Design and Development of a Gear Test Fixture for Nexteer Automotive

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Abstract

The scope of this project is to develop a gear test fixture that will test a welds ability to fix a worm gear to a drive shaft. The worm gear and shaft assembly are used to drive an electric power steering system that is in development at Nexteer Automotive. The fixture will need to perform several tasks in order to properly analyze the welds ability to avoid failure. The fixture must continuously apply a load on the gear as the gear rotates about the shaft. As a Load is being applied to the gear a screening process will continuously calculate average load. In the event that the weld has any failure the load will sufficiently decrease, exceeding the load parameters in the software which will trigger the motor to be stopped. The applied load and displacement of the gear will be recorded throughout the test in order to compare the load and number of bottoming cycle completed before failure.

Introduction

The current gear test fixture, Figure 1-2, has many flaws. Due to the fixed gear set-up, only one position on the gear can be tested at a time. This enables the user to determine the weakest point in the weld. Because of alternating cycles the weld is experiencing a load that is different than that in application. The gear must be removed from the fixture and checked every 50k cycles. The coupling experiences more torque than it is made for causing it to fail more often, increasing the testing time. If the gear fails it is only known during interment cycle checks. The loads applied to the gear cannot be regulated directly. The stroke distance of the worm is used to calculate a hypothetical load. The current testing process is extremely time consuming and inaccurate.

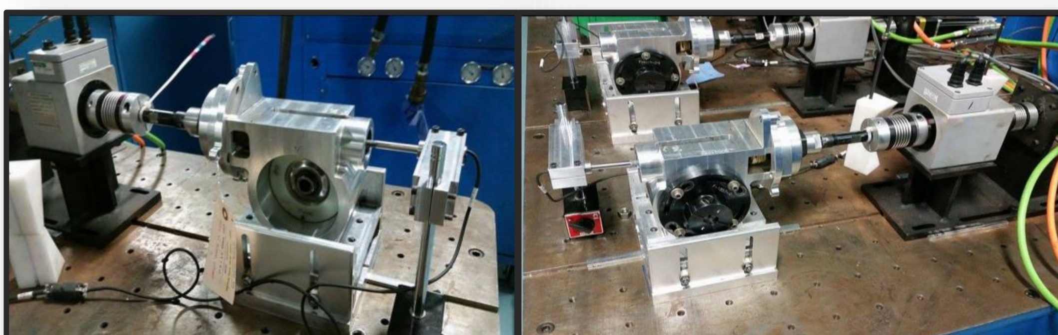

Figure 1-2: Current Gear Test Fixture

Mechanical engineering is the discipline that applies the principles of engineering, physics, and materials science for the design, analysis, manufacturing, and maintenance of mechanical systems. It is a branch of engineering that mainly involves the design, production, and operation of machinery. Innovative design requires high performance components, materials, and processes due to that fact that failure can potentially compromise safety and reliability. On the other hand, economic considerations such as costs incurred during development and unit cost must also meet the demand of the current market. The final design is validated through performance testing of the computational model.

The scope of this project is to develop a gear test fixture to reduce test time and improve reliability of an over-molded gear welded to a metal shaft. The current process is not capable of impact testing and limits the testing area to one specific point on the gear. The proposed fixture will allow multiple locations of impact to be measured during the test while improving reliability of the data collected during test. In the current design, a predetermined load is applied to the hub at a desired location while the hub is rotating. The proposed fixture will allow a uniformly distributed load around the hub to determine the location of maximum stress in the weld joint as well as in other locations of the test fixture. The initial design will consider all desired performance and reliability of the fixture. The process of applying load to the gear and data collection methods will be developed. Based on the loads on the gear, proper materials and processes will be determined. The impacts of the loads and torque on the system will be used to calculate fatigue and number of cycles to failure. The layout of the fixture and the mounting of the gear assembly will be used to determine initial dimensions of the fixture. The fixture design will control robustness and fatigue life. The fixture design will incorporate two load cells and two digital indicators to measure stress and deflection of components including the weld joint. To measure stresses on the gear, a compressive load will be applied to one side of the gear and tension to the other side. The load cells will be mounted in line with the forces on the gear to produce the accurate data. The indicators will measure deflection from the point of contact.

