An Efficient Approach for Optimization of Nonlinearity Response in Linear Variable Differential Transformer

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Abstract: **This paper proposes an efficient approach for optimization of non-linearity response reflected in output of Linear Variable Differential Transformer / in Linear Variable Differential Transducer (LVDT). Customarily, the non-linearity in LVDT was reduced by windings/coils tuning, which was very difficult to get fine tune. This problematic situation can overawe by implementation of the projected scheme. The Functional link artificial neural network (Fun-LANN) has been effectively implemented for nonlinear optimization of the senor's response. The effectiveness of the proposed method is demonstrated through MATLAB simulation and the response has validated with various nonlinear effects. The experimental analysis of the proposed scheme produces high sensitivity, good linearity and insensitivity to excitation variations.**

Index Terms: **LVDT, Fun-LANN, Optimization, Sensor, Tuning, Non-linearity.**

I. INTRODUCTION

In the field of engineering automation, transducer plays a vital role for measuring, monitoring, recording and control. Various environments are exposed to the transducers for performing the sensing activities. So, the response of the transducer is influenced by the excitation source and operating temperatures. Hence, it is highly necessary for optimizing the issues related to these factors, as a result the sensing element will be smarter enough for reduction of nonlinearity.

Linear Variable Differential Transformer / Linear Variable Differential Transducer (LVDT) is an electrical transformer used for measuring linear displacement. The LVDT converts a position or linear displacement into a proportional electrical signal. This LVDTs are broadly used for displacement, pressure, and flow measurements [1]. LVDT performance is affected by its geometrical structure, Primary and secondary coil arrangement, core material quality, current and frequency variation in excitation source and variation in operating temperature [2]-[3]. Furthermore, the aging factor of transducer is also inviting the nonlinearity. Due to these reasons, the transducers are limited for a particular usable span. The reported nonlinearity is a function of time and depends on several uncertain factors. The linearity is achieved [3] by considering the geometrical structure modification and same also realized by an introduction of twin series connected the secondary coils. Lately, some researchers [4]-[5] have considered the signal

conditioning circuit for effective response. The LVDT displays nonlinearity with variation of core null position and at middle position it indicates linearity. By considering this, the proposed scheme is realized with Fun-LANN in order to better linear response.
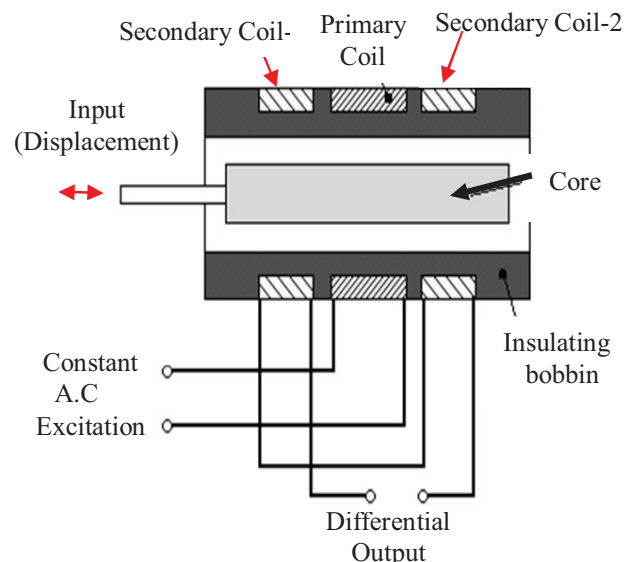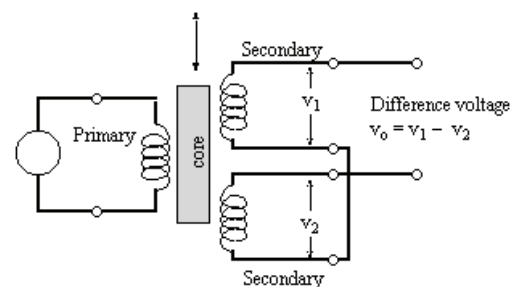

Figure 1. Schematic LVDT arrangement

Figure 2. Electrical equivalent circuit arrangement for LVDT

LVDT consists of two coils namely Primary and Secondary. The Primary is excited externally by means of A.C. Excitation with a stable source and two secondary coils are connected in series opposition in order to provide single differential output. Schematic of LVDT arrangement is presented in figure 1. When an A.C. Supply excitation 'E$_{AC}$' with frequency 'F$_S$' is applied across primary coil and the core position with respect to primary and two secondary

windings, the developed output potential 'V$_{Out}$' is found across the secondary winding.

