Real Time Systems: Parameter Identification for Speed Sensor Wheels

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Abstract: Modern diesel fuel injection system (common rail and pump-nozzle-units) requires the reference of crank angles, engine speed and load to estimate the two parameters: crank angle at the start of fuel injection and amount of fuel to inject for a diesel engine. Measurement of engine speed of a combustion engine is carried out by sensor wheels mounted on the crankshaft. Crank angles can be estimated from the measured engine speed. But geometrical tolerances of a sensor wheel result in systematic errors in the measurement. To get the corrected speed, we have to determine these errors due to geometric tolerances. These geometrical tolerances can be estimated by solving a nonlinear system of equations which is formulated using a suitable physical model of kinetic energy balance of the crankshaft and the measurement of engine speed.

Keywords: Real Time Operation; Numerical Methods; Sensor Wheel; Geometric Tolerances.

1 INTRODUCTION

Generally, measurement of the speed of combustion engines is carried out by sensor wheels held on the crankshaft. The geometric tolerances of a sensor wheel can cause a systematic deviations that can reduce the quality of engine speed sensing. Therefore, to obtain the appro- priate speed, we have to determine the deviations due to geometric tolerances. Here two parameters are very important in combustion engine control systems: the crank angle which is at the start of fuel injection and the amount of fuel to be in- jected. To assess these parameters, a modern diesel fuel injection system (common rail and pump-nozzle-units) re- quires engine speeds, crank angles, load etc. Engine speeds and crank angles can be measured by a sensor wheel. In the paper we are going to look at how in real time systems can be identification the geometric tolerances of sensor wheel. To get the appropriates speed, we have to de- termine the errors due to geometric tolerances. These geo- metrical tolerances can be estimated by solving a nonlinear system of equations which is formulated using a suitable physical model of kinetic energy balance of the crankshaft and the measurement of engine speed.

2 USING A SENSOR IN REAL TIME OPERATION

Speed of combustion engines is estimated by sensor wheels mounted on the crankshaft. Geometric tolerances of a sensor wheel produce systematic deviations from the actual speed of the engine. Therefore, the measured speed differs from the actual speed due to imperfect sensing of engine speed by the sensor wheel with some geometric tolerances. To get the actual speed, we have to determine the deviations due to geometric tolerances.

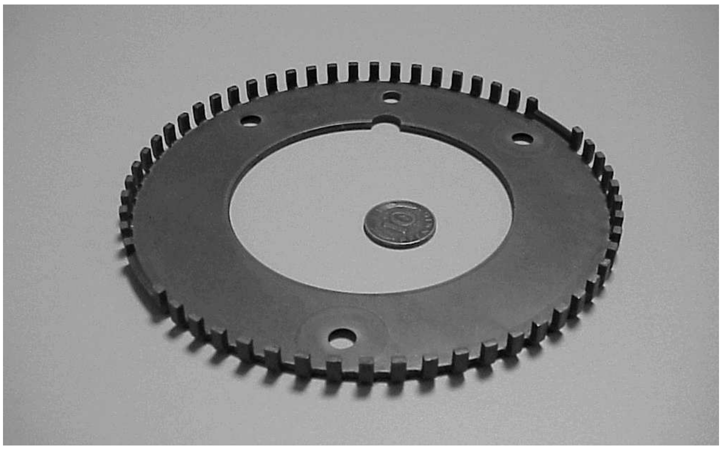

FIGURE 1: A 60-2-2 sensor wheel for diesel engines with 56 teeth and 2 gaps. This figure is reproduced by the courtesy of IAV GmbH, Germany

Two parameters are very important in combustion engine control systems: the crank angle at the start of fuel injection and the amount of fuel to inject. To estimate these parameters, a modern diesel fuel injection system (common rail and pump-nozzle-units) requires engine speeds, crank angles, load etc. Engine speeds and crank angles can be measured by a sensor wheel.

FIGURE 1 shows a 60-2-2 sensor wheel for diesel engines with 56 teeth with two gaps. The wheel mounted on the crankshaft rotates with it. The wheel is fitted with teeth sensible by a stationary magnet which field changes with the movement of teeth. The change is sensed by the voltage generated in a coil of wire in the magnetic field.

