Proceedings of the 17th IASTED International Conference
MODELLING AND SIMULATION
May 24-26, 2006, Montreal, QC, Canada

DESIGN OPTIMIZATION OF AN AUTOMOTIVE UNIVERSAL JOINT CONSIDERING MANUFACTURING COST

Nick Cristello, and Il Yong Kim
Mechanical and Materials Engineering, Queen's University
130 Stuart Street, Kingston, Ontario
Canada
iykim@me.queensu.ca

ABSTRACT

This paper presents the shape optimization of an automotive universal joint, by simultaneously considering manufacturing cost, maximum drivable joint angle and part volume. Comprised of three main components – two yokes and a cross trunnion - a *universal joint* is a linkage used to transmit rotational motion from one shaft to another when the axes are coplanar, but not coinciding. In this research, universal joint designs are analyzed and compared using a weighted sum of three objective functions: minimization of machining cost, maximization of adjoining shaft joint angle, and minimization of total part volume. Part modeling and analysis is conducted using the Finite Element Analysis package ANSYS and optimization is implemented using MATLAB. The results show Pareto frontiers for both the flange and weld yoke, constructed using the Adaptive Weighted Sum technique. These frontiers clearly illustrate the trade-off between machining cost and joint angle; that is, to increase the joint angle, a corresponding increase in the cost of the part is required. It has been shown that maximization of driveable joint angle requires a simultaneous increase in machining cost of 4.4% and 2.7% for the flange and weld yoke, respectively.

KEY WORDS

Optimization, automotive universal joint, and manufacturing cost

1. INTRODUCTION

A universal joint is a device used to connect rotating shafts that are coplanar, but not coinciding. Each universal joint assembly consists of three major components: two yokes (flange and weld) and a cross trunnion. An automotive flange yoke has a machined flat face which may be affixed through a bolted connection to the rear differential of a vehicle. A weld yoke incorporates a machined step, and is inserted into the end of the driveshaft and welded in place. The cross trunnion is used to deliver rotation from one yoke to another using four needle pin bearings.

To protect the expensive driveline components in a vehicle, the cross trunnion in a universal joint is designed to fail at a pre-determined load. For this research, a Series 1350 universal joint from Neapco Inc. was acquired and modeled. This type of universal joint is commonly used on heavy duty ¾ ton trucks, and is designed to fail at 2520 lb•ft of torque.

Since driveline manufacturers are typically more concerned with the geometry and failure limit of the cross trunnion, little research has been conducted into the optimal shape and configuration of the flange and weld yokes. This lack of focus may lead to yokes which are over-designed; unnecessarily heavy and/or costly.

Multidisciplinary and multi-objective shape optimization can be used to quantitatively differentiate one design from another, by systematically searching the design space for optimum configurations. The simultaneous consideration of multiple performance measures is challenging to implement, however yields a valuable trade-off curve (Pareto frontier) outlining the interconnections between them.

In 1674, Robert Hooke first recognized the non-uniformity of rotational motion in a universal joint. However, it was Jean-Victor Poncelet in 1822 who first analytically derived the movement of Hooke's joint and identified the equations of motion between the linkages. Schmeltz, v.Seherr-Thoss and Aucktor [1] provide a concise overview of Hooke's joint, Poncelet's original equations and their applications to similar joint styles.

Modern literature indicates that substantial effort continues to be put forth to understand the kinematics and dynamics of a universal joint. Universal joint design for automotive applications is considered extensively in a comprehensive text compiled by the Society of Automotive Engineers in [2], and offers valuable insight into common design practices and guidelines.

The term 'optimization' is often used to describe the process of finding improved solutions. However, without a formal statement of objective functions, performance measures, constraints and design variables, the selection of the 'best' design may be subjective. Indeed, Hummel & Chassapis [3] conducted optimization on a universal joint with manufacturing tolerances by using process flow diagrams, but did not employ gradient-based search techniques to analytically map the design space.

Optimization of multiple performance measures requires a multi-objective weighting scheme to address all measures simultaneously. The Weighted Sum technique combines multiple objectives into one, through the use of weighting factors. These weighting factors indicate the relative importance of each objective. The main drawback to the Weighted Sum technique is that it produces an uneven distribution of optimal designs in the design space, making interpolation of the Pareto frontier of optimal designs increasingly difficult. In 2005, Kim and de Weck [4,5] introduced "adaptivity" into the Weighted Sum method to address this problem and provide a uniform distribution of optimal designs along the Pareto frontier.