According to mutual induction principle, the induced potential in one secondary coil is presented in equation-1.

$$V_{Secondary\ coil} = V_{Sec} = -N\frac{d\phi}{dr} \tag{1}$$

Considering the primary current, the secondary voltage is as per equation-2.

$$V_{Sec} = -M\frac{dI_{primary}}{dt} \tag{2}$$

In the above equation, the term 'N' represents number of turns in the secondary coil, 'ϕ' represents magnetic flux, $I_{Primary}$= Primary coil current. Similarly, when two secondary coils are connected in series opposition, the developed output can be presented in equation-3.

$$V_{OUT-Sec} = V_{Out-Sec1} - V_{Out-Sec2} = -(M_1 - M_2)\frac{dI_{primary}}{dt} \tag{3}$$

Where M_1 and M_2 are functions of displacement 'x'. Let $M_1 - M_2 = M(x)$. At certain range when the function is linear, $M(x) = kx$, as a result the displacement can be presented as per equation -4.

$$x = \frac{V_{out-Sc}}{K\,dI_{Primiary/dt}} \tag{4}$$

The electrical equivalent circuit arrangement for LVDT is presented in Figure 2. In this arrangement, all the loss components are compensated and corresponding output voltage per unit displacement and phase angle are presented in equation -5 and equation-6.

$$\left|\frac{V_{Out-Secondary}}{V_{Input}}\right| \times \frac{1}{x} = \frac{KwR_m/\{(R_s+R_m)R_p\}}{\sqrt{\left[\{1-w^2(\tau_m^2+\tau_p\tau_s)\}^2 + w^2(\tau_p+\tau_s)^2\right]}} \tag{5}$$

$$\text{And } \phi = 90^0 - \tan^{-1}\frac{w(\tau_p+\tau_s)}{1-w^2(\tau_m^2+\tau_p\tau_s)} \tag{6}$$

Where $\tau_m = \frac{M_1 - M_2}{\sqrt{(R_m+R_p)R_p}}$ and $\tau_p = \frac{L_p}{R_p}$ $\tau_s = \frac{L_s}{R_s+R_m}$

With input excitation of V_{input}, operating frequency F_{Input} and meter resistance R_m. In all LVDT structure, there is some existence of nonlinearity due to some limitations. Hence, the proposed model is developed for overcome these limitations.

II. PROPOSED EXPERIMENTAL SETUP

The Figure 3 represents an experimental setup for the proposed structure. In the given experimental setup presented in Figure 3, a stepper motor-controlled displacer is arranged for uniform movement of the LVDT core arm. The controller output tunes the displacement actuator as a result the core in LVDT is moved accordingly and then the nonlinear output of LVDT is again fed to Neural network model (NNM). Meanwhile the actuator output is also acting as setpoint value by the NNM. With the input and setpoint values, the NNM weights are revised in order to optimize an error. This NNM also enhances the linear response of the LVDT in a significant way. Researchers have found a useful alternative for artificial neural network as functional link artificial neural network (Fun-LANN) [6-7]. This Fun-LANN has advantages over ANN like it takes less computational time and a simple hardware structure.
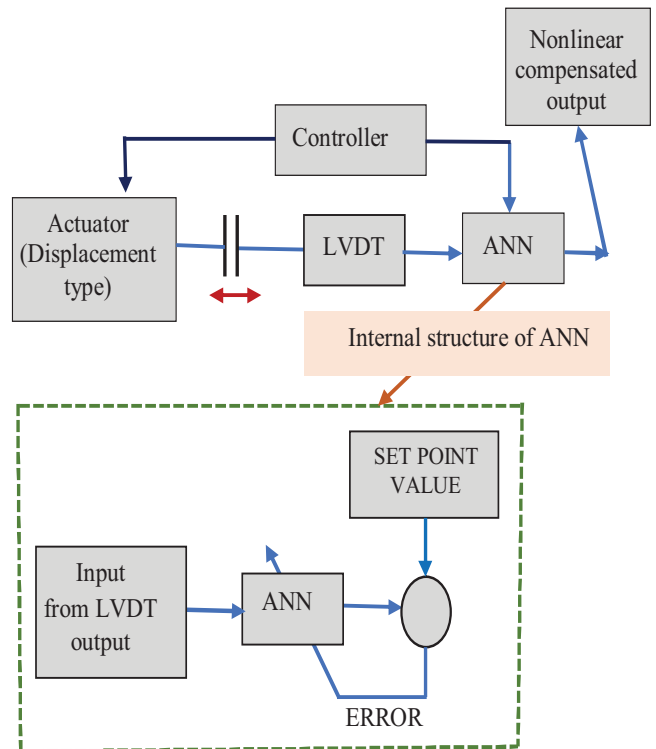