A controller receives each voltage pulse from the sensor and records its time of arrival $T_0, T1, \cdots$. With this information, the period $\Delta T_i = T_{i+1} - T_i$ can be determined where the index $i = 0, 1, \cdots$ indicates the tooth number. The speed $\dot{\phi}_e$ can be measured by

$$\dot{\phi}_e = \frac{\Delta\phi_e}{\Delta T_i}.$$

The teeth are evenly spaced except for missing teeth in the gap. The voltage signal is interpolated over two missing teeth in each gap. The sensor wheel in FIGURE 1 has 60 teeth (including 4 missing teeth), and therefore $\Delta\phi_e = 360^0/60 = 6^0$. The distance between two successive teeth should be constant. However, geometric tolerances in distances between two successive teeth of sensor wheels lead to systematic deviations of the actual engine speed. Since geometric tolerances are related to these deviations by some simple formula, we will investigate the method in [2] to compute the deviations by different variations of Newton's method.

3 PHYSICAL MODEL

Identification of geometric tolerances in sensor wheels is based on the balance of the kinetic energy of the crankshaft [1], [5], [9], [10], [11]. The kinetic energy can be modeled by the energy E_0 due to the engine speed and the energy E_1 due to the load:

$$E_{kin} = E_0 + E_1.$$

The kinetic energy is related to the actual engine speed by the equation

$$E_{kin} = \frac{1}{2}\Theta\dot{\phi}^2,$$

where Θ is the moment of inertia and $\dot{\phi}$ is the actual engine speed. Combining above equations together we have

$$\frac{1}{2}\Theta\dot{\phi}^2 = E_0 + E_1.$$

Due to the sensor wheel deviation, we obtain the deviated engine speed ϕ_e (which is the measured speed). The actual engine speed $\dot{\phi}$ can be given by

$$\dot{\phi}_e = \dot{\phi}(1-\delta), \tag{1}$$

where δ is the speed correction due to sensor wheel deviation. Using this relation to the previous equation we get

$$\frac{1}{2}\Theta\frac{\dot{\phi}_e^2}{(1-\delta)^2} = E_0 + E_1.$$

This equation can be set up for each tooth i of the sensor wheel:

$$\frac{1}{2}\Theta_i\frac{\dot{\phi}_{e,i}^2}{(1-\delta_i)^2} = E_{0,i} + E_{1,i}, \tag{2}$$

where the index $i = 0, \cdots, n-1$ indicates the tooth number. Notice that the tooth position n corresponds again to the tooth position 0. We suppose that the load is constant during measurement of the engine speed.

Computing Θ

The moment of inertia Θ_i depends on the crank angle. It can be calculated by the rotating and oscillating masses of the engine. In practice, the stiff part of the moment of inertia cannot be accurately determined. Therefore, an offset Θ_{offset} is applied to the estimated moment of inertia $\Theta_{1st,i}$. Hence,

$$\Theta_i = \Theta_{offset} + \Theta_{1st,i}. \tag{3}$$

Computing E_0

The energy E_0 due to the engine speed changes with the friction, load, etc. The speed correction δ_0 effects on E_0 which must be taken into account. At $i = 0$, the energy E_0 due to the engine speed is given by

$$E_{0,0} = \frac{1}{2}\Theta_0\frac{\dot{\phi}_{e,0}^2}{(1-\delta_0)^2}. \tag{4}$$

Similarly, at $i = n$ we have

$$E_{0,n} = \frac{1}{2}\Theta_0\frac{\dot{\phi}_{e,n}^2}{(1-\delta_0)^2}. \tag{5}$$

During a crankshaft revolution, the energy due to the engine speed has approximately a linear variation. Therefore the energy $E_{0,i}$ between $E_{0,0}$ and $E_{0,n}$ can be computed by the equation

$$E_{0,i} = E_{0,0} + \frac{E_{0,n} - E_{0,0}}{n}i, \quad \text{with } i = 0, \cdots, n-1. \tag{6}$$