To generate the concept, a function structure was developed to determine interactions between different function requirements. The function structure diagram, figure 1-1, also helped in determination of the power source used for each mechanical component. This enabled in generation of feasible concepts. The Analytical Hierarchical Process (AHP) method was used to finalize the concept for the next step in design. After finalizing a concept, the embodiment process and product architecture were developed using customer requirements and engineering characteristics. A combination of requirements, constraints, characteristics, and generated concepts led to parametric designs, in addition to detailed designs and component drawings being developed.

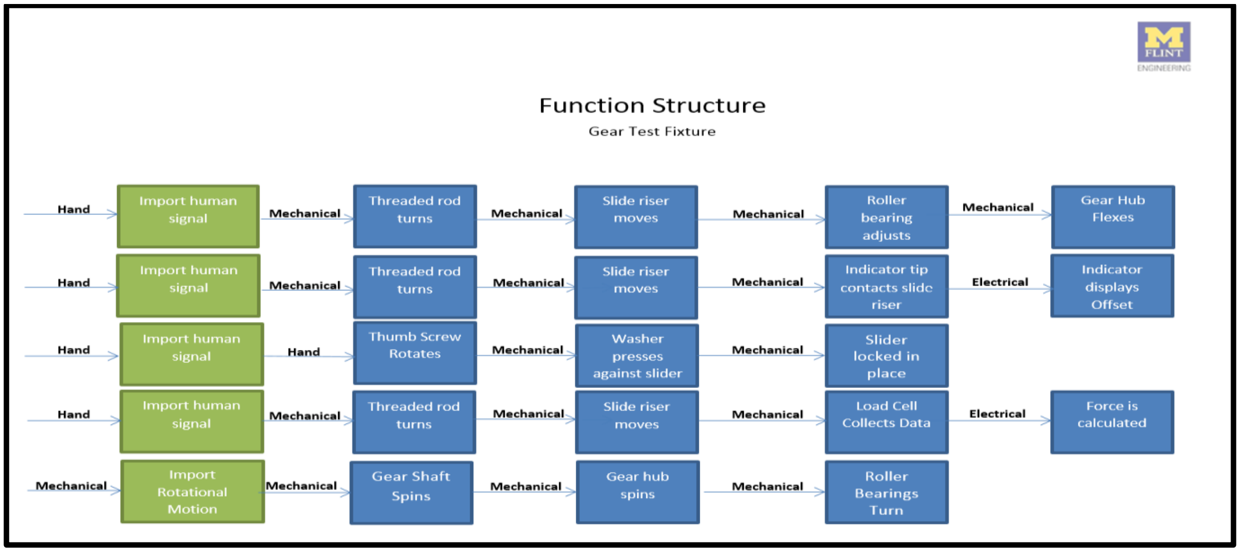

Figure 1-1: Function Structure

Literary Review

Computer Aided Fixture Design (CAFD) eliminates several timely steps in the design process. There are always situations that arise and contradict the results of CAFD. Zheng noted that, "With growing demands on improved product quality and shorter time to market, there is need for rigorous but practical tools to support the fixture design and analysis process. Computer-aided fixture design (CAFD), with predictable fixture stiffness, becomes a means to provide an appropriate solution in fixture design. The effectiveness of previous CAFD systems is not fully satisfactory partially because analysis of fixture stiffness has not kept pace with the development of CAFD[2]."

