A METHOD TO EVALUATE TRANSMISSION EFFICIENCY OF GEAR REDUCER

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Abstract - This paper presents a method for determining the transmission efficiency of a gear reducer. The proposed method contains an identification theory to derive a dynamical model of motors. Using the identification theory, we propose a method to measure the torque transmission efficiency of the gear reducer. The identification theory is derived from the error between input and output data of the mathematical model of a target plant and actual time series data of the plant by an experiment. The dynamic characteristics of the gear reducer are calculated by identification theory for a system installing the motors. The target plant means a motor or a combined system consisting of the motor and the gear reducer. We discuss the torque constant as one parameter that determines motor characteristics. The torque constant value of the motor can be determined using the identification theory. Then, the torque transmission efficiency of the gear reducer can be decided by the torque constant value. In this paper, we first explain the algorithm of the identification theory, second discuss the results of identifying the motor torque constant, and finally examine the transmission efficiency of the gear reducer in the experiment.

Keywords: Transmission Efficiency, Identification, Gear Reducer.

1. Introduction

Generally, factors that affect the performance of reduction gears in gear series include transmission efficiency, durability, gear backlash, etc. The performance of the general gear reducer is related to the arrangement and structure of gears and also depends upon the value of reduction ratios. Recently, there have been various types of gear reducers. As the typical ones, multistage gear reducers, planetary gear reducers, worm reducers, bevel gear reducers, ball reducers, harmonic drive reducers, RV reducers, and cycloidal gear reducers, etc. are included. Along with the development of various gear reducers, various measuring instruments have been produced to measure the transmission efficiency of gear reducers. Among measuring devices to evaluate the performances of gear reducers, some general torque measuring instruments employ the torsion and strain characteristics of the rotating shaft as a principle. There is a limit to the amount and accuracy of torque when each torque-measuring instrument is measured. As the dynamic characteristics of the rotating shaft affect the measurement results of torque when measuring torque, it is necessary to accurately select the measuring instruments and devices with an appropriate specification that can accommodate the magnitude of the conduction torque of the gear reducer to be measured.

In this study, to find the torque transmission efficiency of the gear reducer, we estimate the physical parameters of the DC motor and input/output characteristics of the gear reducer using an identification method. First, the physical parameter of a single DC motor is estimated by the identification algorithm. Second, two DC motors for input and output whose parameters have been already identified are attached to the input and output shafts of the gear reducer. Third, the angular velocity of each DC motor and currents flowing in the motors are measured after rotating the motors. Finally, the torque transmission efficiency of the gear reducer can be estimated by measuring the actual currents and angular velocities of the DC motors. Consequently, by the above procedures, a new estimation system that identifies the dynamic characteristics of the DC motors is developed.

It is well known that the current value flowing in the DC motor and the generated torque have a proportional relationship. In experiments, we measured the current value when any load was not applied and the motor torque when the motor rotation was stationary using the well-known conventional measuring methods. Then, we calculated the proportionality constant of the motor from the relationship between the measured torque and current value.

As the next step, the torque transmission efficiency is decided by comparing the torque generated by both DC motors. During measurement, as the DC motor has a commutator, the value of the current flowing through it was changed slightly for each phase, and there are moments when no current flows temporarily. Therefore, there is a slight difference between the measured values of dynamic torque and static torque compared to the theoretical values, respectively. Thus, the torque transmission efficiency of the reduction gear using a DC motor based on the conventional identification method is determined.

Next, as another target in the measurement, we determine the torque transmission efficiency of the cycloidal gear reducer and continuously variable transmission manufactured by the authors. Using the proposed identification system for the general gear reducer, we observe the proportional constant between the torque and current value of the cycloidal gear reducer by identifying parameters from actual measured values that indicate DC motor dynamics. Then, we compare the proposed identification method with experimental data obtained by the measurement system and confirm the effectiveness of the identification system. It is understood that torque transmission efficiency determined from the measurement results using the proposed identification method becomes higher, and it has more accuracy value than the one derived from the conventional methods.