This paper therefore premieres the successful comparison of universal joint designs, considering optimization of analytical performance measures using gradient-based search techniques. Pareto frontiers are constructed using the Adaptive Weighted Sum method for three objective functions: cost, joint angle, and volume. Results illustrate the trade-offs between these performance measures; in particular manufacturing cost and joint-angle.

2. PROBLEM STATEMENT

This paper presents multi-objective shape optimization of an automotive universal joint, considering machining cost, maximum drivable joint angle and part volume.

In particular, this research considers the component level optimization of an automotive universal joint flange yoke and weld yoke according to the following:

- Minimize: *(Machining Cost)*
  - (Joint Angle)
  (Volume)

- Subject to: *VM Stress ≤ Max VM Stress*
  SED ≤ Max SED

- Design Variables: $lb_i \le x_i \le ub_i \quad i = 1..10$

where *VM Stress* represents the Von-Mises Stress in the part, *SED* represents the Strain Energy Density in the part, and lb_i and ub_i are the lower and upper bounds of the design variables, respectively.

In a universal joint, rotational motion from one shaft is transferred to the other through needle pin bearings in the cross trunnion. As the joint angle increases, so does the variation in output displacement and velocity, with respect to the input. Equation 1 depicts how the rotation angle of the output shaft (β_1) is proportional to that of the input shaft (β) and the joint angle between shafts (θ).

$$\tan(\beta_1) = \cos(\theta) \cdot \tan(\beta) \qquad [1]$$

This relationship indicates that the output shaft experiences both acceleration and deceleration twice per revolution. By differentiating Equation 1, it can also be shown that as the joint angle increases, so does the angular velocity and acceleration experienced by the output shaft. This periodic change in velocity creates unwanted vibrations in the output shaft. These induced vibrations are one of the limiting factors in universal joint design.

Despite its limitations, one of the primary objectives of universal joint manufacturers is to maximize drivable joint angle. Restrictions on this maximum are caused by the induced vibrations previously mentioned and the interference between yokes.

In this research, a Pareto frontier is used to illustrate the interactions between performance measures by generating a plot of optimal designs. It is constructed such that an improvement of one objective can only be accomplished through the worsening of another. This type of graph helps design engineers decide which type of part geometry to employ, given the relative importance of each performance measure.

Initial geometry for this optimization assumes a series 1350 universal joint. The Pareto frontier for each yoke will be constructed using the traditional Weighted Sum technique, and the modified Adaptive Weighted Sum (AWS) technique, to systematically determine intermediary points and properly construct the frontier. Finally, this Pareto frontier will be examined to determine global relationships between applied performance measures, and quantitatively identify how a change in one performance measure will affect another.

3. MODELING

Modeling and simulation of the universal joint was conducted using the commercial Finite Element Analysis software, ANSYS v9.0. Since shape optimization requires systematic modification of part geometry, a robust and parametric model was constructed using a technique known as "bottom-up" modeling. This method begins by defining keypoints, then lines, then areas, then volumes, and finally meshing the structure. For increased accuracy, all parts were meshed using well-shaped quadratic, quadrilateral elements (SOLID95).

Figures 1 and 2 show the physical part obtained from Neapco and the resultant models for the flange yoke and weld yoke.

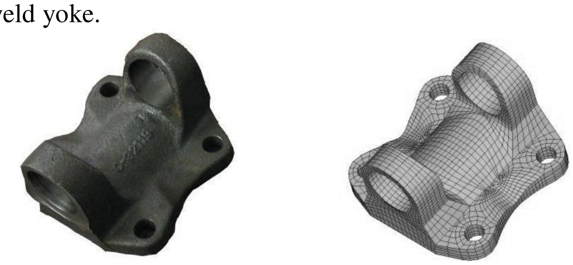

Figure 1: Flange Yoke Part & ANSYS Model (30,000 nodes)

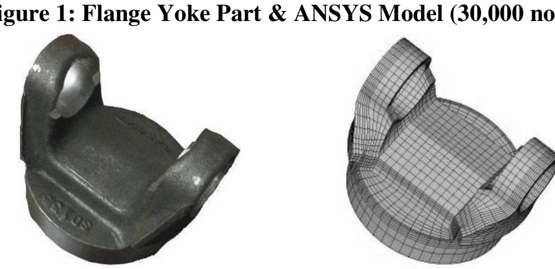

Figure 2: Weld Yoke Part & ANSYS Model (40,000 nodes)

Each component was first modeled as a ¼ section and then duplicated to create the entire structure. One assumption was that geometry would remain symmetric, even though loading conditions were not. Further research would define the *entire* model parametrically, without duplication, to construct an asymmetrical design with strength characteristics in more localized regions.

