

Development of Stiffness Analysis Technology for Transmission Housing

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ABSTRACT

A technique was developed for simulating the stiffness and strength of a transmission housing by reproducing the behavior of the housing contact surface. This technique uses non-linear modeling methods to reproduce bolt tightening, positioning with dowel pins, the behavior of contact surfaces with consideration to gasket material and the stiffness of inner parts such as the differential case. The predictive accuracy regarding behavior in an actual transmission increased greatly as a result, and the discrepancy with test results fell to 15% or better. This made it possible to conduct evaluations by simulating the housing stiffness and strength in bench torsion testing at the stage of design. Specialized pre- and postprocessing tools were also developed for widespread dissemination of this simulation technique among designers, shortening the calculation time and labor to the amount of one-third of what it had been.

1. Introduction

Recently, there has been increasing demand lighter and more compact transmissions as well as for improved efficiency in the development of automotive transmissions. Developmental efficiency will require reductions in the number of prototypes; techniques for high-precision predictions of the behavior of the machines are desired for that purpose. The transmission housing in a front wheel drive car typically consists of two parts, left and right halves, joined at large contact surfaces through which the drive reaction forces are transmitted. Since large drive reaction forces of differing directions are applied to the halves of the housing, which are bolted together, the halves slip with respect to each other at the contact surfaces, and it is impossible to predict the stiffness and strength of the housing at the design level with any accuracy with conventional linear analysis. Therefore, it has been necessary to expend much labor time performing repeated tests with prototypes in order to develop mature specifications.

The objective of this study was to construct a versatile,

high-precision simulation technology for predicting the stiffness and strength of housings in transmission housing assemblies containing contact surfaces. Special pre- and post-processing tools were also developed to ease use by designers.

2. Behavior in Actual Transmissions

Figure 1 shows the main section of the automatic transmission used for this study. Figure 2 provides the shaft layout and the directions of bearing loads during forward motion. The mating structure where the transmission housing (TM housing) joins with the torque converter housing (TC housing) contains large contact surfaces. The bearing load occurs due to gear reaction forces, which are applied in different direction upon the two housings on each side of those surfaces. The deformation and behavior of the two housing bodies are assumed to be determined not only by the housings themselves but also by the behavior of the contact surfaces.

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Deformation and behavior of the housings have been observed under peak load conditions in bench torsion testing of a transmission. Specifications of the test transmission are provided in Table 1. Since the primary concern in a housing is the stiffness at the bearings, displacement was measured at each bearing. A mark was made at the edge of each bearing and the displacement of this mark was recorded with a camera during torque loading (see Fig. 3). The results of these observations are given in Fig. 4. Displacement by every TM housing bearing was, regardless of load vector, in the same direction as the displacement of the differential case support bearing. This indicates that the load on the differential case support bearing of the TM housing dominated the behavior of the housing as a whole. The relative displacement between the TM and TC housings was observed in the vicinity of the differential case support bearing, which carries the highest load of all the bearings (see Fig. 5)⁽¹⁾. The results of those behavioral observations are presented in Fig. 6. Slipping occurred on the contact surfaces around the differential case due to the bearing loads on both halves of it; this confirmed the above assumption that this slipping affected the bearing displacements.

