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Highlights

- Estimation of Steady State
- A Signal Conditioner System
- River Flow Rate into a Dam
- Improvement of Forecasting Method

Discovering Thoughts, Inventing Future

VOLUME 20 ISSUE 4 VERSION 1.0

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Contents of the Issue

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Improvement of Forecasting Method of Recession Characteristics of River Flow Rate into a Dam by using Estimation of Steady State

By Tomonari Kawai, Katsuhiro Ichiyanagi, Takuo Koyasu, Kazuto Yukita & Yasuyuki Goto

Aichi Institute of Technology

Abstract- This paper describes an application of neural networks for forecasting the flow rate upper district of dams for hydropower plants. The forecasting of recession characteristics of the river flow after rainfalls is important with respect to system operation and dam management. We present a method for improving the precision of forecasting flow rate upper district of dams by utilizing steady-state estimation and recession time constant of the river flow. A case study was carried out on the upper district of the Yahagi River in Central Japan. It is found from our investigations that the forecasting accuracy is improved to 18.6% from 25.8% with a forecasted error of the total amount of river flow by using steady-state estimation.

Keywords: river flow rate, recession time constant, estimation, forecasting, steady state of river flow, neural network.

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IMPROVEMENTOFFORECASTINGMETHODOFRECESSIONCHARACTERISTICSOFRIVERFLOWRATEINTOADAMBYUSINGESTIMATIONOFSTEADYSTATE

Strictly as per the compliance and regulations of:

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Tomonari Kawai [α], Katsuhiro Ichiyanagi [σ], Takuo Koyasu [ρ], Kazuto Yukita [Ѡ] & Yasuyuki Goto [¥]

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I. Introduction

Recently, natural energy is paid to attention because environmental problems such as global warming and acid rain become remarkable. In such situation, it is necessary that the hydro-energy stored in water reservoirs is converted into electric energy as effectively as possible in hydropower plants [1].

On the other hand, it is important to accurately grasp the inflow to the dam due to rainfall from the viewpoint of safety in the downstream area and efficient operation of the reservoir [2]. So far, "unit-hydrograph" [3], [4], "tank model method"[5],[6], "storage function method" [7], "Kalman filter method"[8], etc. have been used for river flow forecasting. These have been used for dam discharge control and power supply operation [2], [9]. However, in these forecasting methods, the flooding phenomenon due to rainfall and snowmelt is expressed using various mathematical models, but it is difficult to determine the parameters of the model [10].

Until now, we have developed a practical forecasting method of time series of river flow rate following rainfall upstream of a dam. The method is based on the artificial neural network theory [4] [5].

It is important that the water level on dam operation and management after peak rainfalls is forecasted. This paper describes an application of neural network for estimation of the recession time constant of river flow rate into a dam after the rainfall. We proposed the forecasting system of recession characteristics of river flow rate by using estimated recession time constant. An estimation system of recession time constant composed by neural network is developed through a case study on a dam for hydropower plant located the upper district of the Yahagi River in Central Japan. The estimation possibility of recession time constant and forecasting possibility of water level of dam is discussed.

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II. Steady State of River Flow and Recession Time Constant

a) Basin used as a Case Study

In order to confirm the forecasting of the river flow rate, we used the upper district of the Yahagi River in Central Japan as shown in Figure. 1. The basin is 505 km2 area and gradually elevated from west to east. There are five rain gauges as shown by A to F in Figure. 1.

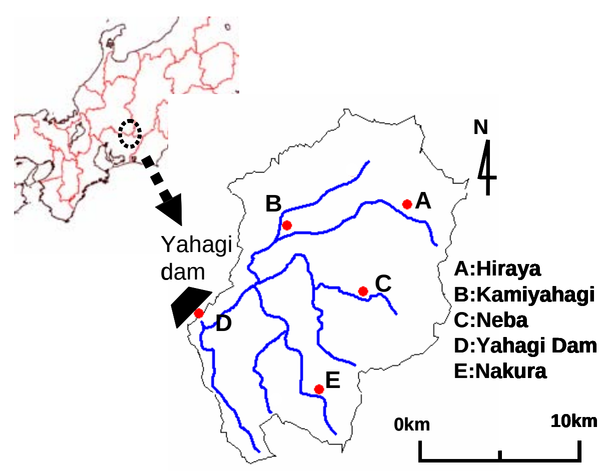


Figure 1: Basin used as a case study (Upper district of Yahagi Dam in Central Japan)

b) Recession Characteristics of River Flow Rate

A method of expressing the diminishing part of the flow rate by a mathematical model has been introduced in many documents for a long time [11]-[16]. In this paper, regarding the flow rate prediction after the

Global Journal of Researches in Engineering (F) Volume XX Issue IV Version I Year 2020 1

rainfall stops, we propose a forecasting method of recession characteristics of river flow rate into a dam by using the information obtained at the peak flow time.