The bearing forces generated in the yoke ears were approximated according to the Gencoz distribution. In addition, to realize maximum volume reduction, a pseudo-topology optimization scheme was implemented to create a void in the centre boss.

3.1 Gencoz Distribution

During assembly, the bearing of the cross trunnion is press-fit into the yoke ear such that rotation, but no translation (sliding), is permitted. When considering each component separately during optimization, the applied loading in each yoke ear must be approximated. In 1980, Gencoz [6] proposed a pressure distribution scheme for a pin in a plate, considering an unsupported end and no sliding. Results were substantiated through experimental trials indicating a non-intuitive pressure distribution. This distribution was used to simulate the static loading delivered by the cross trunnion bearing to the yoke ears in this universal joint model.

Equation 2 shows the infinite series representing this distribution. Empirically, it can be shown that the infinite summations only need to be taken to the fourth terms.

$$\sigma_r = \frac{4P}{\pi Dt}\left[\cos\theta - \sum_{n=5,9}^{\infty}\frac{5}{14(n-1)(n-8)}\cos n\theta - \sum_{n=3,7}^{\infty}\frac{2}{5(4-n)^2}\cos n\theta\right] \quad [2]$$

To facilitate flexibility in shape, design and mesh density, the pressure load was applied to each element in the yoke ear individually. While this produced an accurate representation of the Gencoz distribution, it required more computational time than a uniform loading distribution. In addition, the pressure was applied normal to the element surfaces as suggested by Gencoz, inducing a force couple in the entire yoke. No axial forces were included in this design optimization.

3.2 Topology Optimization

To achieve the maximum possible volume reduction, a pseudo-topology optimization was implemented such that the centre points of the yoke moved outwards, forming a void in the centre of the part. When the size of the void reached a specified tolerance, the entire centre boss was eliminated from the computational domain.

Figure 3 shows the progression of the flange yoke with no void, to one with the entire centre portion un-meshed. A similar procedure is used for the weld yoke.

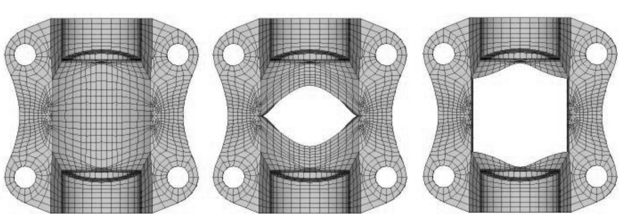

Figure 3: Pseudo-Topology Optimization

It must be noted that the geometry of this central void was not optimized, and for manufacturing and aesthetics purposes, any final part design should have a more continuous interior structure. These design refinements would be carried out in the final design phase of the development cycle.

4. OPTIMIZATION STRATEGY

Bi-objective optimization, considering manufacturing cost and joint angle, is conducted in this research using the Weighted Sum method. By employing this strategy, the optimization routine minimizes the objective function J_{total}, which is a weighted sum of each of the original objective functions: J_1 and J_2. Equation 3 shows how this total objective function value is calculated to determine the optimal design.

$$J_{total}(x) = w_1 \cdot J_1(x) + (1-w_1)\cdot J_2(x) \quad [3]$$

where w_1 is the weighting factor on objective function #1, $(1-w_1)$ is the weighting factor on objective function #2 and x is a vector of design variables. Note that w_1 must be between 0 and 1.

Executing multiple optimization simulations at several weighting factors and initial conditions will generate a set of optimal designs. The optimum design at each weighting factor is selected based on the lowest value of the total objective function. These designs are then plotted and connected to form a Pareto frontier.

The Adaptive Weighted Sum (AWS) method is applied to this research to obtain the most representative curve of optimum designs by generating a Pareto frontier with evenly distributed optimum designs.

For computational efficiency, gradient-based search techniques are employed using the *fmincon* function available in MATLAB. During each function evaluation, ANSYS is executed via batch-mode to determine the values of the performance measures and constraints based on the design variables.