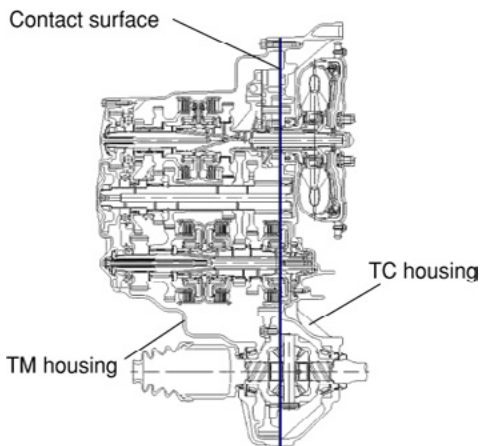


Fig. 1 Main section

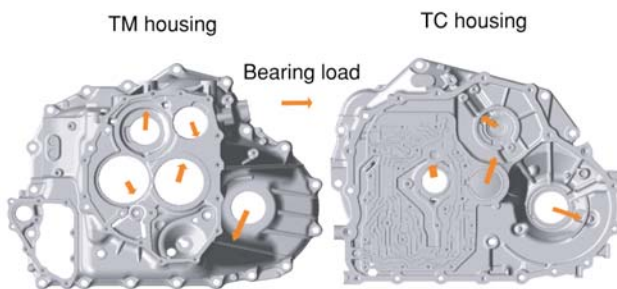


Fig. 2 Direction of bearing load

Table 1 Specification of transmission used in experiments

Type	Transmissible torque	Total gear ratio	Drive system
Type-A	196Nm	12.2	2WD

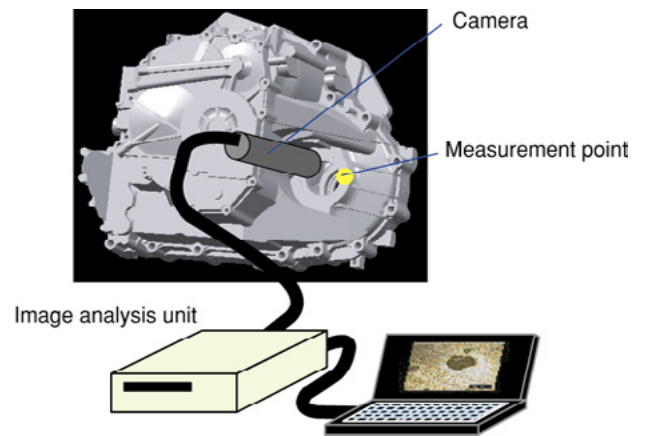


Fig. 3 Measurement method for displacement of bearing

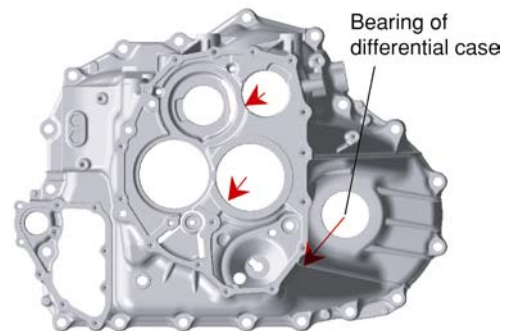


Fig. 4 Result of measurement of displacement of bearing

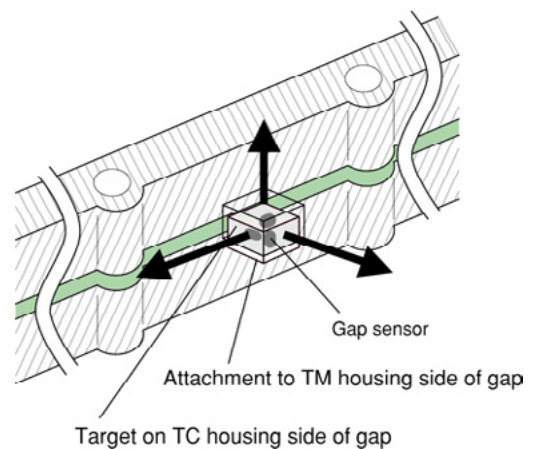


Fig. 5 Measurement method for slip behavior of housing

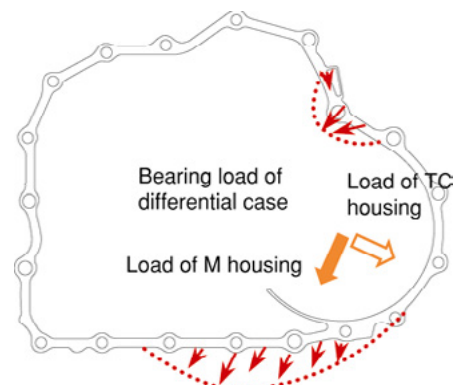


Fig. 6 Result of measurement of relative displacement of housing

3. Establishment of Nonlinear Modeling Technology

Figure 7 shows a graph of the coincidence between the actual observed bearing displacements and the calculated displacements according to conventional linear method relations. Two points were quite inconsistent with the calculation, indicating that linear relations were not accurate enough to be usable. As shown in Fig. 8, these points were on the opposite side of contact surfaces from the standard surface of constraint, and are thus assumed to be affected by the contact surface behavior. It then follows from the above observed behavior that the behavior of the contact surfaces and the loads from the differential case must be reliably reproduced in order to predict housing behavior. Non-linear methods were used in order to reproduce the behavior in the actual transmission. The items incorporated in the model are shown in Fig. 9 and explained in detail below.

3.1. Reproducing Contact Surface Behavior

Slipping on these contact surfaces is believed to occur due to the following factors: the difference in contact pressure between locations immediately under tightened bolts

and locations between bolts, and also the application to the contact surface of a shearing force, which is greater than the frictional force caused by the pressure due to the tightening of bolts. Because the shearing force is transmitted from the bearings carrying the loads in the housings via the ribs and the wall surface to the bolt flange, the slip varies with the shapes of these components. The dowel pins and bolts inserted to fasten the housings together also constrain slipping behavior. In other words, in order to reliably reproduce the behavior of the contact surface, it is necessary to reliably reproduce the surface pressure distribution due to bolt tightening, the slipping behavior of the contact surface, and the load transfer path of the housings. In order to reproduce the surface pressure distribution, a separate model of each housing was made and the models were connected to each other with surface contact elements which had been given soft contact properties corresponding to those observed in pressure tests of real gaskets (see Fig. 10). Bolt tightening was modeled as a multi-point constraint at the bolt surfaces and the screw parts using the axial tensions as the loads. The precision of the pressure distribution was confirmed by testing a component. This test piece and the test results are

