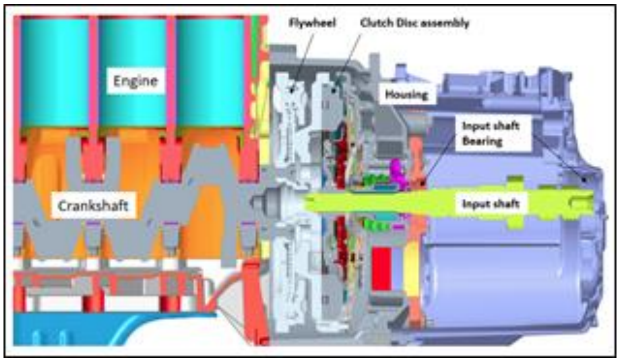

Figure 1: System layout for DVA study

Variation Modelling Approach

To simulate manufacturing and assembly variability, a Monte Carlo statistical method is used. Each simulation iteration applies randomized deviations to relevant features based on their defined tolerance zones. A three-sigma (3σ) acceptance criterion is applied to represent high-confidence production capability while still capturing worst-case expected variation. This approach enables the analysis to capture the combined effect of multiple tolerances acting simultaneously across the system.

Simulation workflow

In this study we want to analyze the alignment in between the center axis of the engine crankshaft and the transmission input shaft. Ultimately calculating the misalignment whether it is within acceptable range of the clutch disc assembly in worse case tolerance range conditions.

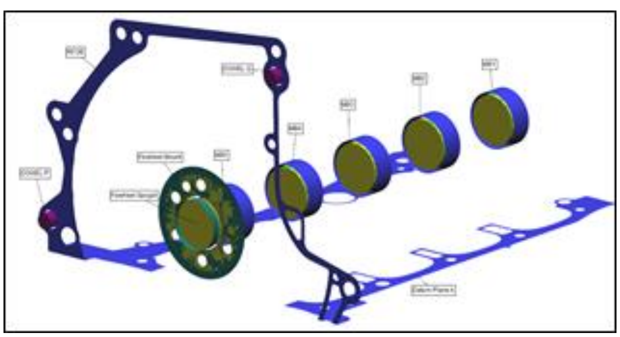

Figure 2. Engine assembly DVA model

Engine crankshaft center position was determined considering the manufacturing process flow including engine block, crankshaft bearings, crankshaft and flywheel center. Datum and GD&T as per the engineering drawing was considered in the model to define its center axis. Engine block to crankshaft bearing positions were defined, from crankshaft bearing datum flywheel spigot end was defined. Hence a crankshaft center axis was located considering above flow path with its dimensional positioning. From crankshaft center further engine and transmission assembly dowel position was defined on the engine block and similarly dowel holes on the transmission housing considering position from input shaft.

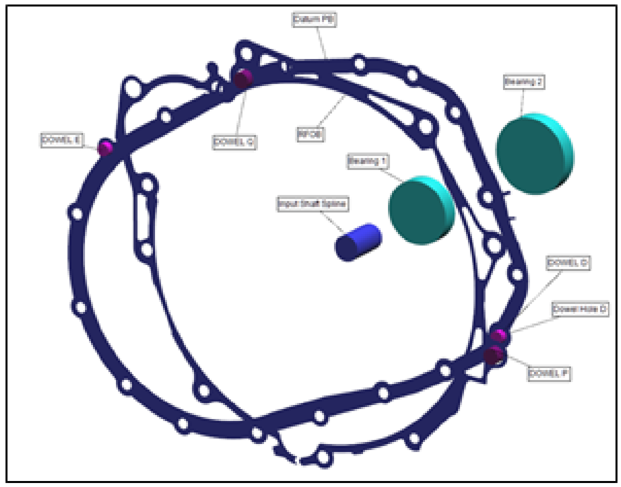

Figure 3. Transmission assembly DVA model

In transmission input shaft axis is mainly defined by the bearings located on the two halves of the housing which are further positioned to each other by dowels. From housing to input shaft bearings and further input shaft location at spline end is determined. A complete assembly is modelled with engine assembly and transmission assembly coupled by dowels on the engine block and holes on the transmission housing. As shown in the below figure.