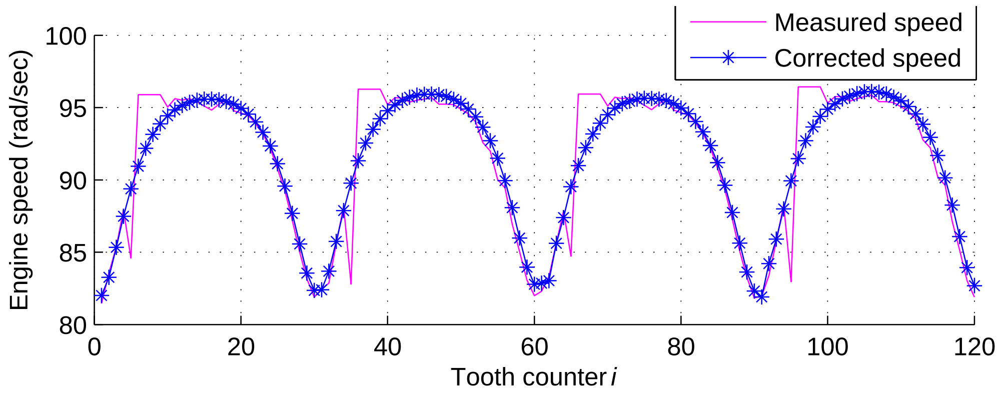

FIGURE 2: Measured and corrected engine speeds.

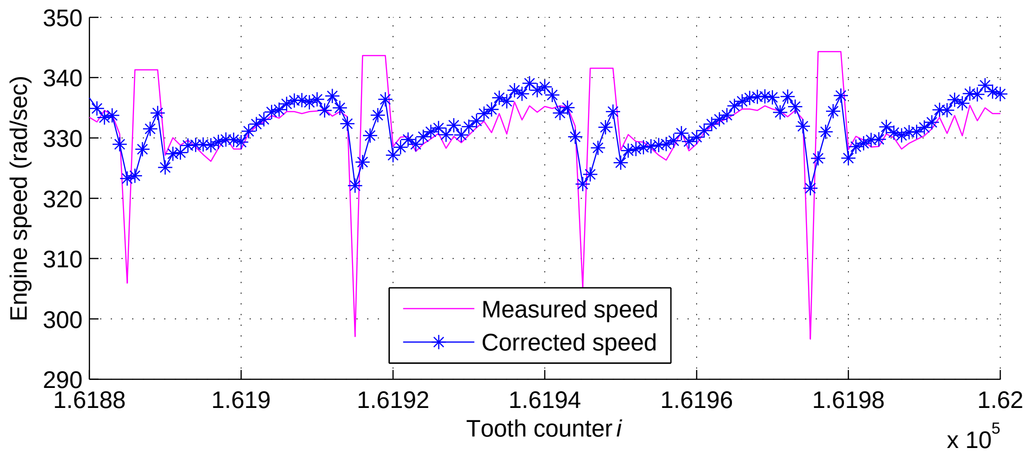

FIGURE 3: Measured and corrected engine speeds.

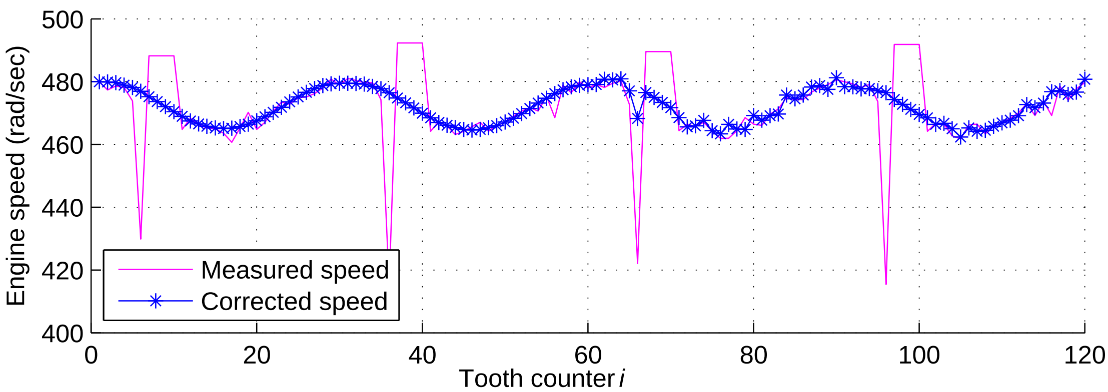

FIGURE 4: Measured and corrected engine speeds.