The ability to create a fixture that will properly test the reaction of the gear: shaft interface is very detrimental to the performance of the gear in application. The reaction of the gear will alter several factors of performance for the steering system. The worm gear interface will be affected by each reactive force which in turn effects contact pattern which alters the frictional state and creates noise and back drive issues. "Transmission error is usually due to two main factors. The first is caused by manufacturing inaccuracy and mounting errors. Gear designers often attempt to compensate for transmission error by modifying the gear teeth. The second type of error is caused by elastic deflections under load. Among the types of gearbox noise, one of the most difficult to control is gear noise generated at the tooth mesh frequency. Transmission error is considered to be one of the main contributors to noise and vibration in a gear set. This suggests that the gear noise is closely related to transmission error. If a pinion and gear have ideal involute profiles running with no loading torque they should theoretically run with zero transmission error. However, when these same gears transmit torque, the combined torsional mesh stiffness of each gear changes throughout the mesh cycle as the teeth deflect, causing variations in angular rotation of the gear body. Even though the transmission error is relatively small, these slight variations can cause noise at a frequency which matches a resonance of the shafts or the gear housing, causing the noise to be enhanced. This phenomenon has been actively studied in order to minimize the amount of transmission error in gears." [1]

As materials become more complex in their ability to bond with each other, welding becomes more common throughout the assembly of vehicles. This not only saves time, labor, and material costs, but also reduces weight, which improves efficiency of the vehicle. Mali and Inamdar (2012) help define welding: "Spot welds are the dominant joining method in the automotive assembly process. A spot weld is materialized by clamping the sheets with two pincers while applying force and transmitting current. The electrical resistance of the contacting sheets generates sufficient heat at the faying surfaces to melt the metal; eventually a nugget develops and the interface locally disappears. When the parts are in contact, an electric current is applied and the result is a small spot, heated to the melting point, in which the parts are joined."[7]

Welding is very difficult to simulate through CAFD or FEA programs. A weld is made up of thousands of contact points that were applied with variable electrode forces. Because of this, welds must be analyzed at each contact point in order to achieve a correct simulation. Wung, Walsh, Ourchane, Stewart, and Jie (2000) found that in order to properly model a spot weld thorough computational analysis, there must be some 5000 to 11000 quadratic solid elements. A vehicle may contain upwards of 2500-4000 spot welds. Due to the limitations of computer engineering costs, it is impractical to model each spot weld by solid elements. Because of this impracticality, welds must be manually tested.[4]

Along with the increase of spot welding usage in the automobile industry, there is an increase in development of computer aided spot welding programs. Mali and Inamdar, once again, found that, "Tecnomatix is a comprehensive portfolio of digital manufacturing solutions that link all manufacturing disciplines together with product engineering from process layout and design, process simulation and validation, to manufacturing execution. Built upon the open PLM (Product Life Cycle Management) foundation called the Team center manufacturing platform, Tecnomatix provides a versatile set of manufacturing solutions. NX CAM and CAM Express allow NC programmers to maximize the value of their investments in the latest, most efficient and most capable machine tools. NX CAM provides the full range of functions to address high speed surface machining, multi-function mill-turning, and 5-axis machining. CAM Express provides powerful NC programming with low total cost of ownership.[6]

Donders, Stijn, Brughmans, Hermans, and Tzannetakis stated that, "Noise, Vibration and Harshness (NVH). A vehicle's NVH (and derived structure-borne vibro-acoustic) properties are typically studied on a global level. Individual spot welds can transmit dynamic push and pull forces, shear forces and shear moments. Size, number and position of spot welds therefore influence the vibro-acoustic performance (modal basis, frequency response functions) of the vehicle. In general, the role of mechanical joints in vibration transmission and attenuation is important and quite complex. High-frequency, vibro-acoustic properties of spot-welded joints is derived. Joints are considered as a mechanical filter, with frequency-dependent transmissibility, reflectivity and absorption properties of the vibration energy." The importance of the type, size, volume, material, and process of the weld will drastically impact the NVH of the steering system. NVH becomes very critical in steering systems because of the steering column's ability to amplify any noise or vibration directly to the driver's seat.[5]

Development of Design Specifications

A meeting was held at Nexteer in Saginaw, MI, on August 14th, 2015, to discuss the required capabilities of a new gear test fixture. We met to discuss the root cause of failure and potential failure modes of the current weld break fixture. The customer requirements for a new fixture were discussed and documented.