When the rainfall stops and then the light or no rainfall continues, the flow rate gradually decreases from the peak value. In this paper, the characteristics during the recession period after the peak flow rate are expressed by the following equation using the recession time constant TRTC and the steady flow rate qfin(see Figure.2).

$$q(t_i) = \{q_p - q_\infty\}e^{\frac{-t_i}{T_{RTC}}} + q_\infty \tag{1}$$

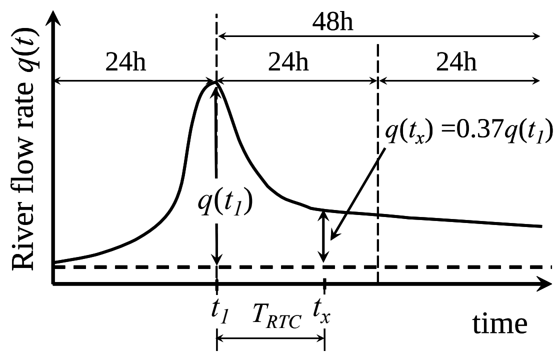


Figure 2: Algorism of recession time constant

c) *Steady States of River Flow Rate*

The runoff of rainfall to the river is mainly composed of three components .The "Surface runoff" is flowing on the surface of the earth and the "Intermediate runoff" appears at the surface of the earth after it has permeated shallowly and then flows out with a little delay. The "Groundwater runoff" is gradually becomes groundwater and flows out[17]. In this paper, we study a method for predicting the time-dependent change in discharge for both surface and intermediate flow components that flow into a river in a relatively short period after rainfall.

In order to roughly understand the runoff component of the discharge in the basin used as a case study shown the Figure 1, the decreasing part after the peak of the discharge is plotted by semi-logarithm and shown in Figure 3. From the figure, the sudden change in slope can be confirmed around 12 hours (shown by term A: Surface runoff), around 48 hours (shown by term B:Intermediate runoff) and over 48 hours (shown by C:Groundwater runoff) in the recession characteristics. In this paper, based on the analysis results of the runoff components in the recession term of the flow rate in the case study, it is assumed that rainfall in the basin flows directly to the river in about 48 hours, and the rest flows out as the groundwater for a long time. Therefore, it is also assumed that the steady flow rate is the flow rate after 48 hours of flow peak. Since the time until the steady flow rate is reached is a value that is peculiar to the basin, it should be determined by performing a river flow component analysis for each basin.

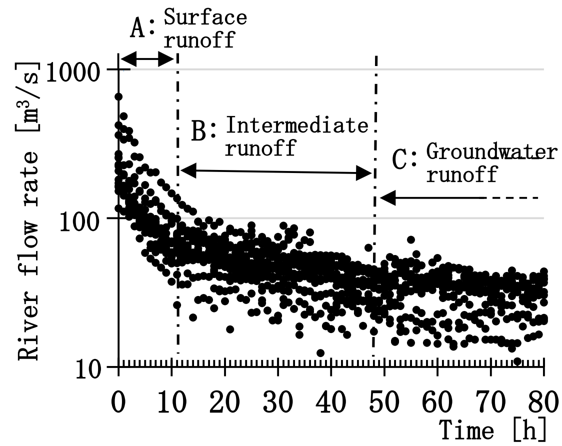


Figure 3: Analysis of outflow components in recession term of river flow rate

d) *Calculated Results of Recession Time Constant and Steady States of River Flow Rate*

As a pre-processing for forecasting the recession characteristics in flow rate, the recession time constant T_{RTC} and steady flow rate q_{fin} were simultaneously estimated from the past rainfall/flow data and used as the actual values of steady flow rate and recession time constant. In order to obtain the solutions of unknown parameters, T_{RTC} and q_{fin}, these may converge to values different from the actual values depending on the initial value given. Therefore, instead of q_{fin}, q_{BASE} (base flow rate) is given, the T_{RTC} is calculated using equations (2) and (3). Furthermore, to find the q_{fin}, the obtained the T_{RTC} value is given to equations (4) and (5). The mutual substitution and solution are repeated for the T_{RTC} and the q_{fin}, and finally a stable solution is obtained (the details are as shown by the flow chart in the Appendix).

$$T_{RTC} = \sum_{i=1}^{n} t_i^2 \Big/ \left(\sum_{i=1}^{n} \{t_i \times z(t_i)\} \right) \tag{2}$$

$$z(t_i) = \log\left(\frac{q(t_i) - q_{fin}}{q_p - q_{fin}}\right) \tag{3}$$

$$q_{fin} = \frac{-\sum_{i=1}^{n} q(t_i) - q_p x_i}{\sum_{i=1}^{n} x_i - 1} \tag{4}$$

$$x_i = e^{\frac{-t_i}{T_{RTC}}} \tag{5}$$

Global Journal of Researches in Engineering (F) Volume XX Issue IV Version I Year 2020

In equations (2) to (5), i = 1 is the peak time of the flow rate, and $i = n$ is the time when the flow rate is reached at the steady states value after the flow peak. From the analysis result of outflow components in recession term of river flow rate as shown in Figure. 3, n=48 is used. Furthermore, it was assumed that there was no preceding rainfall within 48 hours before the start of rainfall, and the rainfall during the recession period of 48 hours after the peak of discharge was less than 30 mm. The base flow is the river flow rate at the start of a series of rainfall (beginning of rainfall), and in this paper, it was the average value of river flow for five hours before the start of rainfall.