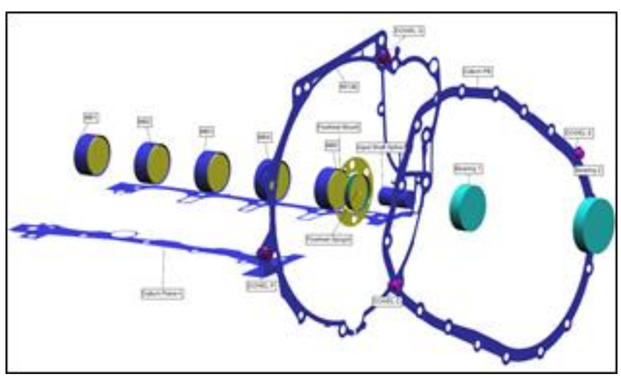

Figure 4. Complete powertrain assembly DVA model

Misalignment and Output

As a final outcome of the above DVA model, axis misalignment measurement in the perpendicular directions of the center axis was calculated. Further simulation was done with 5000 iterations by Monte Carlo method. Following figure shows results of the same.

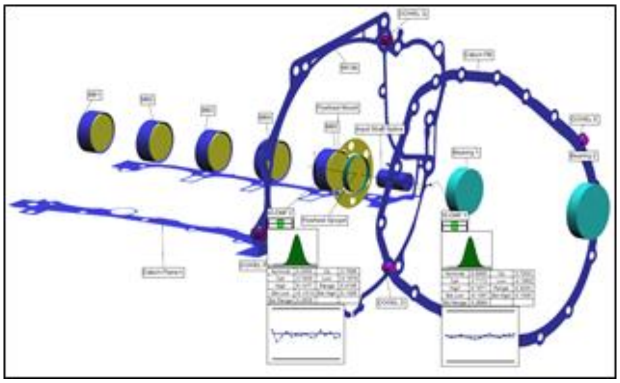

Figure 5. DVA simulation misalignment results

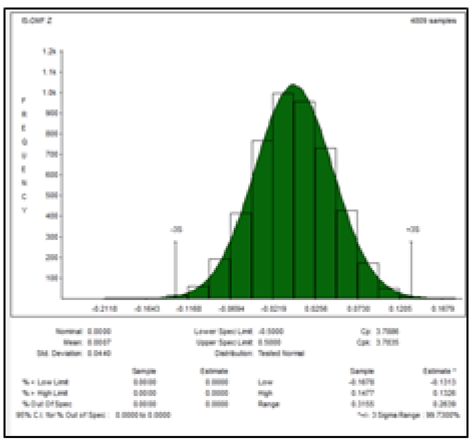

Figure 6. Result of Monte Carlo simulation

	Nominal	High	Low	Range
Axis Y	0	0.15	-0.16	0.32
Axis Z	0	0.14	-0.16	0.31

With above results of misalignment in the shaft axis it is observed that in Nominal condition input shaft and crankshaft axis is aligned and also the worse case high and low conditions are determined which can be evaluated based on the allowable limits of the clutch disc misalignment condition.

Incase if the range is out of the allowable limit, the assembly tolerances need to be re-designed considering the major contributors as highlighted in the below report image.

Figure 6. Major contributors in the stack study

IV. CONCLUSION

The methodology presented enables early-phase digital validation of clutch-disc misalignment. It takes account of the crankshaft center axis using manufacturing process flow, datum, and GD&T. By capturing worst-case positional variation through simulation rather than physical measurement, the approach eliminates the need for complex prototyping and reduces dependency on late-stage hardware evaluations. As a result, potential misalignment issues can be identified and mitigated earlier in the design cycle, improving product robustness, reducing development time, and enhancing overall manufacturing feasibility. This framework can be readily applied across multiple engine–clutch applications, supporting a more reliable and efficient development process.

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