To achieve meaningful results and to ensure an appropriate Pareto frontier, careful consideration must be given to the selection of performance measures, constraints and design variables.

4.1 Performance Measures

Manufacturing cost, joint angle and part volume are used as performance measures in this analysis to quantitatively compare the designs.

Machining Cost:

To ensure profitability, manufacturing cost must always be kept at the forefront of design, as shown in [7]. The cost of a component consists of many factors, including material costs, machining costs, labour costs and indirect costs. With respect to universal joints, one of the most significant contributors to manufacturing cost (excluding raw material cost) is the machining time and its related cost. Therefore, one of the objective functions in this research is machining cost.

Machining cost can be approximated using analytical equations developed by *Field, Zlatin, Williams and Kronenberg* in [8,9]. This economics formulation includes both direct and indirect costs and heavily depends on the type of machining operation; drilling, turning or milling. Machining of an automotive universal joint requires all three of these operations to arrive at a finished part. For the purposes of this optimization, only a relative comparison between designs is conducted, whereas all indirect costs are assumed to remain constant. Thus, the only variables affecting the machining time are the geometrical features defined by the design variables.

Equation 4 shows the total machining cost in dollars, assuming a labour rate of sixty dollars per hour ($60/hr). All variables prefixed with '*c*' are constants, representing indirect costs. Exemplar values for these constants are extracted from *Field et al* in [8, 9].

$$
\begin{aligned}
C_{total} = &\left[\frac{D_t L_t}{c_{t1}} + \frac{c_{t2} + L_t}{c_{t3}} + c_{t0} + \frac{D_t L_t c_{t4}}{c_{t5}}\right] + \frac{D_t L_t}{c_{t5}} \cdot [c_{t6}] + \\
&+ \left[\frac{D_m(e + L_m)}{c_{m1}} + \frac{c_{t2} + e + L_m}{c_{m3}} + c_{m0} + \frac{L_m c_{m4}}{c_{m5}}\right] + \frac{L_m}{c_{m5}} \cdot [c_{m6}] + \\
&+ \left[\frac{D_d L_d}{c_{d1}} + \frac{c_{d2} u + L_d}{c_{d3}} + c_{d0} + \frac{L_d c_{d4}}{c_{d5}}\right] + \frac{L_d}{c_{d5}} \cdot [c_{d6}]
\end{aligned}
\quad [4]
$$

The first, second and third lines of Equation 4 represent the contributions to machining cost from the turning, milling and drilling operations, respectively. Therefore, the only geometric parameters which affect the cost of machining are D, L, e and u, representing diameter of cut, length of cut, over-travel of cutter and number of similar cuts, respectively. Each of these variables is directly related to the design variables used to construct the Finite Element model in ANSYS.

Although the absolute value of Equation 4 may be inaccurate due to the estimation of indirect costs, results illustrate the *relative* cost advantages between designs.

Therefore, machining cost is considered one of the primary objective functions in this analysis.

Joint Angle:

To permit flexibility in design and re-usability of components in other assemblies, an ideal universal joint would accommodate a wide range of joint angles. However, increasing the joint angle causes vibrations in the output shaft, and this vibration results in an additional torque being imposed on the universal joint. The calculation of this vibratory torque is shown in [2], and illustrates its dependency on both joint angle and rotational velocity.

In this research, the vibratory torque is superimposed on the original input torque to represent vibrations caused by the joint angle offset. This performance measure, joint angle, is represented directly by one design variable such that increasing this design variable will increase the joint angle performance measure.

Volume:

Particularly in the automotive industry, minimizing weight is of critical importance in component design. Vehicle weight has a direct impact on fuel consumption, acceleration, and dynamic stability. Since the universal joint studied in this research is composed of an isotropic material (1050 steel), with uniform density, a reduction in volume will yield a corresponding reduction in weight. Thus, one of the primary objective functions in this research is to minimize part volume.

4.2 Design Constraints

Design constraints are functions which define the boundary between the feasible and infeasible design space; they explicitly detail which designs are acceptable and which are not. In this research, maximum allowable Von-Mises stress and maximum allowable Strain Energy Density (SED) are used as primary constraints.