Computing E_1

The energy $E_{1,i}$ due to the load is stored during the compression stroke of the engine. It varies linearly with the load:

$$E_{1,i} = p_{load} G_{1,i}. \tag{7}$$

The values of $G_{1,i}$ are computed by complicated formulas which include the rules of the crankshaft kinematics and polytrope compression [1], [5], [9]. The goal of the identification is to estimate the unknown parameters using the known/measured set of data, and determine the actual engine speed $\dot{\phi}$. The known and unknown quantities/parameters are listed in the

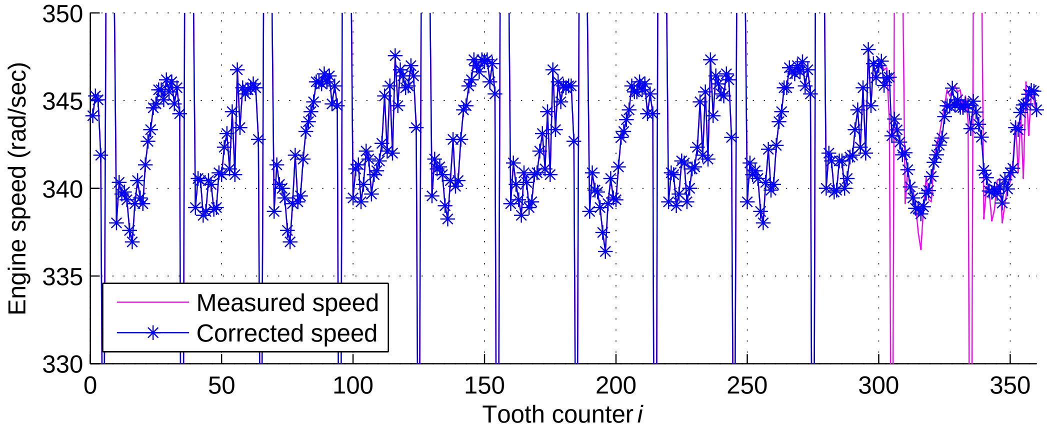

FIGURE 5: Measured and corrected engine speeds.

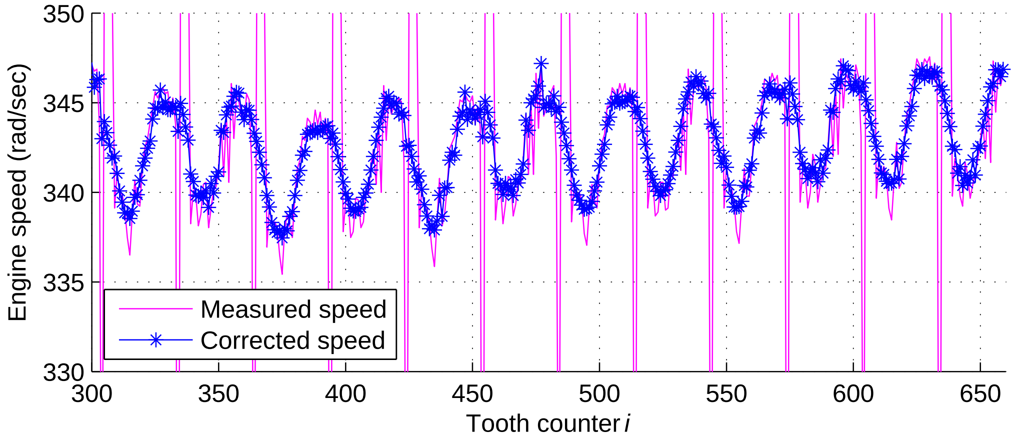

FIGURE 6: Measured and corrected engine speeds.

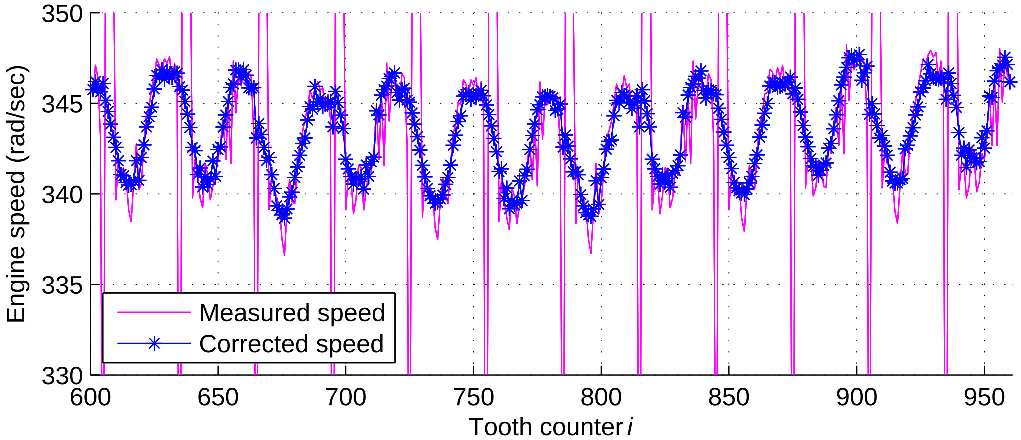

FIGURE 7: Measured and corrected engine speeds.

following table.