In order to confirm the forecasting of the river flow rate, we used the upper district of the Yahagi River in Central Japan as shown in Figure 1. Therefore, we used 26 cases of rainfall from 2003 to 2008 with the peak flow rate of 100 m^3/s or more and a cumulative rainfall value of less than 30 mm after the river flow peak. Furthermore, using the time-series data at the recession period of flow rate after the peaks and the equations from (2) to (5), the steady flow rate q_{fin} and the recession time constant T_{RTC} are used as unknown parameters to calculate the equation (1). It was calculated by the method of least squares. In the following, the estimated values of the recession time constant T_{RTC} and steady state river flow rate q_{fin} obtained by using equations from (2) to (5) are used as the observed values, respectively.

e) Forecasting System of River Flow Rate at Recession period

The flow rate after the rainfall stops is expressed by equation (1) using the recession time constant T_{RTC} and steady state value of river flow rate q_{fin}. Then, we propose a method of estimating T_{RTC} and q_{fin} by giving various quantities obtained at the peak time as input information of the neural network, and a method of forecasting the recession characteristics of the flow rate. As shown in Figure 4, a system is constructed to forecast the flow rate from both the T_{RTC} and q_{fin} estimated values and the peak flow rate. Both the T_{RTC} and q_{fin} estimation methods, and forecasting system of the recession characteristics of river flow rate using these estimated values are described in the following chapters as case study.

III. Estimation of Steady State of River Flow and Recession time Constant

We have constructed a estimating system for the steady flow rate and recession time constant using a neural network with various features. Actually, the verification result of the proposed method is described below for the upper district of the Yahagi River in a case study.

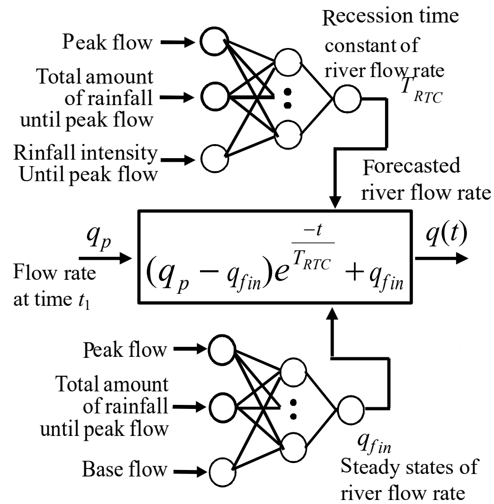
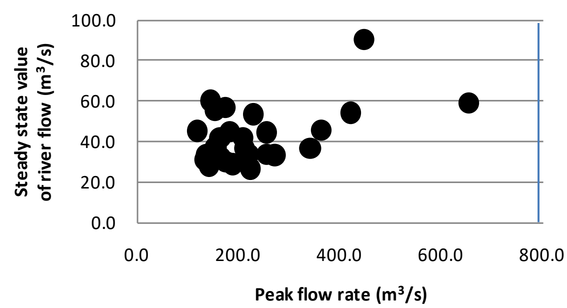
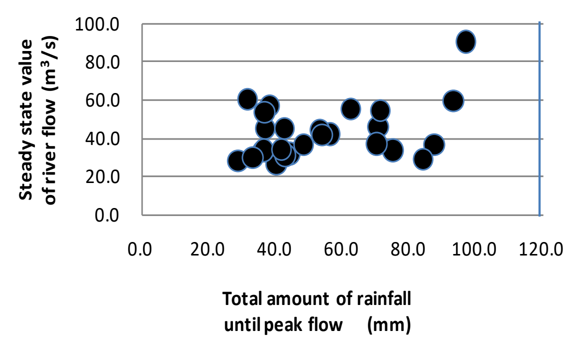


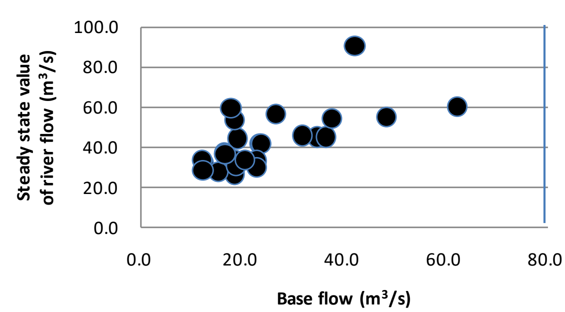
Figure 4: Forecasting system of recession characteristics of river flow rate



(a) Peak flow rate(R =0.49)



(b) Total amount of rainfall until peak flow



(c) Base flow(R =0.66)

Figure 5: Correlation between various quantities at flow rate peak and steady flow rate

a) Steady State Values of River Flow

The steady state value of river flow rate q_{fin} shown in equation (1) is a parameter necessary for forecasting the recession characteristics of the flow rate. Therefore, the value of q_{fin} is estimated at the peak of the flow rate.

i. *Correlation between q_{fin} and various quantities*

In order to select the optimum input information for the estimation of q_{fin}, we investigated the correlation between q_{fin} and various quantities obtained at the peak flow rate. Among the results, the peak flow rate, the accumulated rainfall up to the peak, and the correlation between the base flow and the steady state value after the peak are shown in (a) to (c) of Figure 5, respectively.(The value of the correlation coefficient is shown by the caption R in each figure).