Since the cross trunnion of a universal joint is designed to fail at a prescribed load (2520 lb•ft), application of this load to the yokes need only show a maximum Von-Mises stress and SED marginally below the yield point. Additional factors of safety are unnecessary since the yoke(s) will never experience a loading greater than 2520 lb•ft. The failure limits and other standard material properties for 1050 steel under forging and casting conditions are extracted from ASME handbook.

4.3 Design Variables

Design variables in this research are used to control the *shape* of the flange and the weld yoke.

Preliminary modeling of the yokes yielded 19 design variables for the flange yoke and 16 for the weld yoke. Since each iteration of the gradient-based search algorithm requires $n + 1$ function evaluations, reducing the number of design variables (n) from the analysis will result in significant computational savings. A sensitivity analysis was used to determine the relationship between the design variables and performance measures.

Sensitivity results were monitored for each of the objective and constraint functions by mapping a relative change in the design variable to a percentage change in the performance measures. Results showed that nine design variables could be eliminated from the computational domain of the flange yoke and six design variables could be eliminated from the computational domain of the weld yoke, without significant impact on design flexibility.

Therefore, only 10 design variables are used in each design optimization, yielding reasonable design flexibility with acceptable computational cost.

5. OPTIMIZATION RESULTS

In this research, MATLAB was used to conduct the Sequential Quadratic Programming (SQP) optimization and execute the ANSYS batch solver when necessary. To accurately determine the shape of the Pareto frontier, multiple initial conditions and weighting factors were simulated, using the AWS.

A mesh convergence study was performed in ANSYS to determine the reliability of results and establish that 30,000 and 40,000 nodes were appropriate mesh densities for the flange and weld yoke, respectively.

The flange yoke is constrained in all degrees of freedom throughout the centre of each mounting bolt hole and the weld yoke is constrained in all degrees of freedom along the weld seam. In both models, forces are applied to each yoke ear according to the Gencoz distribution.

The side constraints on all design variables are determined as geometrical constraints; no constraints are required to preserve mesh integrity.

Bi-objective optimization of Machining Cost v. Joint Angle is executed according to section *4. Optimization Strategy*. Six initial conditions were considered for each model, and for each initial condition, five weighting factors were selected. For every weighting factor, the optimum design was used to construct the Pareto frontier.

Figures 4 and 5 show the Pareto frontiers for Machining Cost v. Joint Angle of both the flange yoke and weld yoke. The part volume optimization results are omitted for brevity.

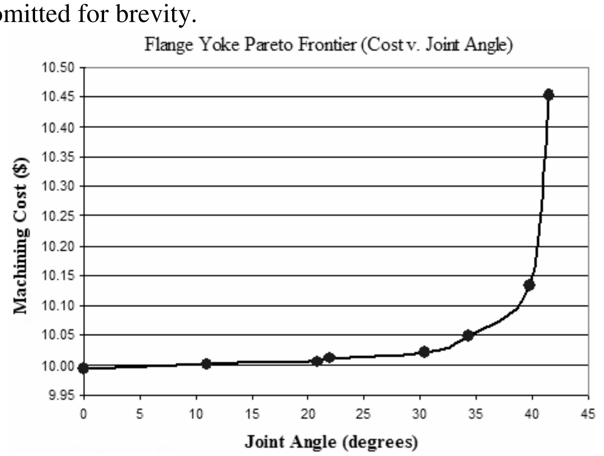

Figure 4: Flange Yoke Pareto Frontier (Cost v. Joint Angle)

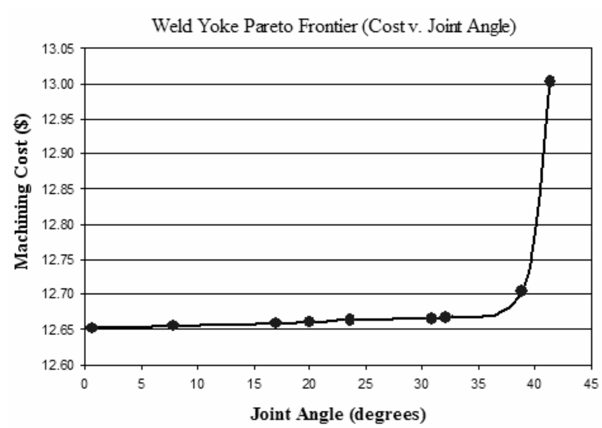

Figure 5: Weld Yoke Pareto Frontier (Cost v. Joint Angle)

In both models, the Utopia point for the multi-objective optimization is unattainable and thus the 'optimum design' is a curve of possible configurations.