Requirements were discussed that must be met in order for this fixture to properly function. The company is in need of a testing fixture that will record load data simultaneously with gear speed and gear flex position. Upon failure of the weld, a change in force of the load on the gear hub will prompt the motor to fault. This feature will allow the tests to continue until failure, eliminating need for incremental pauses in testing to examine the weld.
engineering characteristics

The gear test fixture itself must be capable of withstanding the forces on the gear, shaft welds assembly and other components. The forces acted upon it from the transmission torque. Maximum dimension 41cmX25.4cm. The center of the lower shaft must be 13cm above the surface of the table in order to connect directly with the transmission. The lower shaft engagement must hold a 47mm bearing. All fixture components must be able to withstand a minimum 5kN load. All fixture components must be corrosion resistant. Software must be able to detect fluctuations of load changes greater than 50N. Displacement measuring instruments must detect a 10 micron change. The motor must have a maximum operating speed of no less than 80rpm.

Constraints

Constraints for the new gear test fixture have been established based on economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability of the project factors. All constraints are policy enacted by Nexteer Automotive. The gear test fixture will not exceed 60lbs in order to maintain the ability of the engineer/technician to safely move it to alternate locations. All components must be made of either 6160-aluminum or 4140-black-oxide steel. All screws will be black-oxide steel hex heads with an Allen drive. The cost of this fixture is not to exceed $3500. This will include existing components and calibration that may be necessary. This fixture shall not emit any chemical or noise pollution while in operation or dormant. All mechanical testing fixtures will remain in a protected area free from human traffic while in operation.

Before any well-built component is manufactured, applications of the design are calculated through various mathematical modeling. Mathematical modeling will assist in determining if the component is able to withstand these stresses without yielding. During the modeling process, the maximum amount of stress that may possibly be applied on the component is calculated. Based on the calculation results, the design team can determine which, if any, dimensions need to be changed in order to achieve the most robust design. Calculations, using different component materials allow for maximum property capabilities. Having multiple material options lets the design team not only chose the most cost effective material, but also make decisions based on material availability. Stress analysis was done by performing hand calculations on each crucial component. Once data is analyzed through hand calculations, FEA modeling was performed through Ansys. This modeling software is used to expedite the design change process during the prototyping phase.

The gear test Fixture has several key components that will be subject to various stresses. The Gear Hub mount will be taking more stress than any other component on the fixture. Torque calculations will be performed on this component to ensure that no yielding will take place under cyclical loading. This is crucial due to the displacement values that will need to be collected from the operation of the fixture. The load cell push/pull mounts will then be simulated in order to determine the proper dimensioning of the arms where the track rollers are placed. The load cell weldments will also be stress testing in order to determine if the double rib layout will be the optimal design for the cyclical loading that will be present.

During the prototyping process it was discovered that the Gear Hub mount needed some minor design alterations. The screw pattern was changed in order to accommodate the operator during the gear change out process. Initial designs positioned the screws further inward of the edges anticipating stress fatigues. It was discovered that the screws could be moved closer to the edges of the gear hub mount base. This would allow for simpler removal by the operator. It was discovered, based on the loads being applied, that the load cell push and pull mounts would withstand maximum loading pressure by a large margin. This would allow for most any low carbon steel to be used in this application. Since the slide components are not experiencing any high loading, 6160 aluminum, which is most readily available, will be the optimal choice despite the higher cost.

Design Methods and Processes

The methodology that was employed to arrive at an optimal concept for the design project was the Analytic Hierarchy Process. This particular process is ideal for decision making that involves a set of alternatives with multiple selection criteria. This methodology was used to decide between three unique designs using six selection criteria, reliability, durability, accuracy, reparability, material cost, and mobility. The hierarchy of the selection criteria was consistent. The most important selection criteria to the design are accuracy and reliability. This particular fixture is dependent on how accurately we can measure the deflection of the part along with applying a consistent load for several thousand cycles. It is important that this design is able to measure the deflection to the nearest micron and that it is able to withstand this parameter while operating for several days.