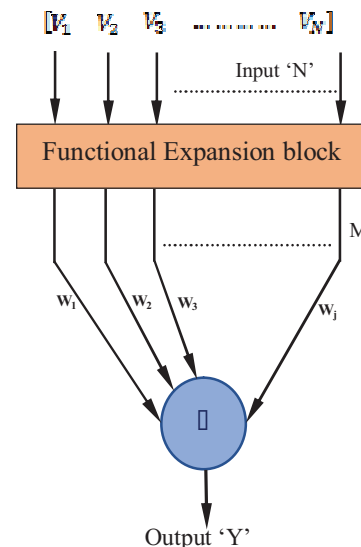Figure 3. An experimental setup for the proposed structure

Figure 4. Simplified Fun-LANN structure

A simplified Fun-LANN structure is presented in Figure 4, where 'N' inputs are fed to the functional expansion block to generate M functionally expanded signals and these signals are combined with M-element weight vector to produce a single output.

In this article, a trigonometric functional expansion is preferred for Fun-LANN. If all the polynomials of xth order with respect to an orthogonal system, the best approximation in the metric space is presented by the partial summation of Fourier series of xth polynomial with respect to system.

Hence, the trigonometric polynomial basis function is expressed as per equation (7).

$$M = \{V_0, Sin(\pi V), Cos(\pi V), Sin(2\pi V), Cos(2\pi V)... ... Sin(x\pi V), Cos(x\pi V)\} \quad (7)$$

The equation 7 signifies the compact representation of the function in mean square sense.

Let the LVDT output is extended functionally 'V_{Out}'. Now functionally extended 'M' vector is linearly joint with weight matrix by subsequent ways [8-9]

$$Y = \sum_{j=1}^{M} M_j w_j + \alpha \quad (8)$$

Where α = bias term and

$$M_j = \begin{cases} V_0 & j = 1 \\ sin(l\pi V_0), & j > 1, j \ even \\ cos(l\pi V_0), & j > 1, j \ odd \end{cases} \quad (9)$$

Where $1 \leq l \leq x$, x is the order of expansion. Now the error signal can be defined as

$$E(n) = D(n) - \sum_{j=1}^{N} M_j w_j \quad (10)$$

Where $D(n)$ is set point value or desired signal or equivalent control signal applied to displacement actuator and 'n' is time index. Let the cost function 'ζ' as residual noise power and it is presented as [10] $\zeta = \epsilon[E^2(n)]$ (11)

The weight vector w_j may be adjusted as the per following in order to optimization of mean square error (MSE) ζ

$$w_{j+1} = w_j - \frac{\mu}{2} \nabla(n) \quad (12)$$

Where $\nabla(n)$ is an instantaneous estimation of gradient of ζ with respect to weight vector w_j.

Hence, $w_{j+1} = w_j + \mu E(n).M(n)$ (13)

Where 'μ' denotes the step size and it controls the convergence speed of the algorithm.