Known/measured quantities	Unknown parameters
$\Theta_{1st,i},\ i=0,\cdots,n-1$ $p_{load},\ G_{1,i},\ E_{1,i},\ i=0,\cdots,n-1$ $\dot{\phi}_{e,i},\ i=0,\cdots,n$	Θ_{offset} $\delta_i,\ i=0,\cdots,n-1$

Table 1: Solutions by different variants of Newton's method

Initial point	Method	Iterations	Norm of residuals	Convergence to true solution	Cause of failure	Time(ms)
0	1	5	8.85174e-09	Yes		5.7
	2	5	8.85174e-09	Yes		5.61
	3	5	8.85174e-09	Yes		6.8
0.1	1	5	0.0255291	Yes		6.45
	2	5	1.88e-9	Yes		6.67
	3	5	0.0255291	Yes		6.8
0.2	1	5	0.0106199	Yes		6.6
	2	5	6.15e-9	Yes		6.68
	3	5	0.0106199	Yes		6.82
0.5	1	6	4.9827e-06	Yes		7.5
	2	6	6.94e-13	Yes		8.1
	3	6	5.06e-6	Yes		8.5
0.7	1	6	0.000174425	Yes		7.95
	2	6	5.48e-11	Yes		8.02
	3	6	0.0016	Yes		8.5
1	1	-	-	No	Singular	10
	2	-	-	No	Singular	15.19
	3	-	-	No	$\Delta \leq \Delta_{min}$	20.2
2	1	7	0.000701749	Yes		10
	2	7	5.8e-19	Yes		9.39
	3	-	-	No	$\Delta \leq \Delta_{min}$	20.2
10	1	-	-	No	Singular	130
	2	8	1.86e-10	Yes		1.37
	3	-	-	No	$\Delta \leq \Delta_{min}$	20.2
-0.1	1	-	-	No	Singular	120
	2	-	-	No	$\Delta \leq \Delta_{min}$	1.37
	3	-	-	No	$\Delta \leq \Delta_{min}$	20.2
-0.2	1	9	0.00471062	Yes		10
	2	-	-	No	$\Delta \leq \Delta_{min}$	1.37
	3	-	-	No	$\Delta \leq \Delta_{min}$	20.2

4 MATHEMATICAL FORMULATION

From (2), the nonlinear residual is given by

$$F_i = E_{0,i} + E_{1,i} - \frac{1}{2}(\Theta_{offset} + \Theta_{1st,i})\frac{\dot{\phi}_{e,i}^2}{(1-\delta_i)^2}, \quad (8)$$

with $i = 0, \cdots, n-1$ which has the unknown parameters $\delta_0, \cdots, \delta_{n-1}$ and Θ_{offset}. This system consisting of n residual components and $n+1$ unknown parameters requires an additional equation for its solution. Now we give the $(n+1)$th necessary equation which implies that the mean sensor wheel deviation vanishes:

$$F_n = \sum_{i=0}^{n-1} \delta_i. \quad (9)$$

Hence we have the following nonlinear system of equations

$$F(x) = 0, \quad (10)$$

with

$$x = [\delta_0, \delta_1, \cdots \delta_{n-1}, \Theta_{offset}]^T, \tag{11}$$

and

$$F = [F_0, F_1, \cdots, F_n]^T.$$

This system of nonlinear equations is solved for x and hence the corrected engine speed can be obtained using (1).

5 TEST RESULTS

The system (10) was solved by Matlab in [2]. We solved the problem by different variants of Newton's method [4], [6], [7], [8] and analyzed the convergence and computational time. Based on this result, we want to choose an appropriate variant to solve the system in the real time operation. Several variants of Newton's method were used to solve the nonlinear system (10) for δ and Θ_{offset}. All the data of $\dot{\phi}_e$, p_{load}, G_1 and Θ_{1st} from the sensor wheel with $n = 60$ teeth were given. The Jacobian matrices were computed using center differences [3], [8]. The test was performed by a GCC compiler of version 3.3.1 under a Linux operating system, and executed on a Pentium 4 processor with 2.40 GHz. We obtained the corrected engine speed from δ and $\dot{\phi}_e$ using (1). The test results are presented in FIGUREs 2–4.

