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Optimization of Hydraulic Fluid Parameters in Automotive Torque Converters

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Abstract**—**The fluid flow and the properties of the hydraulic fluid inside a torque converter are the main topics of interest in this research. The primary goal is to investigate the applicability of various viscous fluids inside the torque converter. The Taguchi optimization method is adopted to analyse the fluid flow in a torque converter from a design perspective. Calculations are conducted in maximizing the pressure since greater the pressure, greater the torque developed. Using the values of the S/N ratios obtained, graphs are plotted. Computational Fluid Dynamics (CFD) analysis is also conducted.

Keywords**—**Hydraulic fluid, Taguchi's method, optimization, pressure, torque.

I. INTRODUCTION

SINCE its introduction in the 1940s, the torque converter has been used as a key component between the engine and the automatic transmission. It is a hydrodynamic device used to transmit rotating mechanical power. It provides an automatic means of coupling engine torque to the input shaft of the transmission. A torque converter has three major components: the impeller, the turbine and the stator. The hydraulic fluid in the converter transfers the torque from the impeller to the turbine which then sends it to the differentials. The torque converter also multiplies the torque transmitted and dampens fluctuation of the engine torque. In recent years, technological developments for automatic transmissions have been aimed mainly at the improvements of fuel economy with emphasis placed on increasing the efficiency of the torque converter. This can be done in two ways: developments can be conducted on the design of the torque converter, or the hydraulic fluid present inside can be given higher priority. The torque converter with the maximum efficiency strikes a perfect balance between the two.

Several previous studies have been conducted to better understand the nature of oil flow within the torque converter, with the primary concern being converter efficiency and performance. One of the earlier studies was by By and Lakshminarayana [1]. They performed analytical modeling and experimental validations using certain geometries. Their results showed that the primary factor on the static pressure rise in the pump is the centrifugal pump, and the static pressure distribution is generally poor at the blade core section. Keunchul C. Lee and Seoung-Chool Yoo [2] conducted an experimental study to reveal the internal flow characteristics within a production torque converter using Laser Doppler Velocimetry (LDV) under the operating conditions. The measurements were conducted on the planed between impeller blades, and the gap between the impeller and turbine blades. The study showed that the internal flow is highly complex and the difference in rotor speeds between the impeller and turbine compound the flow effects. This study led to a better understanding of flow mechanism and provided the guidance needed for the advancement of improved computational fluid dynamics models. Dong *et al.* [3] used a miniature high-frequency-response five-hole probe to find that the flow pattern at the pump exit is complex.

Lakshminarayana and Von Backstrom [4] provided a coherent and critical assessment of the main characteristics of the torque converter flow field and its impact on the performance and design. Fujitani *et al.* [6] computed the flow within a torque converter by assuming that the inlet boundary condition of each element is equivalent to the outlet boundary condition of the upstream-side element. Abe *et al.* [7] conducted numerical analysis of the flow field by adopting the steady interaction technique to connect the boundaries between the neighbouring elements; they did not, however, include a turbulence model. Shin *et al.* [8] presented numerical analysis of the incompressible, three dimensional, viscous and turbulent flow field within the impeller of an automotive torque converter.

In this paper, a detailed analysis on the key parameters of the Automatic Transmission Fluid (ATF) has been conducted. Taking four main parameters into consideration, the Taguchi method has been used to record the best possible values of these parameters. The Taguchi method involved reducing the variation in a process through robust design of experiments [5]. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. The arrays are designed based on the number of parameters (variables) and the number of levels (states).

The primary goal is to investigate the applicability of various viscous fluids inside the torque converter. It is known that the greater the pressure applied on the impeller and turbine blades by the fluid during rotation, the higher the RPM and therefore, the greater the propulsion of the vehicle. Therefore, various fluids have been used and simulated to check the pressure exerted on the impeller and turbine blades.

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II. Analysis

A. Description of Taguchi Method

The general steps involved in the Taguchi method are as follows:

1) Define the process objective, or more specifically, a target value for a performance measure of the process. Total pressure in kPa has been taken as the process objective. The goal is to maximize the total pressure.

2) Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure. Four parameters have been taken in this study – density of the fluid, Brookfield viscosity, inlet velocity and temperature. All these play a vital role and the variations of these parameters strongly affect the overall torque developed. Brookfield viscosity is the viscosity that is measured using the principle of rotational viscometry – the torque required to turn an object, such as a spindle, in a fluid thereby indicating the viscosity of the fluid.

3) Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. In this study, four parameters have been used. Therefore, the L9 Orthogonal Array technique is adopted.

Experiment	P1	P2	P3	P4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Fig. 1 L9 Orthogonal Array

Each parameter has three levels and 9 runs are to be conducted.

4) Conduct the experiments indicated in Fig. 1 to collect data on the effect on the performance measure.

5) Complete data analysis to determine the effect of the different parameters on the performance measure.

B. Basic Equations

To determine the effect each variable has on the output, the signal-to-noise ratio, or the SN number, needs to be calculated for each experiment. Since the target for this study is to maximize the pressure, the formula for maximizing the performance characteristic is used:

$$SN_i = -10\log[(\frac{1}{N_i})\sum_{u=1}^{N_i}(\frac{1}{{y_u}^2})] \quad (4)$$

where,

u = Trial number,
i = Experiment number, and
Ni = Number of trials for Experiment i.

After calculating the SN number for each experiment, the average SN value is calculated for each factor. An example is shown for parameter 3 (P3) in the array in Table I:

TABLE I
CALCULATION OF AVERAGE SN VALUE FOR EACH FACTOR [5]

Experiment Number	P1	P2	P3	P4	SN
1	1	1	1	1	SN_1
2	1	2	2	2	SN_2
3	1	3	3	3	SN_3
4	2	1	2	3	SN_4
5	2	2	3	1	SN_5
6	2	3	1	2	SN_6
7	3	1	3	2	SN_7
8	3	2	1	3	SN_8
9	3	3	2	1	SN_9

$$SN_{P3,1} = \frac{S_{N1} + S_{N6} + S_{N8}}{3} \quad (1)$$

$$SN_{P3,2} = \frac{S_{N2} + S_{N4} + S_{N9}}{3} \quad (2)$$

$$SN_{P3,3} = \frac{S_{N3} + S_{N5} + S_{N7}}{3} \quad (3)$$

Once the SN values are calculated for each factor and level, they are tabulated as shown below. The range R (R = Max SN - Min SN) for each parameter is calculated and entered into the table. The larger the R value for the parameter, the larger the effect the variable has on the process. [5]

TABLE II
FINAL TABLE [5]

Level	P1	P2	P3	P4
1	$SN_{P1,1}$	$SN_{P2,1}$	$SN_{P3,1}$	$SN_{P4,1}$
2	$SN_{P1,2}$	$SN_{P2,2}$	$SN_{P3,2}$	$SN_{P4,2}$
3	$SN_{P1,3}$	$SN_{P2,3}$	$SN_{P3,3}$	$SN_{P4,3}$
Δ	R_{P1}	R_{P2}	R_{P3}	R_{P4}
Rank	…	…	…	…

C. Flow Simulation

Computational Fluid Dynamics (CFD) is recommended as a practical approach to predict the forces, pressure etc. on the impeller and turbine. SolidWorks 2012 Flow Simulation package was used for the simulation of fluid flow inside the torque converter for this study. It was preferred over other software packages as it is a lighter software and it is more user friendly, especially in the simulation of fluids. The Flow Simulation Wizard combines the meshing and calculations together and hence does not bother the user with complex intricacies.

After going through several research articles, the following values were taken into consideration for the L9 Orthogonal

Array:

TABLE III
PARAMETERS AND THEIR MIN, MAX AND MEDIAN VALUES

Range (Factor No.)	A Density (kg/m^3)	B Brookfield Viscosity (Pa.s)	C Inlet Velocity (m/s)	D Temperature (K)
Minimum (1)	851	9	6	313
Median (2)	1030	15	12	338
Maximum (3)	1170	50	18	373

The impeller and turbine were designed in SolidWorks.