2. Historical Background

Tarek A. Tutunji has identified the transfer function of a DC motor system accurately using impulse response data. The described algorithm used an ARMA model with the steepest descent method to match the model output to the original system [1]. Bal´azs Kulcs´ar et al have tested an LPV subspace identification algorithm on a real measurement data set. The predictor-based subspace identification technique was able to be applied for identifying a special case of small-scaled nonlinear systems cast into the parameter-dependent form. Real measured data were collected from a DC motor with an unbalanced rotation disc. The results verify that the LPV-PBSID was a powerful method to identify nonlinearities in the dynamics [2]. Wei Wu has proposed a convenient and effective system identification approach to estimate the DC motor torque constant, mechanical time constant, electrical time constant, and friction. The approach was implemented on two motors, and the results were given. The proposed method does not need any hardware, except for a speed/position sensor and a voltage supply [3]. Kama Azura Othman et al have presented modeling of a discrete DC motor positioning using system identification. The identification of the most suitable discrete model of the DC motor was done by using MATLAB/Simulink. The best discrete model was determined by testing with four different sampling times. Results presented showed that the best model achieved a high performance at the sampling time [4]. Omar Rodríguez-Abreo et al have proposed the use of dynamic response relations as search constraints in metaheuristic algorithms used as parametric estimators. The method was applied to the system with a stable response to the step input. In particular, the parameter identification with metaheuristic algorithms has shown satisfactory results [5]. Mohamad Farid Fazdi et al reviewed several methods and algorithms used to estimate the excess parameters of DC motors from the least squares method. The method has more applications for estimating DC motor parameters than metaheuristic algorithms due to the ease of calculating using the least squares method [6].

Ta-Shi Lai has derived the surface equation of a cycloid drive using envelope theory to deal with the equation of meshing and developed a program to solve the meshing and surface equations that were able to design the required speed ratios of the cycloid drive. The design and manufacturing procedure was an effective approach for cycloid drive manufacturing. The approach not only increases design efficiency but also can improve the machining precision, thus reducing the noise and backlash of cycloid drives [7]. Vladis Kosse has presented the results of systematic experimental research on static efficiency and damping properties of Cyclodrives. A comparative analysis was conducted of the drives and other kinds of drives with a very large reduction ratio in one stage. The experimental Results of the hysteresis phenomenon in the drives and damping properties derived from dickey curves under torsional impact load have been presented. Also, the static efficiency of the drives was given [8]. Piermaria Davoli et al have presented the results of a theoretical and experimental analysis of a cycloidal speed reducer. The profile of the ring gear has been derived by applying the theory of envelope. A simplified procedure to calculate the distribution of forces on cyclo-reducer elements has been presented. Also, the comparison between the results coming from a series of experimental tests and the calculated theoretical efficiency has been performed [9].

3. Identification System

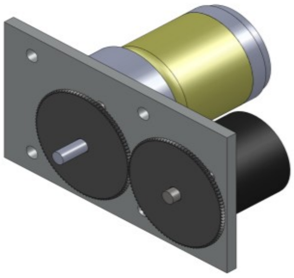
3.1 Modeling of the Identification System and Measurement Method

Here, we provide an overview of the constitution of an identification system to measure torque transmission efficiency. We use the state-space equation to derive the dynamic model of the DC motor. The obtained output data in the input-output time series data in the experiment are compared with the obtained output data given by substituting the input data in the experiment with the state-space equation. It is possible to derive a couple of system matrices of the dynamic motor model that minimize the error between both output data using the identification algorithm based on the state-space equation. Consequently, the torque constant of the DC motor can be estimated based on the obtained system matrices.

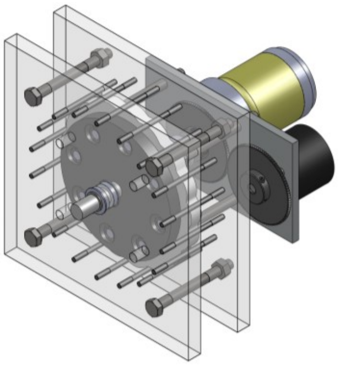
Using the above method, we estimate the dynamic characteristics of each motor installed in the input and output sides of the gear reducer. Next, we attach both DC motors to the input and output shafts of the gear reducer and drive the DC motors. As torque is the product of the measured value of the current and the torque constant that characterizes the motor, by measuring the current flowing in the motor, the output torque of the motors can be estimated based on the torque constant values which are the physical characteristics of both the input and output motors. Comparing these torques with the output torque of both input and output motors, and estimating the torques acted in both input and output shafts of the gear reducer, the torque transmission efficiency can be determined.

3.2 Experimental Setup

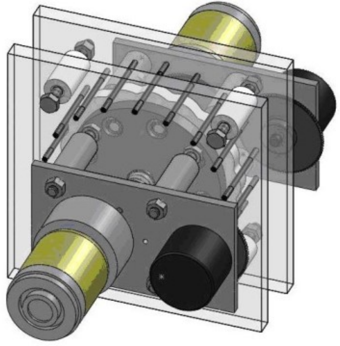
Here, we explain the experimental elements consisting of a DC motor and an encoder, and it measures the input/output rotation speeds and the dynamical characteristics of a cycloidal gear reducer. The encoder is attached to the DC motor via a spur gear and a coupling to measure the rotation angle, as shown in Fig. 1(a). The output axis of the unit is combined with the input axis of the cycloidal gear reducer via a coupling, as shown in Fig. 1(b). Another DC motor used in another unit, as shown in Fig. 1(a) is also combined with the output axis of the cycloidal gear reducer, as shown in Fig. 1(c).