According to these figures, it can be confirmed that although the correlation coefficient $R = 0.66$ to 0.39, there are many variations, but the steady flow rate tends to show a large value when there are many quantities. When the correlation with other quantities was investigated, it was confirmed that the correlation with the steady flow rate was lower than that of the quantities shown in Figure 5.

ii. *Estimating System of Steady State Value of River Flow*

The top three information (base flow R=0.66, peak flow R=0.49, total amount of rainfall R=0.39) in descending order of the value of the correlation coefficient between the steady state of river flow rate and various quantities are taken up. An estimation system of steady state value of river flow q_{inf} is constructed using these as input information is shown in Figure 6. The system consists of a three-layer and simple hierarchical neural network, which gives "peak flow", "total amount of rainfall" and "base flow" are corresponded to the input layer, and "steady state value of river flow" to the output layer. As for the middle layer, as in Figure 6, we selected three units that give a small estimation error at the early learning stage of the neural network. The back propagation method[18] was used for learning the estimation system. For the hidden layer, we selected three units that gave a small estimation error at the early stage of learning when learning the neural network.

iii. *Estimated Results of Steady State Value of River Flow*

The estimation system was trained using 16 cases (No. 1 to 16) in Table 1, and the steady state of river flow rate was estimated by the rainfall of the remaining 10 cases (No. 17 to 26). As a result, the error of estimated value was calculated by equation (6) and summarized by the "Estimated-value-1" in Table-2.

$$Error\ of\ estimeted\ value = \left(\frac{Estimeted\ \ value - Observed\ \ value}{Observed\ \ value}\right) \times 100\ \ [\%] \qquad (6)$$

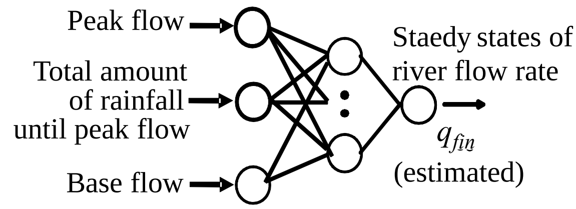


Figure 6: Estimating system for steady states of river flow rate
(input layer: 3 units, middle layer: 3 units, output layer: 1units)

Table 1: Observed data of rainfall and flow rate used for studying

Rain No.	Base flow rate	Peak flow rate	Obtained until peak flow: Total amount of rainfall	Obtained until peak flow: Rainfall duration	Obtained until peak flow: Rainfall intensity	Obtained after peak flow: Total amount of rainfall	Obtained after peak flow: Steady state value of river flow	Obtained after peak flow: Recession time constants of river flow
	m^3/s	m^3/s	mm	h	mm/h	mm	m^3/s	h
1	12.4	163.9	44.0	15.0	2.9	14.3	32.1	6.5
2	62.2	143.0	31.4	12.0	2.6	0.7	60.3	6.4
3	23.5	206.6	56.0	19.0	2.9	9.7	42.0	3.7
4	26.5	171.7	38.0	11.0	3.5	17.9	56.8	4.5
5	19.0	254.2	53.0	5.0	10.6	1.4	44.5	1.8
6	23.7	161.5	53.7	17.0	3.2	5.0	41.7	7.3
7	18.5	222.3	40.0	12.0	3.3	7.4	26.7	4.8
	:		:		:		:	
16	37.5	419.2	71.1	12.0	5.9	18.0	54.2	7.3
17	15.3	140.2	28.6	10.0	2.9	20.9	28.1	6.3
18	18.4	135.1	36.2	11.0	3.3	20.6	33.7	9.3
19	18.8	132.4	42.7	16.0	2.7	1.7	31.0	4.3
20	16.4	153.3	70.0	17.0	4.1	10.4	37.1	5.1
21	16.6	339.0	87.3	18.0	4.8	7.1	36.6	4.1
22	22.8	173.1	33.0	5.0	6.6	18.7	30.0	3.5
23	12.3	186.2	83.8	16.0	5.2	5.5	28.9	6.7
24	16.6	209.1	48.2	5.0	9.6	3.3	36.7	3.3
25	42.1	444.7	96.8	17.0	5.7	8.0	90.5	3.8
26	20.5	219.3	41.5	21.0	2.0	22.2	33.9	3.6

Table 2: Estimated results of steady states of flow rate

Rain No.	Obser-ved m^3/s	Estimated-value-1 (Neural network)		Estimated-value-2 (Base flow)	
		m^3/s	Error %	m^3/s	Error
17	28.1	33.1	18.1	15.3	-45.5
18	33.7	34.0	1.1	18.4	-45.3
19	31.0	33.8	8.9	18.8	-39.4
20	37.2	31.2	-16.0	16.4	-55.9
21	36.6	40.0	9.2	16.6	-54.6
22	30.0	38.7	28.8	22.8	-24.1
23	28.9	28.1	-2.7	12.3	-57.4
24	36.7	33.9	-7.8	16.6	-54.8
25	90.5	53.3	-41.1	42.1	-53.5
26	33.9	46.5	37.1	20.5	-39.7
Average absolute error		-----	17.1	-----	47.0

Estimated-value-1: Estimated values of steady states of river flow rate by using neural network

Estimated-value-2: Estimated values of steady states of river flow rate by using base flow instead of steady flow rate