III. Experimental Simulation

Using experimental data sets, the response of the proposed model has been studied and this experimental data are collected from an LVDT with and without combination of the proposed model. The LVDT structure considered here having 3299 turns in the secondary coils, wound uniformly on each side isolated by Teflon ring. The core dia used in the proposed model is about 4.39 mm and length of core is about 4.6 mm. The primary coil excited by an excitation source of 10.5 V_{P-P} with operating frequency of 5.2KHz. Resistance of Primary winding is 267Ω and resistance of two Secondary coil are 423.5Ω and 412.8 Ω. The two secondary coils are wound in opposite directions (Series Opposition) for single differential output. The experimental measured values are presented in Table-1. The above data are normalized and utilized by Fun-LANN. The normalized LVDT output be considered as input to Fun-LANN and Fun-LANN output is equated with the normalized displacement as per Table-1data. Two experimental analysis are implemented with the same data set. The 1st test has performed through low functional expansion value (i.e $x = 9$) and in 2nd testing through high value of functional expansion (i.e $x = 109$). Figure-5 represents response of LVDT and the non-linear compensator for 1st test. Similarly, the figure-6 shows the same for high value of functional expansion (i.e $x = 109$).

From figure 4, it is concluded that there is substantial upgrading of linearity thru Fun-LANN founded compensator through a greater numeral of functional expansions.

TABLE I.
EXPERIMENTAL MEASURED VALUES

Sl. No	Displacement in mm	LVDT Output Voltage (V_0) in mV
1	-26	3.985
2	-24	3.852
3	-22	3.732
4	-20	3.723
5	-18	3.685
6	-16	3.584
7	-14	3.452
8	-12	3.212
9	-10	2.985
10	-8	2.125
11	-4	1.118
12	-2	0.952
13	-1	0.829
14	Null Position	0.185
15	1	0.812
16	2	0.978
17	4	2.975
18	8	2.145
19	10	2.998
20	12	3.412
21	14	3.652
22	16	3.784
23	18	3.885
24	20	3.926
25	22	3.981
26	24	3.982
27	26	3.985

TABLE II.
COMPARISON OF EXPERIMENTAL MEASURED VALUES

Sl. No	Displacement in mm	LVDT Output Voltage (V_0)	Output Voltage of proposed Model (LVDT with Fun-LANN) in mV
1	-26	3.985	4.985
2	-24	3.852	4.852
3	-22	3.732	4.732
4	-20	3.723	3.883
5	-18	3.685	3.868
6	-16	3.584	3.758
7	-14	3.452	3.652
8	-12	3.212	3.512
9	-10	2.985	3.525
10	-8	2.125	3.125
11	-4	1.118	2.118
12	-2	0.952	1.952
13	-1	0.829	1.829
14	Null Position	0.185	0.175
15	1	0.812	1.812
16	2	0.978	1.978
17	4	2.975	3.975
18	8	2.145	3.984
19	10	2.998	3.998
20	12	3.412	4.412
21	14	3.652	4.652
22	16	3.784	4.784
23	18	3.885	4.885
24	20	3.926	4.926
25	22	3.981	4.981
26	24	3.982	4.982
27	26	3.985	4.985

The proposed model (FANN) with 109 functional expansion is achieving better linearity.

Table II summarizes the comparison statement between the output response of LVDT with and without considering Fun-LANN (Proposed) model.

Figure 5.   Response of LVDT at *x*=9

proposed model has significant response in terms of linearity corresponding to input displacement variations.