(a) Motor and encoder



(b) Cycloidal gear reducer with a motor (Input side)



(c) The experimental setup with two motors.

Figure 1: The experimental setup

The output side of the unit is attached to the output shaft of the cycloidal gear reducer with a mechanical coupling. The device shown in this figure is for measuring transmission efficiency. In addition, the measurement system for estimating the transmission efficiency can also be applied to general gear reducers. For example, in addition to cycloidal gear reducers, the system can be applied to examine the input/output characteristics of a continuously variable transmission using a link mechanism [10]-[12].

3.3 Motor Modeling

As the torque generated by the DC motor is proportional to the current flowing through the coil in the DC motor, the relationship between the current *i* (*t*) and the generated torque *T* (*t*) using the torque constant K_t is expressed as follows:

$$T(t) = K_t i(t) \ . \tag{1}$$

The equation of motion of the DC motor model is expressed as follows:

$$J\,\ddot{\theta}(t) + D\dot{\theta}(t) + C\theta(t) = T(t) \tag{2}$$

using the internal moment of inertia *J*, viscous friction coefficient *D*, torsion spring constant *C*, and the rotation angle of the rotor as *θ*.

From (2), the state-space equation is expressed as>

$$\begin{bmatrix} \dot{\theta}(t) \\ \ddot{\theta}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{C}{J} & -\dfrac{D}{J} \end{bmatrix} \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix} T(t) \tag{3}$$

The upper (3) can be expressed as:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -\dfrac{C}{J} & -\dfrac{D}{J} \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix}, \ x(t) = \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \end{bmatrix}, \ u(t) = T(t)$$

Assuming that the torque constant K_t is time-invariant, the state-space equation of the motor model can be expressed as:

$$\dot{x}(t) = Ax(t) + \tilde{B}\tilde{u}(t) \ . \tag{5}$$

where $\tilde{B}$ and $\tilde{u}$ are expressed as:

$$\tilde{B} = \begin{bmatrix} 0 \\ \dfrac{K_t}{J} \end{bmatrix}, \ \tilde{u}(t) = i(t)$$

3.4 Specific Identification Theory

Here, we explain the derivation to determine the system matrix *A* and the input matrix *B* in (4) using the identification method based on the algorithm that minimizes the error for the input-output relationship between the state-space equation (4) and actual input and output time series data.

We use the identification theory based on equation errors proposed by Goro Ohinata et al [13]. They have also proposed a method for reducing the dimensionality of the complex multi-dimensional model [14]. Their technique consists of the theory based on the minimization of the equation error in the models, such as closed loop systems considering the necessary and sufficient condition for minimizing the equation error used in the proposed design method. In the equation error technique, the mathematical model of the actual system is estimated so that the response of a coincident optimized model can match a specified response in the experiment, approximately.

Let $x_d(t) = [\theta_d(t) \quad \dot{\theta}_d(t)]^{\mathrm{T}}$ be the state vector consisting of the actual measured values $\theta_d(t)$ and $\dot{\theta}_d(t)$ of rotation angle, and angular velocity of the DC motor, and let $u_d(t)$ be the input. Then, the equation-error $d(t)$ when $x_d(t)$ and $u_d(t)$ are substituted into (4), becomes:

$$d(t) = \dot{x}_d(t) - \{Ax_d(t) + Bu_d(t)\} \tag{6}$$

For the error $d(t)$, A_e, and B_e minimize the following quadratic evaluation function:

$$J_d = \int_0^t d^{\mathrm{T}}(t)d(t)dt \tag{7}$$

must satisfy the following formula:

$$A_e \int_0^t x_d(t)x_d^{\mathrm{T}}(t)dt + B_e \int_0^t u_d(t)x_d^{\mathrm{T}}(t)dt = \int_0^t \dot{x}_d(t)x_d^{\mathrm{T}}(t)dt \tag{8}$$

and

$$A_e \int_0^t x_d(t)u_d^{\mathrm{T}}(t)dt + B_e \int_0^t u_d(t)u_d^{\mathrm{T}}(t)dt = \int_0^t \dot{x}_d(t)u_d^{\mathrm{T}}(t)dt \tag{9}$$

where the matrices:

$$\int_0^t x_d(t)x_d^{\mathrm{T}}(t)dt$$

and

$$\int_0^t u_d(t)u_d^{\mathrm{T}}(t)dt$$

must be a regular and non-singular matrix.