In addition, the results of using the base flow rate instead of the steady state of river flow rate are also shown by the "Estimated-value-2" in the same Table-2. From the table, the estimation error of the steady state of river flow rate decreases from 47.0% to 17.1%. From this result, it is expected that the forecasted accuracy of river flow rate will be improved significantly by using the estimated value of steady flow rate.

b) Recession time constant

As in the previous section, the recession time constant T_{RTC} shown in equation (1) is taken as a parameter necessary for forecasting the recession characteristics of the river flow rate, and the value of T_{RTC} is estimated at the peak of the flow rate. In order to select the optimum input information for T_{RTC} estimation, we investigate the correlation between various quantities obtained at the peak flow rate and T_{RTC}, and propose an estimation system of recession time constant.

i. *Correlation between T_{RTC} and various quantities*

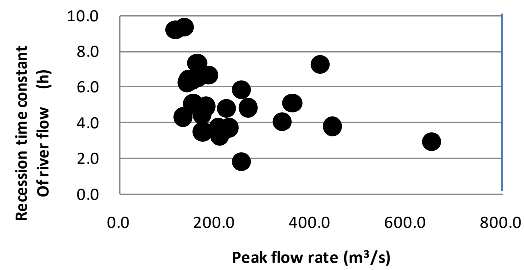
In estimating the recession time constant, we investigated the correlation with various quantities obtained at the peak flow rate. Of the results, the correlations with peak flow rate discharge, total rainfall, and rainfall intensity are investigated and shown in (a) to (c) in Figure 7 respectively (The value of the correlation coefficient is shown by the caption R in each figure). According to these figures, although there are many variations in the correlation coefficient R = -0.56 to -0.38, it can be confirmed that the decreasing time constant tends to show a small value when there are many quantities. When the correlation with other quantities, such as the duration of rainfall to the peak, was also examined, it was confirmed that the correlation with the decreasing time constant was lower than the quantities shown in Figure 7.

ii. *Estimating System of Recession Time Constant*

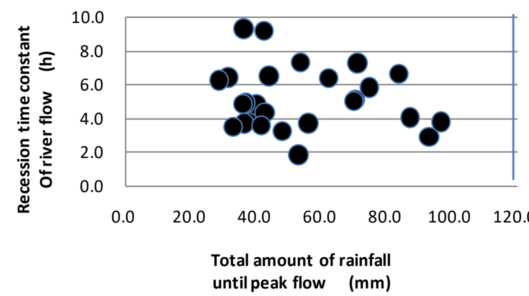
The top three information (rainfall intensity R = -0.56 up to the peak flow rate, peak flow rate R = -0.49, cumulative rainfall up to the peak R = -0.38) in descending order of the absolute value of the correlation coefficient between the recession time constant and various quantities are taken up. An estimation system of recession time constant T_{RTC} is constructed using these as input information is shown in Figure 8. The system consists of a three-layer and simple hierarchical neural network, which gives "peak flow", "total amount of rainfall" and "rainfall intensity" are corresponded to the input layer, and "recession time constant" to the output layer. As for the middle layer, as in Figure 6, we selected three units that give a small estimation error at the early learning stage of the neural network.

iii. *Estimated Results of Recession Time Constant of River Flow*

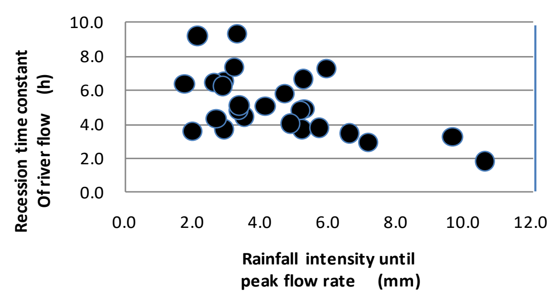
The estimation system was trained using 16 cases (No. 1 to 16) in Table 1, and the recession time constant of river flow rate was estimated by the rainfall of the remaining 10 cases (No. 17 to 26). As a result, the estimation error is summarized in Table-3. The estimation error of the recession time constant is represented by the subtraction (hours) from the actual value, which is reduced from 8.2h to 1.4h.



(a) Peak flow rate (R = -0.49)



(b) Total amount of rainfall until peak flow(R =-0.38)



(c) Rainfall intensity until peak flow (R =-0.56)

Figure 7: Correlation between T_{RTC} and various quantities

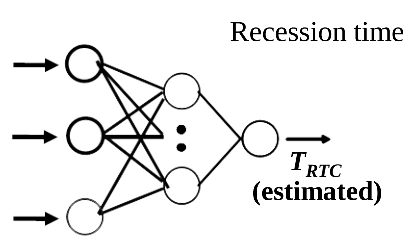


Figure 8: Estimating system for recession time constant of river flow rate
(input layer: 3 units, middle layer: 3 units, output layer: 1 units)

IV. Forecasting River Flow Rate for Recession Term

The river flow after the peak flow rate was forecasted based on the estimated results of the steady-state of flow rate and the recession time constant obtained up to the previous section. Based on the forecasting system shown in Figure 4, the time variation of flow rate was calculated using the steady-state ones q_{fin} in Table 2, the recession time constant T_{RTC} in Table 3, and the peak flow rate $q\ (t_1)$ as input information.