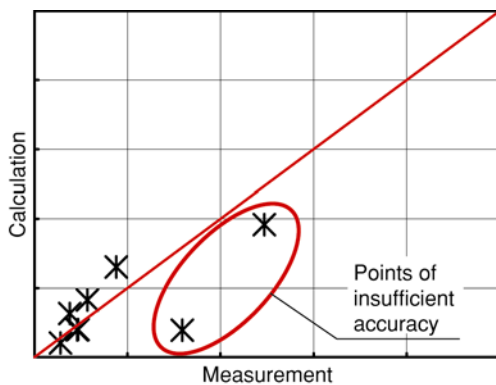


Fig. 7 Comparison of bearing displacement with linear method

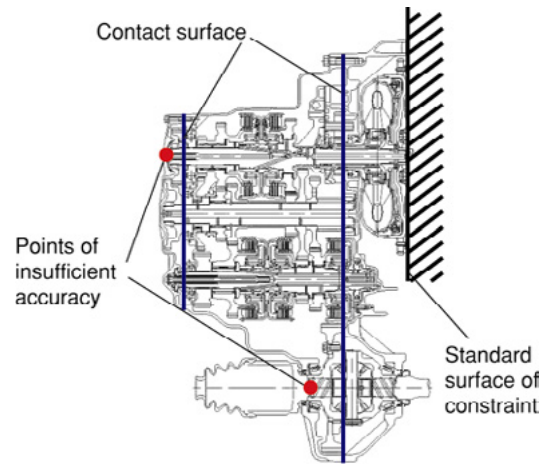


Fig. 8 Point of insufficient accuracy

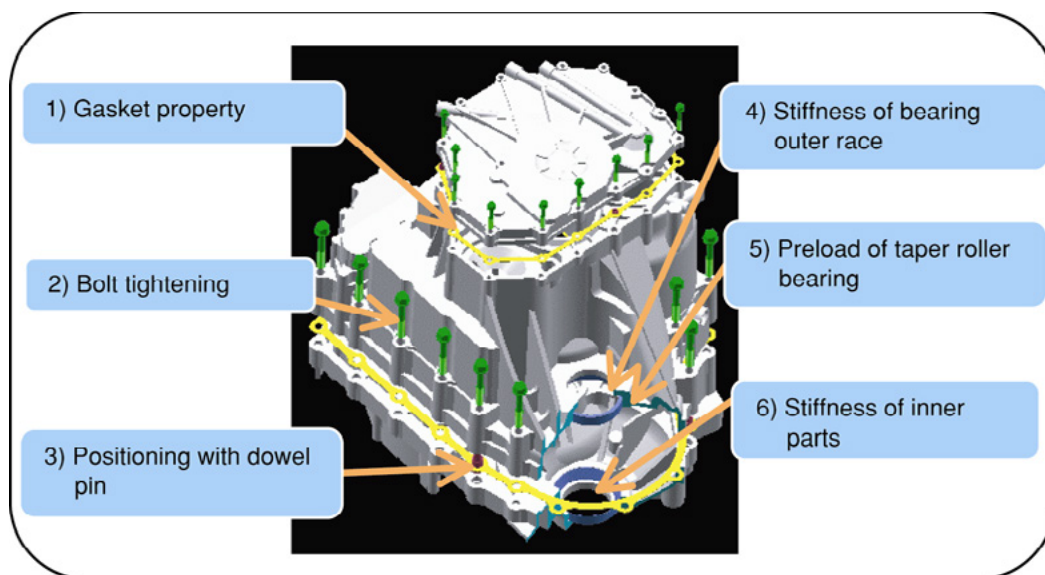


Fig. 9 Items reflected in FE model

shown in Fig. 11. It was found that using the properties of the gasket material enabled good reproduction of the pressure distribution. Next, the following modeling procedure was used to reproduce the behavior of the contact surface. The coefficient of friction of the contact surface was measured