Finally, the parameters of A_e and B_e can be calculated from the following equation:

$$[A_e \quad B_e] = [Q_1 \quad Q_2] \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12}^T & Q_{22} \end{bmatrix}^{-1} \tag{10}$$

where submatrices are given by:

$$\begin{aligned} Q_1 &= \int_0^t \dot{x}_d(t)x_d^{\mathrm{T}}(t)dt \\ Q_2 &= \int_0^t \dot{x}_d(t)u_d^{\mathrm{T}}(t)dt \\ Q_{11} &= \int_0^t x_d(t)x_d^{\mathrm{T}}(t)dt \\ Q_{12} &= \int_0^t x_d(t)u_d^{\mathrm{T}}(t)dt \\ Q_{22} &= \int_0^t u_d(t)u_d^{\mathrm{T}}(t)dt \ . \end{aligned}$$

3.5 Estimation of Motor Torque Constant

Here, using the identification method, we derive the torque constant K_t which is an unknown parameter of the DC motor model. First, we measure the motor current value $\tilde{\imath}(t)$ and angular velocity $\dot{\tilde{\theta}}(t)$ of the DC motor when the motor is driving with no-load.

Setting the measured motor current value as input $\tilde{u}(t)(=\tilde{\imath}(t))$, the system matrix obtained from (5) to (10) as $\tilde{A}$, the input matrix as $\tilde{B}$, and $\tilde{B} = [\tilde{b}_1 \quad \tilde{b}_2]^{\mathrm{T}}$, then $\tilde{b}_2$ can be found as:

$$\tilde{b}_2 = \frac{K_t}{J} \tag{11}$$

from the previous section 3.4.

Next, in the condition that the magnitude of the moment of inertia is already known, the moment of inertia is attached to the output shaft of the DC motor. The equation of motion of the DC motor in (2) is changed as follows:

$$T(t) = \left(J + \hat{J}\right)\ddot{\theta}(t) + D\dot{\theta}(t) + C\theta(t) \tag{12}$$

The state-space equation can be expressed as:

$$\begin{bmatrix} \dot{\theta}(t) \\ \ddot{\theta}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{C}{J+\hat{J}} & -\dfrac{D}{J+\hat{J}} \end{bmatrix} \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{K_t}{J+\hat{J}} \end{bmatrix} i(t) \tag{13}$$

in the same way to derive (3). Furthermore, the upper differential equation (13) is expressed as:

$$\dot{x}(t) = \hat{A}x(t) + \hat{B}\hat{u}(t)\,, \tag{14}$$

where

$$\hat{A} = \begin{bmatrix} 0 & 1 \\ -\frac{C}{J+\hat{J}} & -\frac{D}{J+\hat{J}} \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} 0 \\ \frac{K_t}{J+\hat{J}} \end{bmatrix},$$

$$x(t) = \begin{bmatrix} \theta(t) \\ \dot{\theta}(t) \end{bmatrix},$$

$$\hat{u}(t) = i(t)$$

Next, we measure the motor current value $\hat{\imath}(t)$ and angular velocity $\hat{\theta}(t)$ of the DC motor in the system where the inertial load $\hat{J}$ is added. Using the obtained current value $\hat{\imath}(t)$ as input, the identification method is applied to the inertial load system of the DC motor. Setting the input matrix as $\hat{B} = [\hat{b}_1 \quad \hat{b}_2]^{\mathrm{T}}$, $\hat{b}_2$ can be expressed as:

$$\hat{b}_2 = \frac{K_t}{J + \hat{J}}\,. \tag{15}$$

Substituting (11) into (15), we obtain as:

$$\hat{b}_2 = \frac{K_t}{\frac{K_t}{\tilde{b}_2} + \hat{J}} \tag{16}$$

By rearranging the upper formula (16) regarding the torque constant K_t, we get

$$K_t = \frac{\tilde{b}_2 \hat{b}_2}{\tilde{b}_2 - \hat{b}_2}\hat{J}\,. \tag{17}$$

Next, we define K_{in} as the torque constant value of the DC motor identified using the above algorithm in the input side of the measurement system, and K_{out} as the identified torque constant of the motor in the output side of the system.