In these figures, measured and corrected engine speeds (computed from a converged solution) are plotted against the tooth counter ($i = 0, \cdots, 119$). In FIGUREs 2 and 4, the solution δ computed from the current revolution (with tooth counters $i = 0$ to 59) were used to correct the measured speeds $\dot{\phi}_e$ of the next revolution (with tooth counters $i = 60$ to 119). FIGURE 4 shows good results in estimating the corrected speed during the revolutions. However, In FIGURE 4 we observe a very good result in estimating the corrected speed during the current revolution, while the result deteriorates a little during the next revolution. The cause of the deterioration is the imperfection of computing E_1 and the effect of the crankshaft torsional vibration. The torsional vibration increases with higher engine speed. Therefore, FIGURE 3 shows very bad results for the revolutions in that the solution δ computed for FIGURE 2 (with tooth counters $i = 0$ to 59) were used to correct the measured speeds with tooth counters $i = 161880$ to 162000.

In the real time operation, computation for the current revolution c_k may take more time than the period δT_{k+1} of next revolution c_{k+1}. In such a case, computation continues during the next few revolutions $c_{k+1}, c_{k+1}, \cdots c_{k+p}$, and the previous solution x_{k-1} is set for these revolutions. When computation for the current revolution c_k ends, computation for the revolution c_{k+p+1} starts. This process is set to continue in the real time operation. As a demonstration, we conducted a numerical test which are shown by FIGUREs 5–7.

From FIGUREs 5–7, we assume that the engine speed is 350 radian/sec. Therefore, for 1 revolution it takes $(2\pi/350) * 1000 \approx 17$ ms (millisecond). Assume that computation takes 60 ms in a real time operation, and hence $p = 1 + 60/17 \approx 4$, that is, results of computation can be obtained after 5 revolutions. For FIGURE 5, we used the data of the 1st revolution was used to obtain δ to correct the measured speeds of the 6th revolution. FIGURE 6 shows the measured and corrected speeds where the data for the 6th revolution was used to recalculate δ to correct the measured speeds of the 11th revolution. Note that previous δ was used to correct the measured speeds of 6th to 10th revolutions. For FIGURE 7, the data for the 11th revolution was used to estimate δ again to correct the speeds of the 16th revolution. Previous δ was used to correct the speeds of 10th to 15th revolutions. This procedure continues in the real time operation.

Results from the different variants of Newton's method using the measured speeds shown in FIGURE 4 are listed in TABLE 1. In this table, the first four columns provide the initial point, the variant of Newton's method, the number of iterations and the 2-norms of residuals. Columns 5, 6 and 7 give us whether convergence [3], [4] to a true solution was achieved and the cause of failure and the required time in millisecond. Since a nonlinear system of equations may have more than one solution, the "true solution" is meant a reasonable and practically useful solution which was verified by the criteria

- A true solution must satisfy its bound constraints. The deviations δ should be between the bounds of -0.2 and +0.2, and $\Theta_{offset} > 0$ to be physically meaningful.
- The corrected engine speed from a true solution must fit the measured speed.

In column 6, "singular" indicates that the Jacobian is singular and computation stops. The other case "$\Delta \leq \Delta_{min}$" implies that the current trust-region radius Δ is less or equal to $\Delta_{min} = 1.0\text{e-}6$. In this case, further computation will hardly benefit and computation terminates. Each component of initial x holds the number given in column 1. In column 2, we use the number

- 1 for Newton's method,

- 2 for Newton's method with line search, and
- 3 for Newton's method with trust-region.

Newton's method and Newton's method with line search work better than Newton's method with trust-region for this nonlinear system of equations. With negative initial points the methods do not work properly. The methods mostly succeed if the initial points are larger than or equal to zero. We notice that the methods work well when the initial points lie between 0 and 0.2.

6 CONCLUSION

It is unlikely that a single variant will always give the best performance for different varieties of identification prob- lems. Newtons method for the identification problem of sensor wheels demonstrates better performance than its variants. Key issues are the selection of initial points for the methods. Theory has little to say about such matters, but poor choices lead to poor performance. The model of sensor wheels can be improved by considering the effect of crankshaft torsional vibrations.

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