Table 3: Estimated results of recession time constant

Rain No.	Ob-served h	Estimated-value-1 (Neural network) h	Estimated-value-1 (Neural network) Error h	Estimated- value-2 (Base flow) h	Estimated- value-2 (Base flow) Error h
17	6.3	6.2	-0.1	6.7	0.5
18	9.3	6.7	-2.6	17.3	8.0
19	4.3	8.0	3.7	13.4	9.1
20	5.1	6.8	1.7	16.8	11.8
21	4.1	5.0	0.9	13.0	9.0
22	3.5	4.0	0.5	11.6	8.1
23	6.7	4.2	-2.5	13.1	6.4
24	3.3	3.4	0.1	15.3	12.1
25	3.8	3.9	0.1	13.8	10.0
26	3.6	5.9	2.3	11.2	7.6
Average absolute error		-----	1.4	-----	8.2

Estimated-value-1: Estimated values of steady states of river flow rate by using neural network
Estimated-value-2: Estimated values of steady states of river flow rate by using base flow instead of steady flow rate

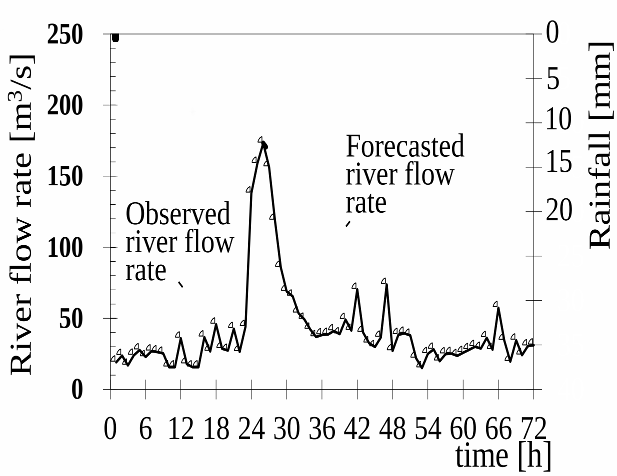


Figure 9: Forecasted result for the recession term after the peak of the flow rate (rain fall No.22)

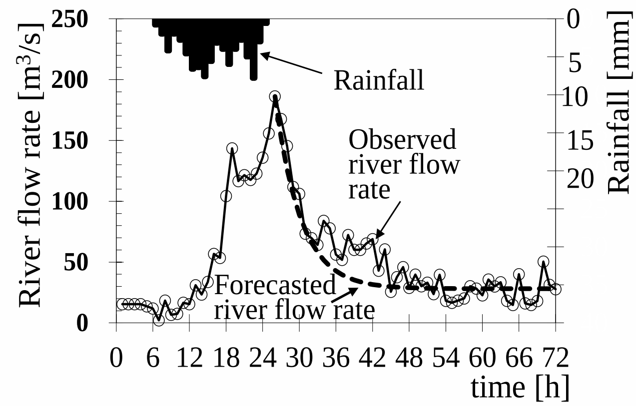


Figure 10: Forecasted result for the recession term after the peak of the flow rate (rain fall No.23)

Among the results, Figure 9 shows an example of rainfall concentrated in a relatively short time (33 mm in 5 hours), and Figure 10 shows an example of rainfall in a relatively long time (84 mm in 16 hours). In addition, the measured value of the flow rate is indicated by a circle, and the forecasted value of the decreasing part is indicated by a broken line. The predicted values in both figures as a whole are relatively close to the actual values. In detail, there is an increase or decrease in the measured flow rate during the time when rainfall is not observed. The reason seems to be the rainfall at points other than the rainfall observation point. Table 4 shows the forecasted error seen from the total amount of runoff. The table also shows the forecasted results when the basal flow rate is used instead of the steady flow rate value.

According to the table, the forecasted error is reduced from 25.0% to 18.6% on average of the absolute values when the steady flow rate is used compared to when the base flow rate is used. This 6% reduction in prediction error corresponds to the amount of electricity used by approximately 22,800 households per day, which can improve the economic operation of thermal power generation (Appendix-2). In addition, the forecasted error is smaller when the estimated steady-state value of flow rate is used for seven of the ten cases than when the basal flow rate is used. From the above results, the effectiveness of using the estimated steady-state value of flow rate can be confirmed.

Table 4: Forecasted results for the recession term after the peak of the flow rate

Rain No.	Observed x 10^6 m3	Estimated-value-1 (Neural network) x 10^6 m3	Estimated-value-1 (Neural network) Error %	Estimated-value-2 (Base flow) x 10^6 m3	Estimated-value-2 (Base flow) Error %
17	7.6	8.3	9.2	5.9	-22.4
18	9.4	8.6	-8.5	10.4	10.6
19	7.0	8.9	27.1	8.8	25.7
20	8.6	8.6	0.0	10.9	26.7

21	12.3	12.8	4.1	18.2	48.0
22	7.7	8.8	14.3	10.4	35.1
23	8.9	7.5	-15.7	10.4	16.9
24	13.9	8.3	-40.3	13.4	-3.6
25	20.9	15.5	-25.8	27.3	30.6
26	8.5	12.0	41.2	11.8	38.8
Average absolute error		-----	18.6	-----	25.0

Estimated-value-1: Estimated values of steady states of river flow rate by using neural network

Estimated-value-2: Estimated values of steady states of river flow rate by using base flow instead of steady flow rate

V. Conclusions

In this paper, we proposed a method for estimating the recession time constant of the river flow rate and the steady flow value for the outflow after rainfall and improved the accuracy of the flow forecasting. We confirmed the effectiveness of the forecasted method for the upper section of the Yahagi River in central Japan. The features of the proposed method are as follows.