3.6 Estimation of Torque Transmission Efficiency

Here, we estimate the torque transmission efficiency of the cycloidal gear reducer using the algorithm and measurement system. As both DC motors rotate on the input and output sides, then the DC motor on the output side applies a load to the output shaft of the cycloidal gear reducer. If the gear ratio of the cycloidal gear reducer is large and both motors have almost the same power, the DC motor on the output side is forced by the load generated at the output shaft of the cycloidal gear reducer when both DC motors installed in both input and output sides of the gear reducer rotate. The DC motor installed on the output side of the gear reducer is subject to the load means that it also receives the load and torque from the output shaft of the gear reducer due to the action-reaction relationship. As the load torque on the DC motor is changed, the current value flowing in the DC motor is changed. Thus, it is noted that energy conversion may work in both directions in the transmission path between input and output.

Next, we assume that the back electromotive force constant is equivalent to the torque constant in the DC motor. It is understood that the relationship between the current and torque of the DC motor remains even when its rotational speed is zero. The scale of change in the current of the input-side DC motor and the output-side DC motor concerning its steady value is set as Δi_{in} and Δi_{out}, respectively. Setting the reduction gear ratio as n, the torque transmission efficiency η is obtained by the following formula:

$$\eta = \frac{K_{out}\,\Delta i_{out}}{n\,K_{in}\,\Delta i_{in}}\,. \tag{18}$$

4. Experiments

Here, we describe the results of experimentally determining the motor torque constant using the identification method.

4.1 Experiment Overview

We explain the experimental procedure to identify the DC motor torque constant using the method described in the previous section.

Fig. 2 shows the entire system configuration used in the experiment to determine the torque transmission efficiency of the gear reducer.

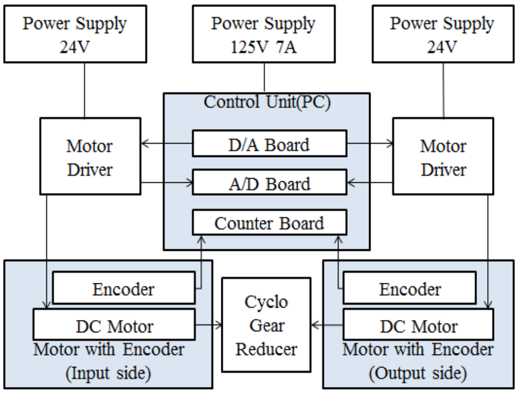


Figure 2: The entire system configuration to identify torque efficiency of gear reducer

Fig. 3 shows another system configuration to estimate the torque constant of a single DC motor. We install Microsoft Visual Studio on a Windows PC, program in the Visual Studio C++ language, and mount the D/A board (PCI-3329, Interface Inc.) on the PC. By applying a voltage command of 0 to 5 [V] to the DC motor driver (JW-143-2, Okatech) through the D/A board, speed control of the DC motor (82800502, Crouzet, 24 [V], 4,000 [rpm]) is executed. Using a counter board (PCI-6201, Interface Co., Ltd.) and a couple of rotary encoders (CB-2500LC, Line Seiki, resolution 2,500 [ppr]), the rotational speed can be measured by reading the frequency quadruple harmonic in real-time. The voltage and current values of the current flowing through the motor driver correspond to the value of the actual current consumption of the motor. The output voltage value corresponding to the current flowing in the DC motor can be output from the current detection terminal in the DC motor driver. The current consumption value of the motor can be estimated from the output voltage value of the motor driver via the A/D board (PCI-3166, Interface Inc.). The output voltage value from the motor driver is proportional to the value of the current flowing in the motor.

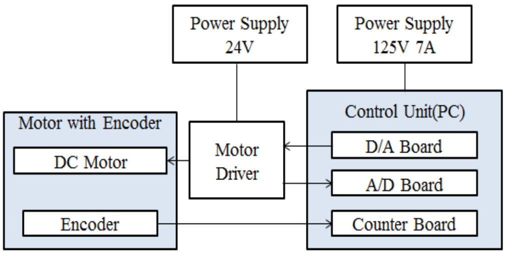


Figure 3: System configuration for identifying torque constant of motor

Based on the motor current value and rotation angle data obtained in the experiment, identification calculations were executed by programming using Microsoft Visual Studio and the numerical analysis software Octave.

Setting the sampling interval to Δt =15 [ms], the command voltage to the DC motor driver, the current value $\tilde{i}(t)$ [A] flowing through the DC motor, and the rotation angle $\tilde{\theta}(t)$ [rad] of the DC motor are detected, respectively. As starting the measurement of the DC motor from the stop state, the data for the number of samples within an arbitrary period are observed.

It is general to use white noise waveforms as input signals to identify the dynamical characteristics in general mechanical systems. Considering the influence of the no-load current, the output command voltage to the motor makes the motor rotate in the forward direction. When measuring the motor torque constant and the torque transmission efficiency in the experiment, mechanical instruments were placed on a horizontal base to avoid the influence of gravity. On the other hand, it has set that the rotation axis of the motor is oriented vertically.