Component geometry

Considering the overall size limitation of 25cm X 45cm, the first coordinates for the base of the fixture were determined. For detail dimensioning of the mounting base, the first step was to lay down the proper screw threads as the rest of the design was moving forward. A general purpose low-Carbon Steel is sufficient to support a fixture with approximate weight of 60 lbs. A 2.0cm thick base was selected by analysis of stress and deflection.

The next step in the process was to mount the gear. A low-Carbon Steel was used based on the stress analysis performed on the hub mount and availability of the material. There were two dimensioning constraints. The center of the gear shaft had to sit level with the motor coupling that will attach to the shaft in order to drive the gear and the height of the motor coupling. It had to be 13.3cm from the testing table. The gear mount design was intended to be recessed into the base in order to achieve dimensional accuracy and overcome torque loads. With this recess, the height from the center of the shaft to the bottom of the component is 12cm. The other dimensional constraint is that the component must house two 47mm bearings to support the shaft. These bearings must be placed 1.0cm apart.

Based on the stress analysis and availability of the material, the roller mounts were made of low-Carbon Steel. One mount will push a roller into the gear. Therefore, a center mount track roller was chosen. Clearance of the roller to the gear must be greater than 0.8cm. The other roller is designed to be pulled against the gear. A side mount track roller was selected. The roller mounting hole must be designed for a 1.1cm slide shaft. The arm must be 1.27cm thick to overcome stress. Both roller mounts must attach to load cells. This will require a 1.0-14 UNC thread.

The functional adjustment was designed next. A slider system was chosen to be a good fit dimensionally and aesthetically. A slider that is driven by a threaded rod can be adjusted in increments small enough to adjust in microns. This slider system will not experience any reciprocal movement that will result in any type of fatigue. Due to the mechanical movements required, a multipurpose 6061 Aluminum will be used in the construction of the slide system. The slide system is made up of three pieces: a riser, saddle, and base. These are common parts that can be bought or manufactured. The deciding factor is the budget for the project. To purchase the parts is much more costly ($500+) than purchasing raw material ($100) and machining them. There will need to be two sets of sliders manufactured. These sets will have the exact same dimensions and functions.

Since the general puropse low-Carbon Steel was purchased, it will be used for the load cell mount design. A simple ribbed right-angle bracket was designed. This will allow for load cell mounting access. The base will leave room for a 4 point screw system in order to mount the component to the slide saddle. A double ribbed bracket will be sufficient for sustaining 5kN loads without yeilding. The hole for the load cell will need to be a slip fit for a 2.54cm shaft. The screw holes will be through holes that will be tapped for a #10 steel head cap screw. The dowel mounts will be drilled thru at a 4.76mm dia. The height of the bracket will accommodate the position of the load cell and connect to the slide saddle.

In order to determine deflection of the gear, an electronic indicator must be mounted. Mitutoyo Electronic Indicators have a mounting option that's located on the backside of the indicator. In order to get the most accurate demensions, the indicator will be mounted to the slide riser and be positioned to take reading directly from the slide saddle. This will greatly reduce any opportunity for error. An opening for the mounting to the slide riser will continue half of the length of the componant in order to adjust the axial postion. This indictor mount will not experience any forces; therefore, it can be manufactured from the same 6061 aluminum that is already available. There will be two indicator mounts.

Results and Conclusion

The overall experience with this design process has been insightful. The first thing that comes to mind is our advantage over most projects. Being sponsored by a company is a major advantage over not being sponsored and relying on the meager school grant.

Upon completion of this project, we have found that conducting a proper weld failure experiment can be done in just a fraction of the time it took to simulate with the previous gear test fixture. By applying the maximum load, we can simulate thousands of bottoming cycles in just a few hours. While the load is being applied to the gear, the gear will be rotating at 80 RPM. The weakest point in the weld will fail first. Upon failure of the weld, the load cells will experience a drop in force. This drop in force will trigger a shut-off that stops the gear from rotating. From the data recorded, we are able to determine how many cycles before failure, the force applied at the time of failure, and the position of the gear during failure. This data allows us to compare different welds and weld materials that are most suitable for the application of the specific type of gear.

