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Fractional Order System Identification of Maglev Model from Real-Time Data

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***Abstract*—This paper deals with real-time identification of magnetic levitation model. For this motive, two methodologies are adopted namely, integer order identification and a new concept of fractional order system identification that has been incorporated for the first time in this particular model. A comparison of the two is shown in which the latter fares better. It is worth mentioning that all identifications have been performed on real time, unlike most identifications which are done only on simulation basis. The main contribution of this work has been basically the applying of fractional calculus in system identification, a concept less explored but with remarkable results.**

Keywords— fractional order system identification; nonlinear model; Maglev system; output-error method

I. INTRODUCTION

The process of levitating a ferromagnetic object with magnet is known as magnetic levitation. This technology has been applied in many engineering fields like Maglev trains, Maglev bearings etc. due to no frictional losses made by mechanical contacts. However Maglev system is highly unstable nonlinear system because of the state variables i.e. coil current and ball position which is an argument of nonlinear function. For better controlling action a system model is required. Hence this paper focuses on obtaining a relatively better system model than those reviewed in literature survey.

Several methods has been developed for identification purpose of Maglev system. Only integer order identifications have been developed based on the system dynamic equation and a few identification methods for fractional order identification.

A hybrid Maglev system is identified in [1] however this is limited to only integer order identification. The Maglev system can be mathematically modelled from its dynamic equation as given in [2, 3, 4]. System modelling from force equation may not give exact response especially for a real-time model. Hence the controller design will not be accurate. In [5, 6] the same system as taken in this work i.e. 33-210, has been considered but the problem of exact physical identification based on simulation still prevails. In addition to this, the design is not applicable to the hardware model as was tried by the author. Maglev system is an unstable system so it is required to perform the identification with closed loop as shown in [7, 8]. Several definitions of fractional calculus is provided in [9, 10].Some of the fractional order model identification schemes are discussed in [11].There is no fractional order identification performed for the system considered here.

Section 2 of this paper introduces the Maglev system and its modelling. Section 3 discuss about the identification process, integer order as well as fractional order. Section 4 contains the validation of the identified model. Section 5 provides the results and discussions. Section 6 gives the conclusive summary.

II. MAGNETIC LEVITATION SYSTEM

Magnetic levitation system is an electromechanical system which overcomes the gravitational force by applying counter magnetic force. The magnetic levitation system considered here uses electromagnet to suspend a steel ball in air by magnetic force. The diagram of Maglev system is shown in Fig. 1.

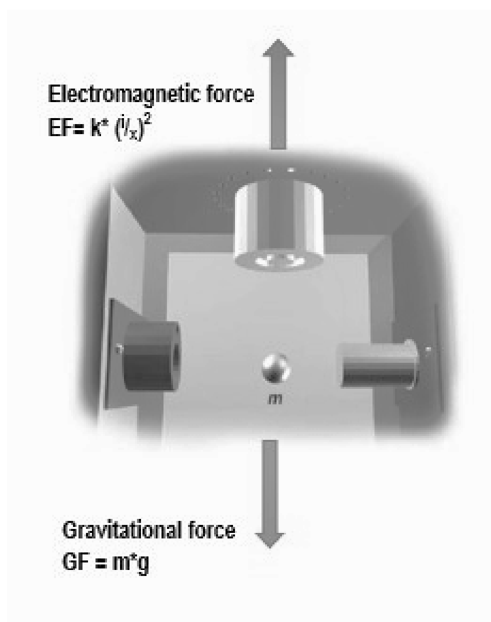

Fig. 1. Schematic diagram of Maglev system

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The system dynamics can be found by applying Kirchhoff's voltage law and Newton's 3rd law of motion. The forces acting on the ball is both gravitational force acting downward and magnetic force acting upward.
So the net force acting on the ball is:

$$F_{net} = F_{gravitational} - F_{magnetic} = mg - k\left(\frac{i}{x}\right)^2 \quad (1)$$

Where
m: mass of the ball
g: gravitational constant
k: magnetic force constant
i: coil current
x: ball position

Equation (1) describes the nonlinear model of Maglev system. By linearizing the nonlinear model at equilibrium point the plant transfer function can be easily design. But the problem remains the same that will the controller designed for transfer function estimated from system dynamics give the same result for the real-time model.

III. SYSTEM IDENTIFICATION OF MAGLEV MODEL

System identification is the process of constructing mathematical model using input and output system response. The identified model response must fit with the measured response for the same input applied to the real system [11].
The best fit which determines the system is calculated as:

$$fit = 100 * (1 - norm(y_{new} - y) / \text{norm(y} - \text{mean(y)))} \quad (2)$$

Where y is the measured output and y_{new} is the output of the identified model.

This paper proposes both integer order and fractional order identification for the real-time system from the measured input and output value.