The rotation angle of the DC motor can be obtained every Δt [ms] by the encoder and is defined as $\tilde{\theta}(t)$ [rad]. Angular velocity $\dot{\tilde{\theta}}(t)$ and angular acceleration $\ddot{\tilde{\theta}}(t)$ are obtained as approximate differential by utilizing Euler's method, respectively. As Δt is a sufficiently small value, the angular velocity $\dot{\tilde{\theta}}(t)$ and the angular acceleration $\ddot{\tilde{\theta}}(t)$ can be expressed approximately by the following formula as:

$$\dot{\tilde{\theta}}(t) \simeq \frac{\tilde{\theta}(t+\Delta t)-\tilde{\theta}(t)}{\Delta t}$$

and

$$\ddot{\tilde{\theta}}(t) \simeq \frac{\dot{\tilde{\theta}}(t+\Delta t)-\dot{\tilde{\theta}}(t)}{\Delta t}.$$

4.2 Experiment Method

After measuring the rotational speed under no-load conditions, we attached an inertial load and measured the rotational speed. The experiment was performed with two disks of a moment of inertia of 1.007×10^{-5}[kgm^2] as inertial loads to estimate the torque constant K_t. The number of acquired data was 100, and the acquisition of the data was repeated five times.

4.3 Experimental Results

Figs. 4, 5, and 6 show the step responses of the current value, angular velocity, and angular acceleration of the DC motor during no-load conditions, respectively.

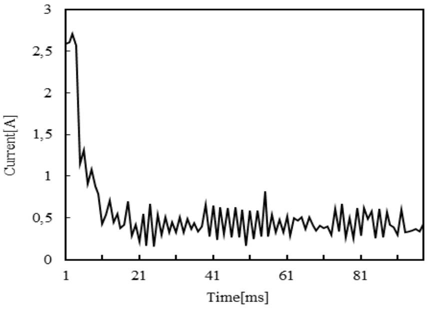


Figure 4: Current in motor

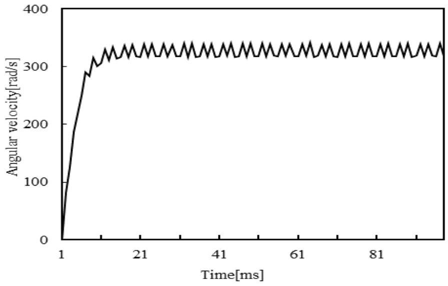


Figure 5: Angular velocity of motor

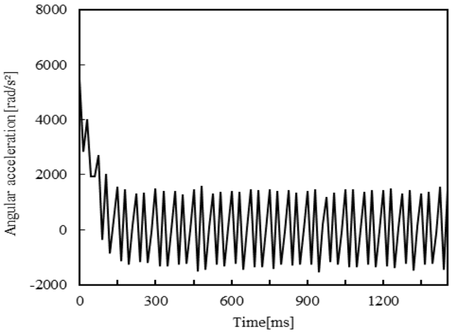


Figure 6: Angular acceleration of motor

The values of $-C/J$ and $-C/(J+\hat{J})$, $-D/J$ and $-D/(J+\hat{J})$, furthermore, K_t/J and $K_t/(J+\hat{J})$ obtained from these experiments are shown in Figs. 7, 8, and 9, respectively.