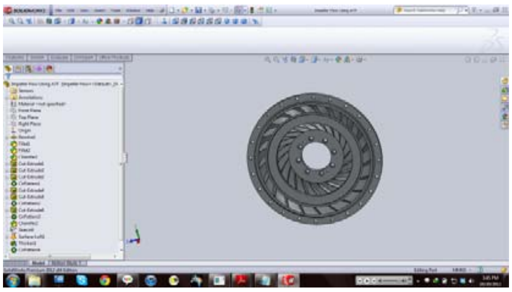

Fig. 2 Impeller Model in SolidWorks

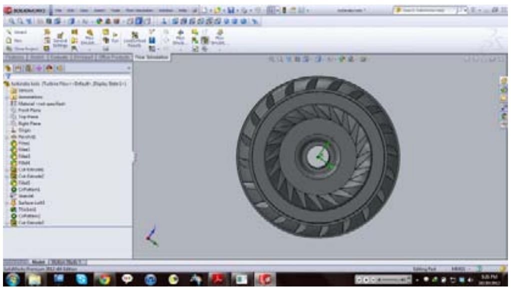

Fig. 3 Turbine Model in SolidWorks

The final table ready for flow simulation is as shown in Table IV:

TABLE IV
FINAL TABLE BEFORE FLOW SIMULATION

Run No.	A Density (kg/m^3)	B Brookfield Viscosity (Pa.s)	C Inlet Velocity (m/s)	D Temperature (K)
1.	851	9	6	313
2.	851	15	12	338
3.	851	50	18	373
4.	1030	9	12	373
5.	1030	15	18	313
6.	1030	50	6	338
7.	1170	9	18	338
8.	1170	15	6	373
9.	1170	50	12	313

III. RESULTS AND DISCUSSION

Nine runs of two trials each were conducted on the impeller and turbine separately by feeding in the properties of the fluid into the SolidWorks Flow Simulation software. Hence, a total of 36 runs were done. The pressures in kPa were recorded as shown in Table V:

For Impeller:

TABLE V
VALUES OF PRESSURES AFTER FLOW SIMULATION IN IMPELLER

Run No.	y_1 Pressure (kPa) Trial #1	y_2 Pressure (kPa) Trial #2	Mean
1.	127.235	127.235	127.235
2.	213.637	213.636	213.6365
3.	366.940	367.108	367.024
4.	218.107	220.012	219.0595
5.	385.105	385.981	385.543
6.	127.346	122.911	125.1285
7.	366.264	366.264	366.264
8.	131.321	130.700	131.0105
9.	209.451	209.621	209.536

Flow trajectories were used in SolidWorks to help visualize the fluid flow. The flow streamlines provide a very clear and comprehensive representation of the flow peculiarities. An example is shown below:

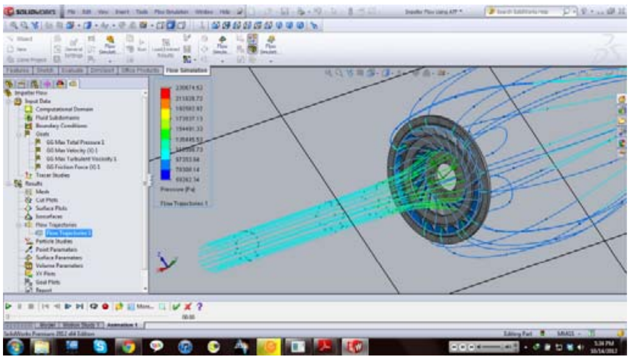

Fig. 4 Flow Trajectory of Hydraulic Fluid in Impeller

For Turbine:

TABLE VI
VALUES OF PRESSURES AFTER FLOW SIMULATION IN TURBINE

Run No.	y_1 Pressure (kPa) Trial #1	y_2 Pressure (kPa) Trial #2	Mean
1.	167.058	166.011	166.535
2.	184.564	176.988	180.776
3.	348.174	351.282	349.728
4.	190.914	190.914	190.914
5.	288.650	288.650	288.650
6.	147.740	147.740	147.740
7.	301.523	301.523	301.523
8.	127.654	127.654	127.654
9.	181.820	181.820	181.820

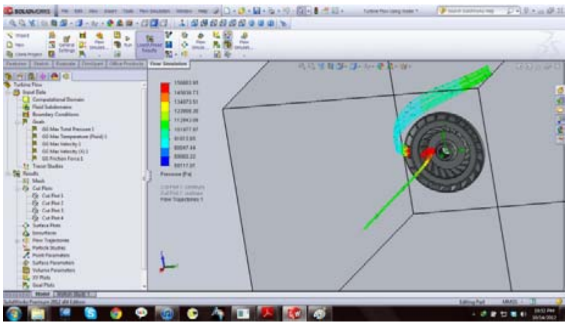

Fig. 5 Flow Trajectory of Hydraulic Fluid in Turbine

Using the formula to calculate the S/N Ratio in the case of maximizing the pressure, the respective S/N ratios along with the Range and Rank were found and mentioned in Table VII:

TABLE VII
RESPONSE TABLE FOR IMPELLER

LEVEL	A	B	C	D
1	46.659	46.707	42.127	46.746
2	46.824	46.886	46.610	46.585
3	46.664	46.554	54.411	46.817
Range	0.165	0.332	9.284	0.232
Rank	4	2	1	3

The rank implies how much effect the parameter has on the pressure. Therefore, it can be observed from Table VII that the inlet velocity has the largest effect on the total pressure and the density has the smallest effect.

TABLE VIII
RESPONSE TABLE FOR TURBINE

LEVEL	A	B	C	D
1	46.814	46.544	43.314	46.277
2	46.071	45.488	45.315	46.038
3	45.633	46.486	49.889	46.204
Range	1.181	1.056	6.575	0.239
Rank	2	3	1	4

Similarly, it can be observed from Table VIII that the inlet velocity plays the most vital role in the final value of the pressure and the temperature has the smallest effect.

By plotting the values obtained and tabulated in the Response Table, graphs can also be drawn. An example for Parameter A for Impeller is given in Fig. 6:

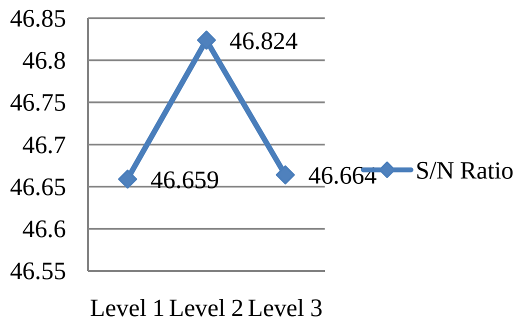

Fig. 6 Graph between S/N Ratio versus Parameter A for Impeller

An example for the graph between S/N Ratio and Parameter C in the turbine is given in Fig. 7:

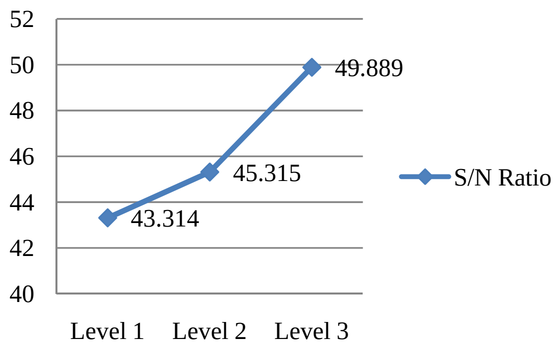

Fig. 7 Graph between S/N Ratio versus Parameter C for Turbine

Therefore, the optimum properties of the hydraulic fluid, when it strikes the impeller, for maximizing pressure thereby increasing torque is,

TABLE IX
OPTIMIZED VALUES FOR IMPELLER

Density (kg/m^3)	Brookfield Viscosity (Pa.s)	Inlet Velocity (m/s)	Temperature (K)
1030 kg/m^3	15 Pa.s	18 m/s	373 K

The optimum properties of the fluid when it strikes the turbine after the impeller is,

TABLE X
OPTIMIZED VALUES FOR TURBINE

Density (kg/m^3)	Brookfield Viscosity (Pa.s)	Inlet Velocity (m/s)	Temperature (K)
851 kg/m^3	9 Pa.s	18 m/s	313 K

It can be observed that according to Taguchi method, the properties of the fluid at the impeller and the turbine are not the same. This is because the density and Brookfield viscosity of the fluid change during the rotation of the torque converter depending on the rotation of the torque converter and the temperature generated inside it. In this investigation, the density gradually reduces from 1030 kg/m^3 to 851 kg/m^3 and the Brookfield viscosity also decreases from 15 to 9 Pa.S.

IV. CONCLUSION

The working principle of the torque converter along with the recent studies conducted around the world has been theoretically studied in this investigation. The properties of the fluid inside the torque converter have also been gone through. The study primarily revolves around the Taguchi method. Finally, the optimized values of the properties of the hydraulic fluid inside the torque converter have been obtained. These values can also be compared with the Automatic Transmission Fluids (ATFs) available in the market to draw further conclusions.

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