1. Regarding the prediction of the recession characteristics of the river flow rate into a dam, the steady state flow rate q_{inf} is taken up as a necessary parameter. The correlation between the various quantities obtained at the peak flow rate and q_{inf} was investigated. As a result, although there were many variations in peak flow rate, total rainfall up to the peak, and base flow rate, it was confirmed that the larger the various quantities, the larger the steady-state flow rate.
2. We proposed a estimation system of the steady-state value of the flow rate by giving "total rainfall up to the flow rate peak", "peak flow rate" and "base flow rate" to the input layer and "steady-state value of flow rate" to the output layer. According to the simulation results of the steady-state estimation of river flow rate, the estimation error was significantly reduced from 47.0% to 17.1% compared with the case where the base flow rate was used as the estimated value instead of the steady-state flow rate.
3. The recession time constant T_{RTC} is taken up as a parameter necessary for predicting the recession characteristic of the flow rate. Although there were many variations in the peak flow rate obtained at the peak flow rate, the cumulative rainfall up to the peak, and the rainfall intensity, it was confirmed that the larger the various quantities, the smaller the recession time constant.
4. We proposed a estimation system of the recession time constant of the flow rate by giving "peak flow rate", "total rainfall up to the flow rate peak" and "rainfall intensity up to the flow rate peak" to the input layer and "recession time constant" to the output layer. The simulation error of the recession time constant of river flow rate was significantly reduced from 47.0% to 17.1%
5. Based on the estimation results of the steady flow rate and the recession time constant, we proposed a forecasting system of the flow rate after the peak flow. The error of the forecasting result using both estimated values of the steady states and the recession time constant reduced from 25.0% to 18.6%. A reduction of about 6% in the forecasting error corresponds to the daily power consumption by about 22,800 households, which can improve the economic operation of thermal power generation.

The proposed forecasting method of the recession characteristic can be applied when the rainfall after the forecasting point (peak flow rate point) is about 30 mm or less and can be ignored. If there is rainfall again after the flow rate peak, it is considered that the same prediction can be applied with the re-occurred flow rate peak point as the new flow rate peak point.

In the future, we would like to investigate the effect of rainfall after the forecast time on the flow rate forecasted result, verify the forecasting method when the rainfall is 30 mm or more after the peak flow rate occurs. And using the forecasted rainfall after the peak we would like to study the forecasting method of the flow rate in the recession time. Furthermore, we will confirm the versatility by applying the proposed method to other rivers.

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Appendix

A-1 Estimating formula for steady flow rate and recession time constant

In this paper, the runoff characteristics to the river during the recession period after the peak flow rate are expressed by the following equation.

$$q(t_i) = (q_p - q_{fin})e^{\frac{-t_i}{T_{RTC}}} + q_{fin} \quad \text{(A-1)}$$

where, T_{RTC} is the recession time constant, qinf is the steady flow rate value, q (t_i) is the flow rate at time t_i, q_p is the flow rate at the peak flow rate.

For the estimation of T_{RTC} and q_{inf}, given q_{inf} = q_{BASE} (base flow rate), T_{RTC} is estimated by equation (A-1). Nextly, the obtained T_{RTC} is given to Eq (A-1) and q_{inf} is estimated. Here after, T_{RTC} and q_{inf} are calculated mutually to find a stable solution. The derivation of each estimation formula for T_{RTC} and q_{inf} is shown below.

i. *Estimating the recession time constant T_{RTC}*

Equation (A-1) is rewritten and expressed by the following equation.

$$e^{\frac{-t_i}{T_{RTC}}} = \frac{q(t_i) - q_{fin}}{q_p - q_{fin}}$$

$$\frac{-t_i}{T_{RTC}} = \log\frac{q(t_i) - q_{fin}}{q_p - q_{fin}}$$

$$at_i = z(t_i) \qquad \text{(A-2)}$$

where

$$a = -\frac{1}{T_{RTC}} \qquad \text{(A-3)}$$

$$z(t_i) = \log\frac{q(t_i) - q_{fin}}{q_p - q_{fin}}$$

The objective function J_1 for deriving the estimation formula of the coefficient *a* using the least squares method from the actual data of *q* (t_i) and the formula (A-2) in the recession period of the flow rate is as follows.

$$J_1 = \sum_{i=1}^{n}(z(t_i) - at_i)^2 \qquad \text{(A-5)}$$

The value of the coefficient a that minimizes equation (A-5) is obtained by $\partial J_1/\partial a = 0$.

$$\partial J_1/\partial a = 2\sum_{i=1}^{n}(z(t_i) - at_i)(-t_i)$$

$$= -2\sum_{i=1}^{n}(z(t_i)t_i - at_i^2)$$

$$= 0$$

Therefore,

$$a = -\frac{\sum_{i=1}^{n} z(t_i)t_i}{\sum_{i=1}^{n} t_i^2}$$

$$= -\frac{1}{T_{RTC}}$$

Therefore, the estimated value of the recession time constant T_{RTC} is calculated by the following equation..