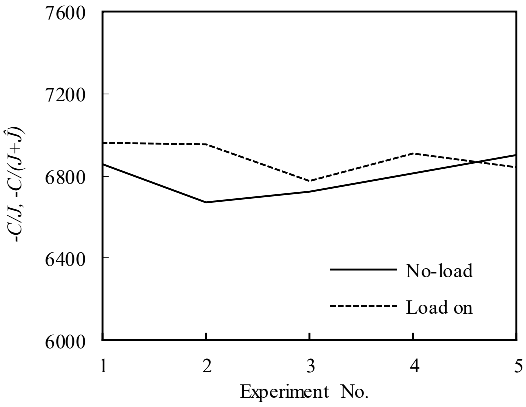


Figure 7: The values of $-C/J$ *and* $-C/(J+\hat{J})$

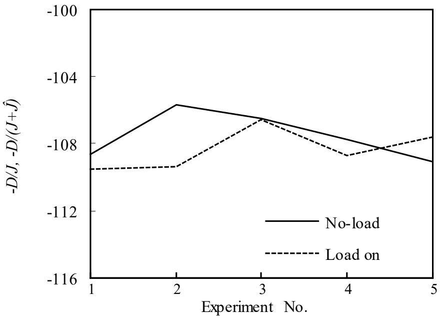


Figure 8: The values of $-D/J$ *and* $-D/(J+\hat{J})$

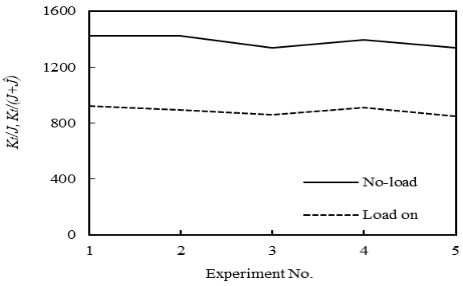


Figure 9: The values of K_t/J *and* $K_t/(J+\hat{J})$

Fig. 10 shows the value of the torque constant K_t determined through the experiments. The constant value of the torque in the motor specifications is 0.0527 [Nm/A], whereas the torque constant K_t obtained in the experiment becomes 89-100 [%] of the torque constant value in the motor specifications.

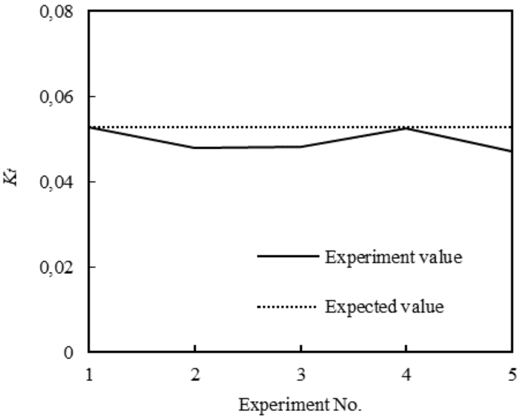


Figure 10: Torque constant

From the experiment, it is observed that some lower values for the torque constant K_t were derived compared to the motor specifications. The result seems to be due to the no-load current. As mentioned before, when the DC motor is in a steady state with no-load, some current is consumed inside the DC motor. Even though the output torque is 0 [Nm], the DC motor current value is not 0 [A]. The state is called no-load current.

In this case, as the output torque of the DC motor equals 0 [Nm], the torque constant K_t is a small value.

As shown in Fig. 4, even though there is a slight vibration from around 300 [ms], it is being held in a stable state. It is considered that the situation where no-load current is generated affects the torque constant from the identification results. Thus, the torque constant may be lower than the actual torque constant. Therefore, to estimate the torque constant K_t accurately, reduce the influence of the no-load current. When the rated voltage for the DC motor was 24 [V], the angular velocity of its rotation was 419.9[rad/s], and the result was the same as the value in the motor specifications. When the operated rated voltage of the DC motor driver was 20 [V], the angular velocity of the motor was approximately 330 [rad/s], as shown in Fig. 5. The main reason the vibration occurs in a steady state is the cogging torque of the DC motor itself.

5. Precise Estimation of Torque Constant of Motor and Torque Transmission Efficiency of Gear Reduce

Here, we discuss the precise estimation method of the motor torque constant and the torque transmission efficiency of the gear reducer.

5.1 Calculation Technique to Reduce No-Load Current

The proposed identification method is performed utilizing the difference between the current value measured in the experiment as explained in the previous section 4.2, and the value of the no-load current to address the influence of the no-load current flowing in the DC motor. The average value of the no-load current measured by repeating the experiment five times was taken as the exact no-load current value.

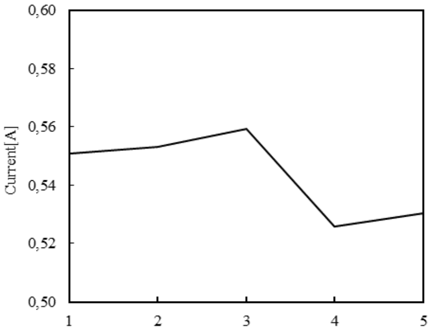


Figure 11. No-load current of motor

Fig. 11 shows the measurement value of the no-load current for each number of experiments in the previous section. Using the method described in the previous section, the torque constant K_t was calculated from the difference between the current in the situation of no-load and the current of the motor with the inertia load. The result is shown in the value of the torque constant K_t of the DC motor obtained by the above-mentioned algorithm was 102~119[%] of the value in the motor specifications.

5.2 Validity of Estimated Value of Torque Transmission Efficiency of Reducer

The response value containing the no-load current was higher than the value of the product specifications of the DC motor. Regardless of the presence or absence of a numerical compensation for the no-load current, the estimated values were close to the value of DC motor specifications, and the DC motor torque constant was identified precisely. Consequently, by substituting the values of K_{in} and K_{out} for each of the input and output DC motors into (18), the torque transmission efficiency is estimated precisely.