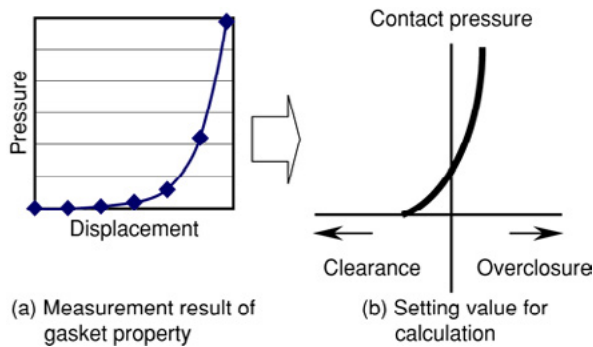


Fig. 10 Softened contact property of gasket

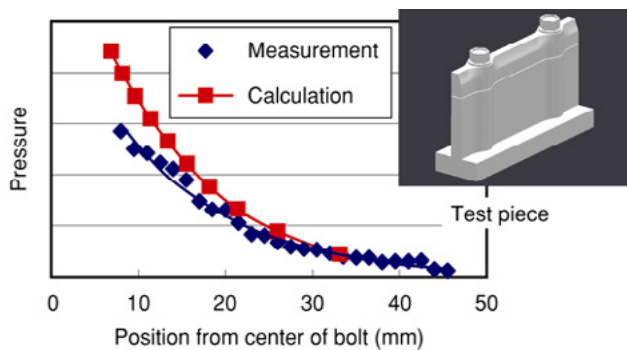


Fig. 11 Comparison of pressure in test piece

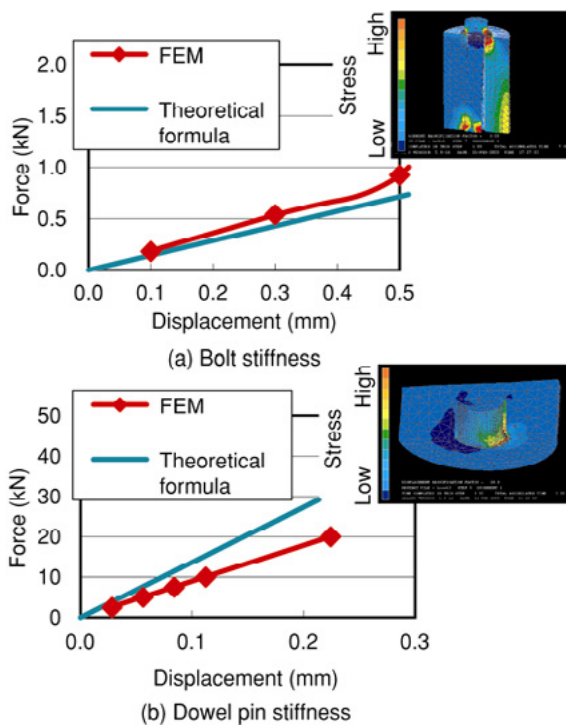


Fig. 12 Verification of stiffness of spring element

and the median of the scattered values was defined as the coefficient of friction. Positioning with dowel pins was modeled using non-linear spring elements possessing backlash and bending stiffness of the bolts was modeled using linear spring elements. The spring constant of those elements was calculated using beam bending theory. Non-linear contact FEM analysis confirmed that this approach was appropriate (see Fig. 12).

3.2. Reproducing the Form of the Load Input from the Differential Case

Modeling the actual shape of the outer races of the bearings and connecting these to the housing with surface contact elements simulated the loads applied by the differential case. The preloads on the tapered-roller bearings were accounted for. The differential case itself was modeled with beam elements, which allowed consideration of the stiffness of components inside the case (inner parts) while reducing the increase in calculation time (see Fig. 13). Figure 14 presents the mesh model of the entire housing.

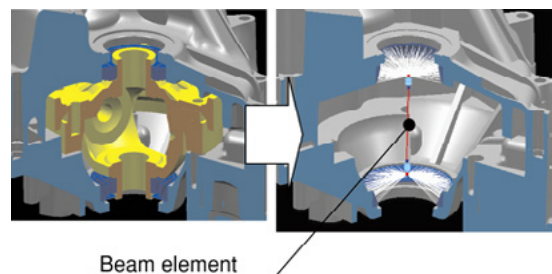


Fig. 13 Modeling of stiffness of differential case

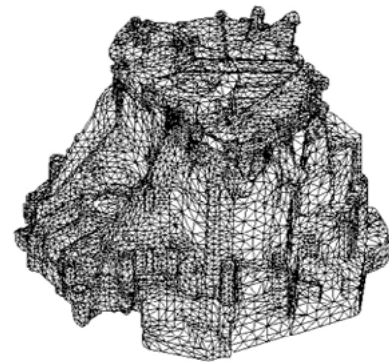


Fig. 14 FE model of transmission housing

4. Improving Precision of Simulation Analysis