A. Integer Order System Identification

If the system specification is not provided it is best to try different available methods and select the best one. Here output-error model has been selected for identification process because of its simplicity for the starting polynomial model [12].
The output error model structure is given as:

$$y(t) = \frac{B(q)}{F(\text{q})} u(t) + e(t) \quad (3)$$

Where $u(t)$ is the input signal, $y(t)$ is output signal sequence and $e(t)$ is zero mean white noise with variance σ^2

Here $\text{B}(q) = b_1 q^{-1} + ... + b_n q^{-n}$, (4)

$$F(\text{q}) = 1 + f_1 q^{-1} + ... + f_n q^{-n} \quad , \quad (5)$$

Where q^{-1} is the delay operator, i.e. $q^{-1}u(t) = u(t-1)$. it is assumed that $B(q)$ and $F(q)$ have no common factor i.e. no pole zero cancellations [12],. The transfer function of the system is $G(q) = B(q)/F(q)$.

The next task is to determine the model order. The model order should not be higher if it is not necessary. The magnetic levitation system is an unstable system so it is advised to perform the identification process with a running stabilizing controller [13]. The controller introduces output noise and control signal correlation, which can be broken by applying an excitation signal with the control signal. However this approach will only allow for the linear model identification.

B. Fractional Order System Identification

Several definitions of fractional calculus is proposed in [14]. In this paper the method opted for fractional derivative definition is Grunwald-Letnikov derivative, [15]. The Grunwald-Letnikov derivative of order α of function $f(t)$ at time t is, [14]:

$$D^{\alpha} f(t) = \frac{1}{h^{\alpha}} \sum_{k=0}^{K} (-1)^k \binom{\alpha}{k} f(t - kh) \quad (6)$$

Where h is sample time and $\binom{\alpha}{k}$ is Newton's binomial generalized to non-integer order.

Fractional order systems are defined as

$$a_n D^{\alpha_n} \text{y}(t) + a_{n-1} D^{\alpha_{n-1}} \text{y}(t) + ... + a_0 \text{ y}(t) = u(t) \quad (7)$$

Where $\text{y}(t)$ is system output and $\text{u}(t)$ is system input. It should be noted that the differential order $\alpha_n, \alpha_{n-1} ..., \alpha_0$ are fractional.
By applying (6) on (7), the fractional order transfer function is obtained:

$$\frac{Y(s)}{U(s)} = \frac{\sum_{j=0}^{m} b_j s^{\alpha_{bj}}}{\sum_{i=0}^{n} a_i s^{\alpha_{ai}}} \quad (8)$$

where $a_i, b_j \in \mathbb{R}$, $i = 0,1,...,m, \quad j = 0,1,...,n$

From literature review it is clear that the coefficients differential operators act linearly where the derivative order act non-linearly [16]. This leads to two case study:

- Equation-error method: In this method the derivative orders are fixed and only the coefficients of operators are estimated. This optimization method allow a direct estimation of linear parameter.
- Output-error method: Here the derivative orders are estimated keeping the coefficients of operators fixed. This method involves the algorithm called non-linear programming.

The objective of system identification is to estimate the model parameters and fractional order vector $[\alpha] = [\alpha_1, \alpha_2, ... \alpha_n]$.

IV. RESULTS AND DISCUSSIONS

Identification experiment is performed on FEEDBACK's Maglev unit. A PD controller is already connected to make the system stable. The reference signal i.e. random binary sequence was chosen to excite the system. 2500 input and output sampled data is collected from the system. Sampling period of 1 ms was selected for identification. The input and output sampled data of Maglev unit is shown in figure: 2.

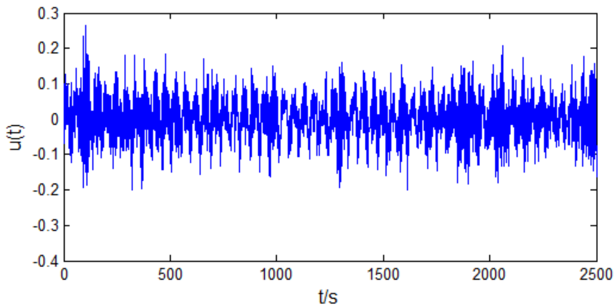

Fig. 2. Input sampled data

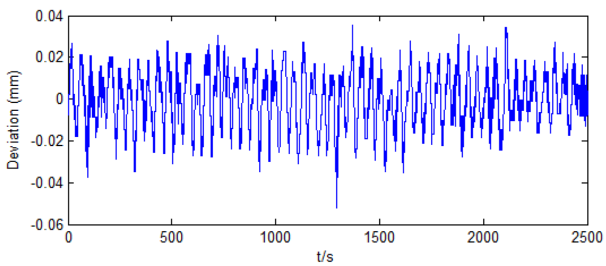

Fig. 3. Output sampled data

Fig: 4 shows the comparison between the measured outputs with the identified one. The input and output data is taken from the Maglev system for real-time identification. The best fit obtained is 91.43% for integer order identification which gives the closed loop transfer function with PD controller is:

$$\frac{Y(s)}{U(s)} = \frac{21.2s + 1046}{s^2 + 172.7s + 2047} \quad (9)$$

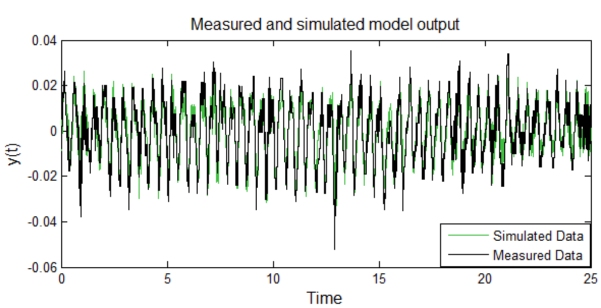

Fig. 4. Comparison between measured and simulated data for integer order identification

The cross validation data of Fig.4 is provided in magnified view in Fig. 5 for clear visibility.

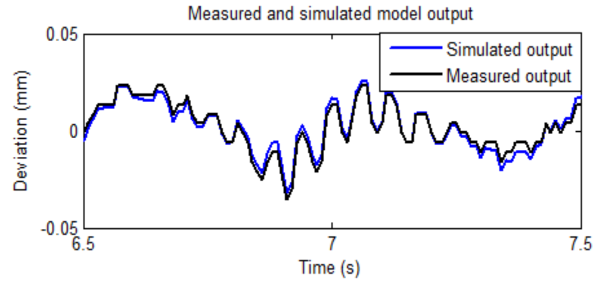

Fig. 5. Cross validation data for integer order identification

However using the same data for fractional order identification is carried out with a commensurate order of 0.3 and model order 2. The error between the measured and simulated output is 0.01. Fractional order identification is performed with FOMCON toolbox implementing the Grunwald-Letnikov differintegral method. The closed loop system transfer function of the Maglev system with PD controller in fractional order is:

$$\frac{Y(s)}{U(s)} = \frac{53.012s^{0.17885}}{23.62s^{0.81016} + 27.575s^{0.01899} + 28.663} \quad (10)$$

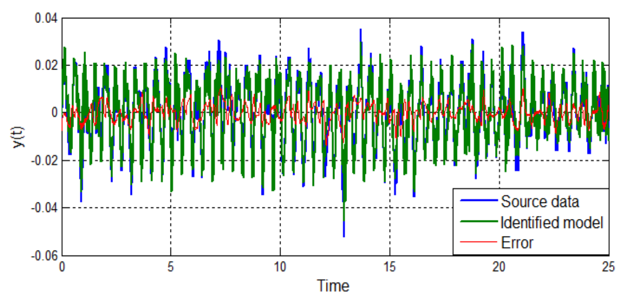

Fig. 6. Comparison between output data of fractional order identification

The error in identification has been reduced to .01 as shown above in Fig. 6.

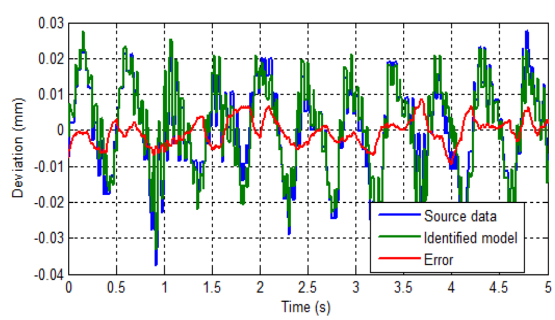

Fig. 7. Comparison between output data of fractional order identification

Fig.7 is the magnified view from 0-5 seconds of Fig.6 where the error variations are shown and found to be minimal. The comparison is shown in Table I.

TABLE I. IDENTIFICATION COMPARISON TABLE

Sl. No.	Identification type	Fit %	Error
1	Integer order	91.43	0.09
2	Fractional order	98.10	0.007

For comparison purposes, it is worth mentioning that only one paper has been found in literature that has worked on real time data, while all other available works have been on simulation basis. Shahab et al. in [17] has worked with real time data for identification of Maglev System, however *a priori* known structural constraint on system model has been used in that particular scheme. The work proposed in this paper requires no such priori knowledge of the system model. In addition to this the error has been found to be significantly minimal.

V. CONCLUSIONS

This paper demonstrates two identification methods. The integer order identification is carried out with output error model structure. The Grunwald-Letnikov method is adopted for fractional order system identification. The measured and simulated data is compared in both integer order and fractional order system. The best fit of measured data with simulated data is obtained from fractional order system. It has been distinctly shown that the transfer function in fractional order provides more improved results than its integer counterpart as verified by the reduction in error as well as the percentage of fit.The future work will focus on controller design in both integer order and fractional order for the identified system.

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