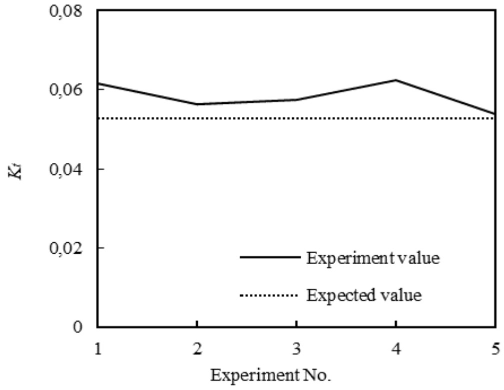


Figure 12: Torque constant
(No-load current is considered)

6. Conclusions

In this paper, after determining the torque constant of a single motor using the proposed identification method in advance, we estimated the torque transmission efficiency of gear reducers, such as cycloidal gear reducers and continuously variable transmissions, etc based on the proposed identification method. At present, we plan to evaluate the accuracy of the transmission efficiency of the gear reducer, examine whether it is necessary to consider the dynamics of the reducer or not, and confirm the effectiveness of the proposed method. With regards to the theory, systems, and experimental method to more accurately determine the torque transmission efficiency, there is still room for improvement.

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References

[1] Tarek A. Tutunji, "DC Motor Identification using Impulse Response Data", EUROCON 2005, pp. 1734-1736, 2005.

[2] Bal´azs Kulcs´ar, Jianfei Dong, Jan-Willem van Wingerden, and Michel Verhaegen, "LPV Subspace Identification of a DC motor with unbalanced disc", Proc. of the 15th IFAC Symposium on System Identification, pp. 856-861, 2009.

[3] Wei Wu, "DC Motor Parameter Identification Using Speed Step Responses", Modelling and Simulation in Engineering, Vol. 2012, pp. 1-5, 2012.

[4] Kama Azura Othman, Mahanijah Md Kamal, Nasirah Mamat and Norhayati Hamzah, "System Identification of Discrete Model for DC Motor Positioning", Recent Advances in Circuits, Systems, Electronics, Control and Signal Processing, pp. 212-216, 2016.

[5] Omar Rodríguez-Abreo, Juvenal Rodríguez-Reséndiz, José Manuel Álvarez-Alvarado and Alfonso García-Cerezo, "Metaheuristic Parameter Identification of Motors Using Dynamic Response Relations", Sensors 2022, 22(11), 4050, pp. 1-22, 2022.

[6] Mohamad Farid Fazdi and Po-Wen Hsueh, "Parameters Identification of a Permanent Magnet DC Motor: A Review", Electronics, MDPI, 12(12), 2559, 2023.

[7] Ta-Shi Lai, "Design and machining of the epicycloid planet gear of cycloid drives", Int J Adv Manuf Technol, 28: 665–670, 2006.

[8] Kosse, Vladis, "Using Hysteresis Loop and Torsional Shock Loading to Assess Damping and Efficiency of Cyclodrives", Proc. of 14th Int. Cong. on Sound and Vibration (ICSV14), pp. 1-8, 2007.

[9] Piermaria Davoli, Carlo Gorla, Francesco Rosa, Claudio Longoni, Franco Chiozzi, and Alessandro Samarani, “Theoretical and Experimental Analysis of a Cycloidal Speed Reducer”, Proc. of PTG 2007 ASME 2007 10th ASME International Power Transmission and Gearing Conference, DETC2007-34098, Sept. 4-7, 2007.

[10] Toshihiro Yukawa, Tetsuya Kumada, Goro Obinata, Continuously Variable Transmission Using Quadric Crank Chains, 8th IEEE Int. conf. on Industrial Informatics (INDIN 2010), pp. 1043-1048

[11] Toshihiro Yukawa, "Continuously Variable Transmission using Quadric Crank Chains and Ratchets", JEPE Journal of Energy and Power Engineering, Vol. 6, Number 4, Serial Number 53, pp.645-655, 2012.

[12] Toshihiro Yukawa, Taisuke Takahashi, Yuki Satoh and Shuzo Ohshima, “Combined-Type Continuous Variable Transmission with Quadric Crank Chains and One-Way Clutches”, J. of Computer Technology and Application, pp. 649-656, Vol. 3, No. 10, 2012.

[13] Goro Obinata, Tomio Nakamura and Hikaru Inooka, An equation error method for the design of digital controller, IEEE Trans. Automatic Control, AC-28, pp.384-386, 1988.

[14] Goro Obinata and Brian D. O. Anderson, Model Reduction for Control System Design, Springer-Verlag, pp.17-21, 2000.