Figure 15 shows the contrast between the results of the above non-linear modeling method and the linear simulation. Inclusion of the behavior of the contact surface and of the stiffness of the inner parts in the non-linear model caused a considerable change in predictions of deflection throughout the housing. The reproduction of the input form of the load from the differential case has helped improve the accuracy of predicting the stress state adjacent to the bearings. The previous simulation had inadequately predicted tensile

stresses on the opposite side of the bearing to where the load was applied. The results of this simulation were compared for coincidence with the results of the bench torsion test. As shown in Fig. 16, the calculated pressure distribution on the contact surface due to bolt tightening was quite consistent with that observed, both directly underneath the bolt locations and halfway between the bolt locations. Figure 17 provides measured values of the slipping behavior at the contact surface during application of torque. This displays non-linear hysteresis caused by frictional phenomena; these results show that modeling based on friction theory enables reproduction of gasket slipping properties at the contact surface of real housings. As presented in Fig. 18, the simulation results for slipping match well with measured values. This indicates that the slipping behavior of the contact surface was reproduced, since the slip is a product of a balance between the shearing forces transmitted through the housing and the frictional forces at the contact surface. The results for the bearing displacement are presented for

comparison in Fig. 19. Since the behavior of the contact surface was well reproduced in the non-linear model, the difference with the measured values of bearing displacement was kept within 15%, an improvement in precision over the result with the conventional method.