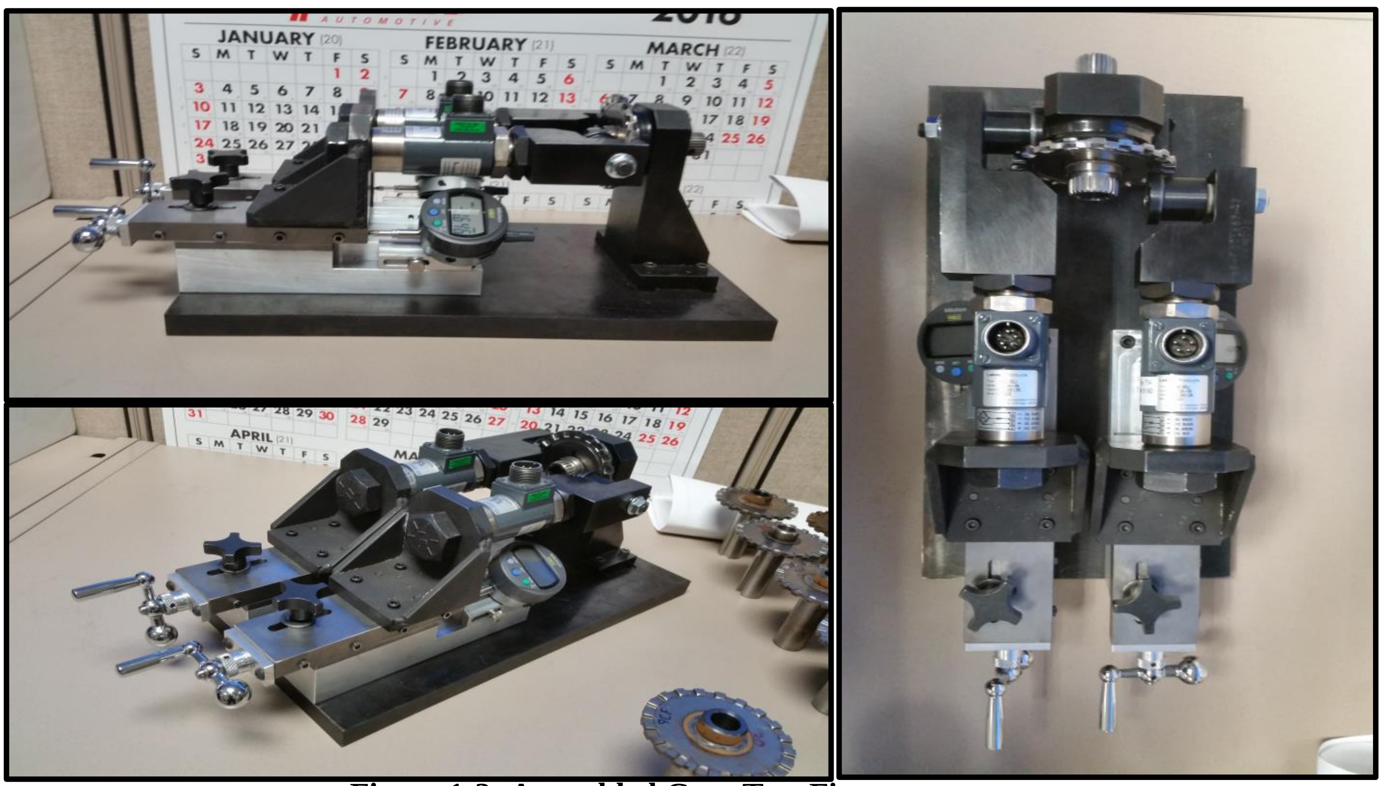

Figure 1-3: Assembled Gear Test Fixture

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