TABLE III.
COMPARISON OF EXPERIMENTAL MEASURED VALUES AT *x*=9

Input Displacement	Output of LVDT Without Fun-ANN	Output of LVDT with Fun-LANN
-0.8	-0.825	-0.981
-0.6	-0.712	-0.675
-0.4	-0.621	-0.494
-0.2	-0.418	-0.297
0	0	0
0.2	0.445	0.298
0.4	0.521	0.589
0.6	0.612	0.795
0.8	0.912	1.045

TABLE IV.
COMPARISON OF EXPERIMENTAL MEASURED VALUES AT *x*=109

Input Displacement	LVDT output (mV) Without Fun-ANN	LVDT Output (mV) with Fun-LANN
-0.8	-0.625	-0.941
-0.6	-0.512	-0.625
-0.4	-0.621	-0.474
-0.2	-0.318	-0.287
0	0	0
0.2	0.445	0.288
0.4	0.621	0.579
0.6	0.792	0.783
0.8	0.812	1.045

IV. CONCLUSIONS

In this article, a simple and an effective way of designing the high linearity LVDT based displacement sensing structure is proposed. The proposed Fun-LANN is successfully applied for nonlinear optimization of the LVDT. The Detailed implementation procedure for training the Fun-LANN model is outlined properly. The proposed scheme also makes the sensing element smarter enough for auto-correction of nonlinear response. The proposed scheme is also suitable for nonlinear compensation of other sensing element.
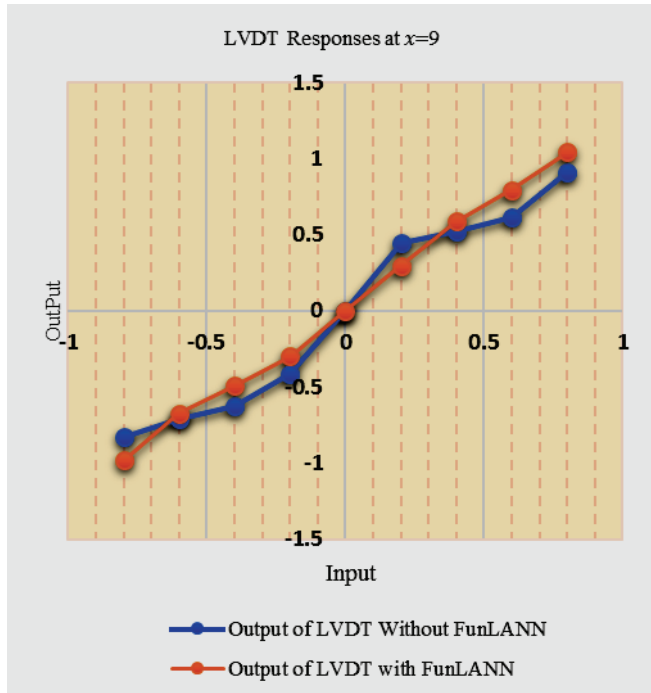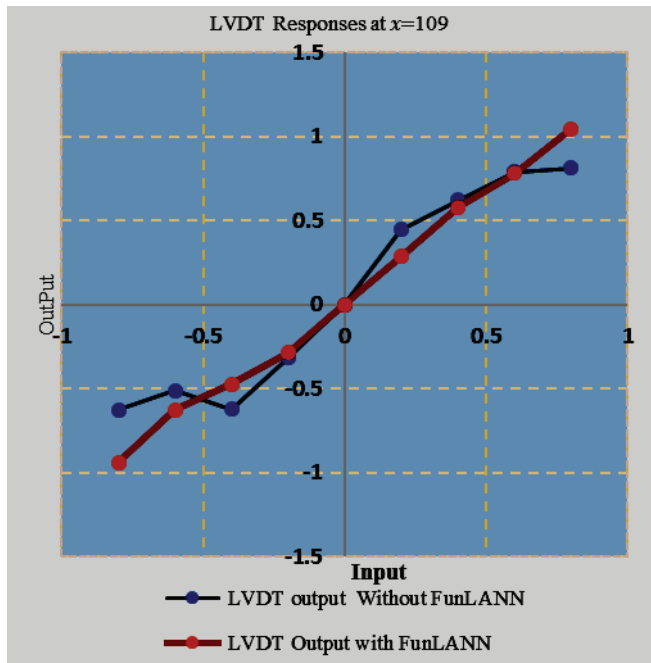

Figure 6. Response of LVDT at *x*=109

The response of the LVDT with and without considering the proposed scheme at various functional expansion values (i.e *x*=9 and *x*=109) are detailed in Table III and Table IV respectively. From these data, it is resolved that the

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