Furthermore, both Pareto frontiers indicate that to minimize the machining cost, a subsequent decrease in joint angle is required. Conversely, to increase the joint angle, a corresponding increase in machining cost is required. Maximization of drivable joint angle requires a trade-off in cost of 4.4% and 2.7% for the flange and weld yoke, respectively. This relationship is not surprising since both parts are located in fixtures using the machined outer surfaces of the yoke ear, and therefore an increase in joint angle, which requires strengthening the yoke ears, will in turn require additional machining time and cost.

Conducting similar optimizations on Volume v. Machining Cost and Volume v. Joint Angle result in a similar trend; to decrease volume, a corresponding decrease in joint angle is required. These results will be presented in future work.

Tables 1 and 2 illustrate the initial configurations and the optimum designs for three different weighting factors in the bi-objective optimization of the flange yoke and weld yoke. Weighting factors of 1.0 and 0.0 correspond to minimization of machining cost, and maximization of joint angle, respectively. Figures 6 and 7 show the optimized flange and weld yoke geometry corresponding to the aforementioned optimum designs.

Table 1: Flange Yoke Optimum Designs

	Initial Design	**$w_1 = 1.0$ MIN: $J_1(x)$**	**$w_1 = 0.0$ MAX: $J_2(x)$**	**$w_1 = 0.6$ $J_1(x)$-$J_2(x)$**
$J_1(x)$	$10.53	$9.99 **(-5.4%)**	-	$10.05 **(-4.5%)**
$J_2(x)$	1.00°	-	41.51° **(+4050%)**	34.3° **(+3430%)**

Table 2: Weld Yoke Optimum Designs

	Initial Design	**$w_1 = 1.0$ MIN: $J_1(x)$**	**$w_1 = 0.0$ MAX: $J_2(x)$**	**$w_1 = 0.3$ $J_1(x)$-$J_2(x)$**
$J_1(x)$	$13.21	$12.65 **(-4.4%)**	-	$12.70 **(-4.0%)**
$J_2(x)$	1.00°	-	41.45° **(+4140%)**	38.8° **(+3880%)**

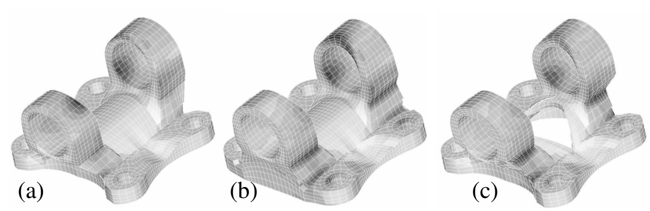

Figure 6: (a) Flange Yoke Optimization considering Cost (b) Flange Yoke Optimization considering Joint Angle (c) Flange Yoke Optimization considering Cost & Joint Angle

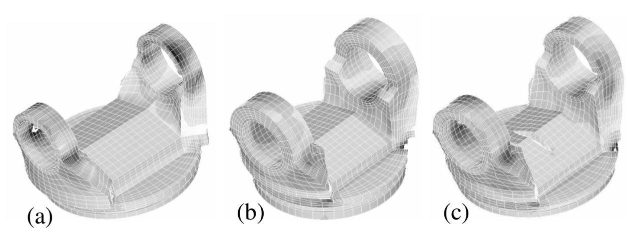

Figure 7: (a) Weld Yoke Optimization considering Cost (b) Weld Yoke Optimization considering Joint Angle (c) Weld Yoke Optimization considering Cost and Joint Angle

The optimum flange yoke design outlined in Figure 6(c) can yield a 4.5% reduction in machining cost and a 34° increase in joint angle (with respect to the initial design), without violating any of the design constraints. Similarly, the optimum weld yoke design of Figure 7(c) permits a 4.0% reduction in machining cost and a 38° increase in joint angle over the initial design. This suggests that in the initial configurations, both yokes may be over-designed.

It must also be noted that as the joint angle increases, the slope of the Pareto frontier also increases in both models. Clearly, the region between 0° and 30° for both parts will yield the most profitable designs, since an increase in joint angle may be realized with minimal effects on manufacturing cost.