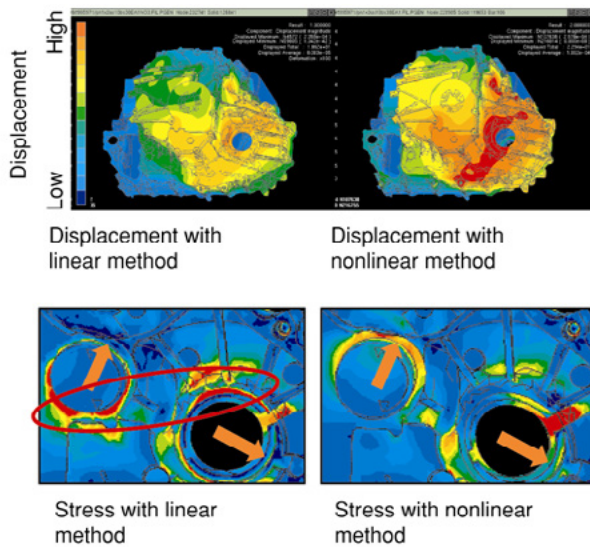


Fig. 15 Comparison of calculation methods

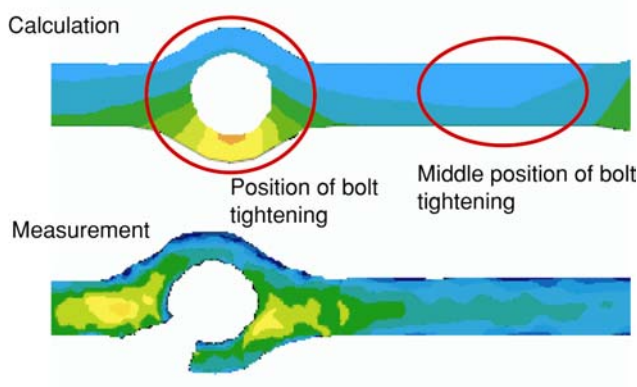


Fig. 16 Comparison of pressure in transmission housing

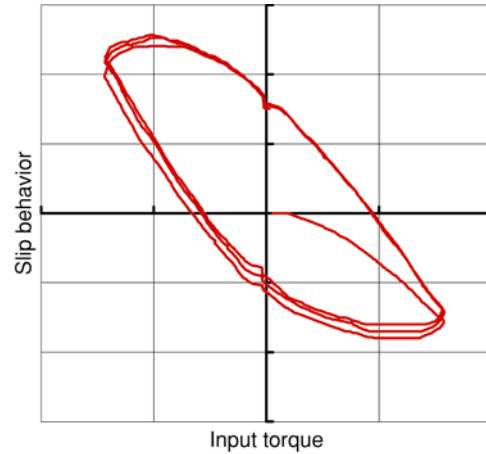


Fig. 17 Result of measurement of slip behavior

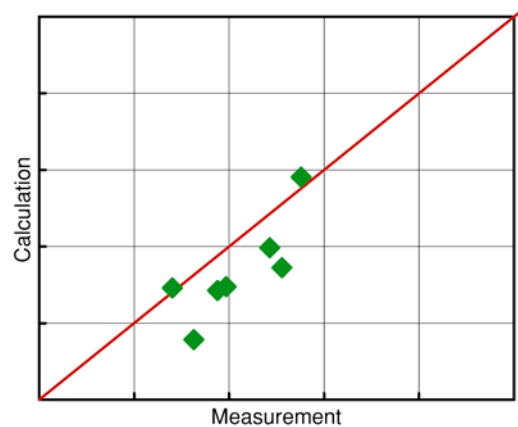


Fig. 18 Comparison of slip behavior

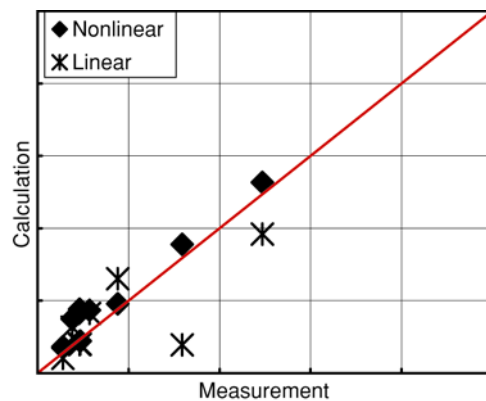


Fig. 19 Comparison of bearing displacement

5. Proof of Applicability

Models of other transmission housings with different shapes, load input paths and torques were created using this simulation technology and their results were compared with measured observations to verify the wider applicability of this method. Specifications of the other models used are presented in Table 2. Coincidence of the results with the bearing displacement is shown in Fig. 20. Predicted strength was also compared with measured strength (see Fig. 21). As shown in these figures, the predictions were quite consistent with the measured values; the model was found fully usable for estimating stiffness and strength of transmission housings. Here, the effect of stiffness of inner parts will be considered. Figure 22 shows the predictions of bearing displacement by the simulations while taking account of or ignoring the stiffness of inner parts, for comparison with the actual measured values. The simulations where the stiffness of inner parts was not considered showed growth in the bearing displacement in the housing types on the right side of the graph. This indicated that the housing stiffness in resistance to input torque was lower among the types on the right side of the graph. There was a glaring difference between the observed displacement and the displacement calculated without stiffness of inner parts in the three types on the right side (Types F, B, E), but when the inner parts were considered, the displacement values matched well. The influence of the stiffness of inner parts was more marked in models with lower stiffness; thus, in those models, it is even more important to account for this factor. Besides the differential case, mentioned before, these key inner parts were found to be the shafts supported by the three bearings.

Table 2 Specification of transmission used in comparison

Type	Transmissible torque	Total gear ratio	Drive system
Type-A	196Nm	12.2	2WD
Type-B	196Nm	12.0	4WD
Type-C	315Nm	12.1	4WD
Type-D	196Nm	11.7	2WD
Type-E	196Nm	15.5	2WD
Type-F	196Nm	14.4	2WD

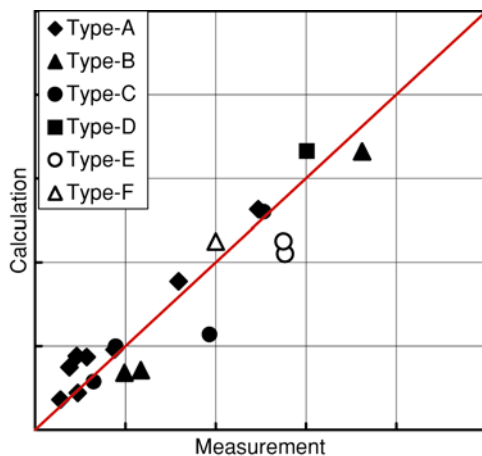


Fig. 20 Comparison of bearing displacement

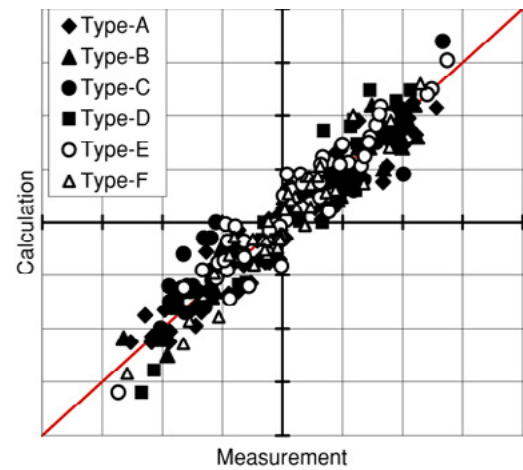


Fig. 21 Comparison of stress

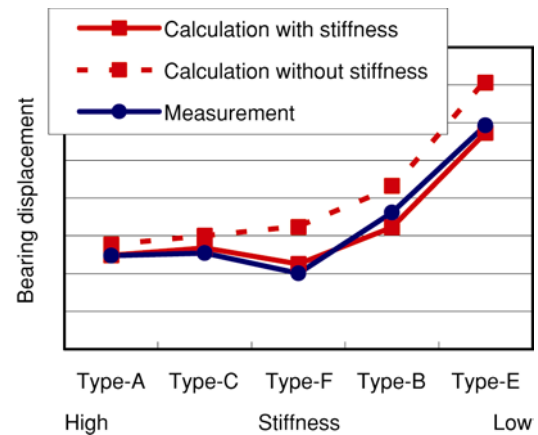


Fig. 22 Influence of stiffness of inner parts

6. Development of Design Tools

6.1. Development of Simulation Tools

In order to encourage wide use of this simulation at the design level, a special pre- and post-processing tool was developed for use on a 3D CAD system. It includes automatic tools for defining contact surfaces and bolt placement. This has proven very practical, and has decreased design labor time to 1/3 of the previous time (see Fig. 23).

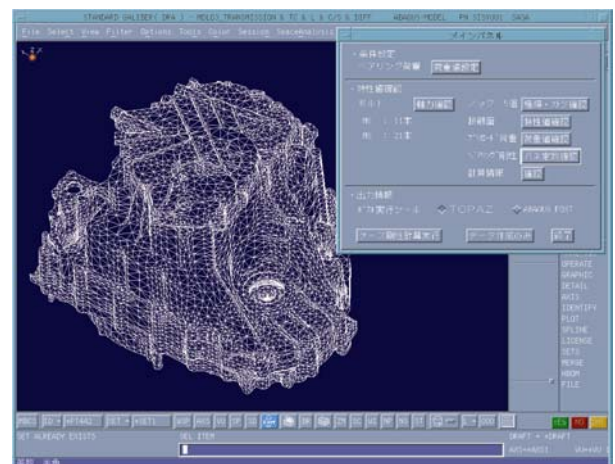


Fig. 23 Simulation tool

6.2. Example of Application

The re-design of a housing on a large transverse automatic transmission is shown below as an example of how this tool was practically applied. This enabled quantitative analysis of the improvement in stiffness and strength thanks to re-design of the shape of the TM housing at the design level (see Fig. 24).

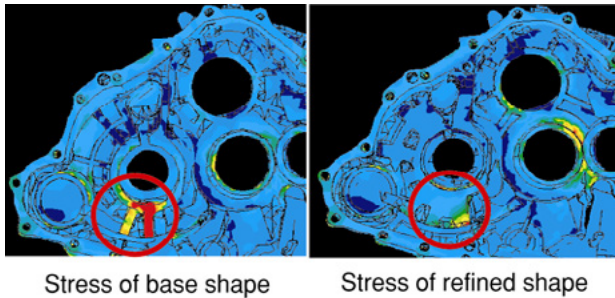


Fig. 24 Application example

7. Summary

A versatile, high-precision simulation technology was constructed for predicting the stiffness and strength of housings in transmission housing assemblies containing contact surfaces. This technology used non-linear modeling to successfully reproduce the behavior described below in actual assemblies. As a result, the difference between results in tests of actual and simulated transmissions was lowered to 15% or less, enabling predictions of bench torsion testing for stiffness and strength at the design level:

- (1) For reproduction of contact surface behavior, input of parameters of gaskets, bolt tightening and positioning with dowel pins.
- (2) For reproduction of the load input from the differential case, input of parameters of stiffness of inner parts of the differential case, bearing outer race stiffness, and taper roller bearing preload.

Also, in order for maximum practicality and acceptance of this tool among designers, pre-processor and post-processor analytical tools were specially developed for this simulation. These reduced design time to 1/3 of the previous time.

8. Acknowledgements

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