6. DISCUSSION

This research showed that the shape of Pareto frontiers for both the weld yoke and the flange yoke are similar. The explicit differences in the absolute values between curves may be attributed to differences in part geometry, machining operations and loading conditions. Regardless, it is evident that in both components, the manufacturing cost and joint angle are competing objective functions.

It must also be noted that both curves increase in slope at the uppermost regions of the joint angle range. This behaviour is indicative of the increased vibrations at large joint angles. Alternatively, the interior region of the curve shows that a substantial increase in joint angle may be achieved with minimal effects on manufacturing cost.

Since the original design configurations do not lie on the Pareto frontier, this research suggests that with respect to machining cost and joint angle, both the weld yoke and flange yoke may be over-designed. Indeed it is shown that both performance measures may be improved with only minor modifications to part geometries.

Although the current models accurately represent the behaviour of each component, some areas for improvement still exist. Only fillets with critical structural importance were included in this modeling and analysis. Similarly, draft angle was also omitted to simplify the modeling. A more refined model would include all aspects of the part design. Such detail would require significantly more modeling resources and should be conducted using Computer Aided Design software.

In addition, while machining cost was considered in this research, manufacturability in terms of forging and casting was omitted. It was assumed that the basic procedure for manufacture would remain the same, and only minor tooling modifications would be required. However, it is recognized that the pseudo-topology optimization and extreme geometry modifications may significantly alter the flow of material during manufacturing, thereby requiring entirely new tooling.

This research generated a Pareto frontier of optimal designs for the components of a universal joint, but did not consider the assembly as a whole. Future work will include the optimization of a complete assembly and may consider a more robust optimization method such as Genetic Algorithms to provide useful results independent of an initial design vector.

7. CONCLUSION

This research showed the relationship between the manufacturing cost and joint angle performance measures of an automotive universal joint, through the use of a Pareto frontier constructed using the Adaptive Weighted Sum technique. The results illustrate that an increase in the drivable joint angle requires a corresponding increase in manufacturing cost. However, for both the flange and weld yoke, a substantial reduction in manufacturing cost may be realized by restricting the joint angle to less than 30°. Exemplar designs on the Pareto frontier illustrate that the manufacturing cost of the flange and weld yokes may be decreased by 4.5% and 4.0%, respectively, while simultaneously increasing the joint angle by 34° and 38°. Furthermore, since the initial configurations of both the flange and weld yoke do not lie on the Pareto frontier of optimal designs, these original designs may be considered over-designed with respect to both cost and joint angle.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and assistance of Mr. Michael Jones and Neapco Inc. for their generous donation of component samples. This research is funded by AUTO21, a member of the Network of Centres of Excellence of Canada program. This research is also funded by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

[1] Schmelz, v.Seherr-Thoss, Aucktor, , *Universal Joints and Driveshafts* (New York: Springer-Verlag, 1991).

[2] Sevin, & Raymond, *Universal Joint and Driveshaft Design Manual*, (Warrendale, PA: The Society of Automotive Engineers, 1979),

[3] S.R. Hummel, & C. Chassapis, Configuration Design and Optimization of Universal Joints, *Mech. Mach. Theory, 33*(5) , 1998, 479-490.

[4] I. Y. Kim & O. de Weck, Adaptive weighted sum method for multiobjective optimization: a new method for Pareto front generation, *Structural and Multidisciplinary Optimization, 31*, 2006, 105-116.

[5] I. Y. Kim & O. de Weck, Adaptive weighted-sum method for bi-objective optimization: Pareto front generation, *Structural and Multidisciplinary Optimization*, *29*, 2005, 149-158.

[6] D. Gencoz, U.G. Goranson, & R.R. Merrill, Application of finite element analysis techniques for predicting crack propagation in lugs, *International Journal of Fatigue*, July, 1980, 121-129.

[7] C. Rush, & R. Roy, Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cycle, *Department of Enterprise Integration,* 2000, Carnfield University.

[8] M. Field, M. Zlatin, R. Williams, & M. Kronenberg, Computerized Determination and Analysis of Cost and Production Rates for Machining Operations. Part 1-Turning, *Journal of Engineering for Industry, August*, 1968, 455-466.

[9] M. Field, M. Zlatin, R. Williams, & M. Kronenberg, Computerized Determination and Analysis of Cost and Production Rates for Machining Operations. Part 2-Milling, Drilling, Reaming and Taping, *Journal of Engineering for Industry, August*, 1969, 585-596.