$$T_{RTC} = \frac{\sum_{i=1}^{n} t_i^2}{\sum_{i=1}^{n} z(t_i)t_i} \qquad \text{(A-6)}$$

ii. *Estimating the steady state value q_{inf} of flow rate*

equation (A-1) is rewritten and expressed by $x(t_i) = e^{\frac{-t_i}{T_{RTC}}}$

$$\partial J_1/\partial a = 2\sum_{i=1}^{n}(z(t_i) - at_i)(-t_i)$$

$$q(t_i) = (q_p - q_{fin})x(t_i) + q_{fin}$$

$$= q_p x(t_i) - q_{fin}(x(t_i) - 1) \qquad \text{(A-7)}$$

The objective function J_2 for deriving the estimation formula of the steady flow rate q_{fin} from the actual data of *q* (t_i) in the recession period of the flow rate and equation (A-7) using the least squares method is as follows.

$$J_2 = \sum_{i=1}^{n}(q(t_i) - (q_p x(t_i) - q_{fin}(x(t_i) - 1))^2 \qquad \text{(A-8)}$$

The value of q_{fin} that minimizes equation (A-8) is obtained by $\partial J_1/\hat{q}_{fin} = 0$

$$\partial J_2/\partial q_{fin}$$

$$= 2\sum_{i=1}^{n}\{q(t_i) - (q_p x(t_i) - q_{fin}(x(t_i) - 1)\} \times (x(t_i) - 1)$$

$$= 0$$

Therefore,

$$\sum_{i=1}^{n}\{q(t_i) - (q_p x(t_i) - q_{fin}(x(t_i) - 1)\}$$

$$= \sum_{i=1}^{n}\{q(t_i) - q_p x(t_i) + \hat{q}_{fin}(x(t_i) - 1)\}$$

$$= 0$$

Accordingly, the estimated value q_{fin} is calculated by the following equation.

$$\hat{q}_{fin} = \frac{-\sum_{i=1}^{n} q(t_i) - q_p x(t_i)}{\sum_{i=1}^{n}(x(t_i) - 1)} \qquad \text{(A-9)}$$

To obtain the estimated values T_{RTC} and q_{fin} for the unknown parameters T_{RTC} and q_{fin}, give q_{BASE} (base flow rate) instead of q_{fin}, and obtain T_{RTC} from equation (A-6).

Furthermore, the obtained T_{RTC} value is given to (A-9) to obtain q_{fin}. T_{RTC} and q_{fin}, are calculated mutually to find a stable solution.

Figure 1 shows the calculation flow for obtaining the estimated values T_{RTC} and q_{fin} for T_{RTC} and q_{fin}.

A-2 Power generation

The amount of power generated for the flow rate equivalent to a forecasted error of 1% in the upper reaches of the Yahagi River (from Table 4 in the main text, the average total flow rate per rainfall is 0.1 x 106 m^3) is estimated as follows[32].

Power generation output; $P = 9.8\eta QH$ [kW]

Power generation; $S = P \times T$ [kWh]

However, η is the total efficiency of the turbine and the generator, *Q* is the flow rate [m^3/s], *H* is the effective head [m], and *T* is the generator operating time [h].

In addition, referring to the various quantities of the Yahagi Dam power plant [33], Flow rate Q=234 m^3/s Effective head H=163m, Efficiency η=0.86 are used.

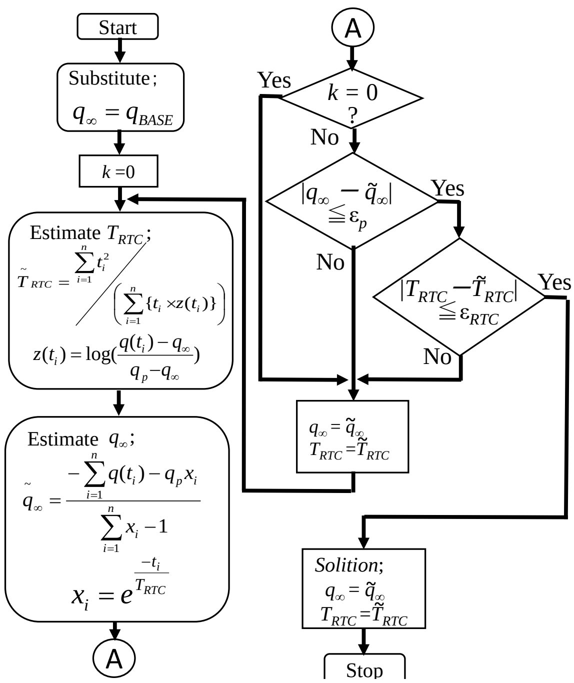

Figure A1: Estimated calculation flow of recession time constant T_{RTC} and steady flow rate q_{inf}

When the flow rate equivalent to 1% error per rainfall (0.1 × 106m^3) is converted into the amount of power generated at the target power plant, it can be calculated as follows.

Power generation time

$$T = 0.1 \times 106/234/3600 = 0.12\text{h}$$

Power generation output

$$P = 9.8QH\eta$$

$$= 9.8 \times 234 \times 163 \times 0.86 = 321{,}461 \text{ kW}$$

Power generation

$$S = P \times T = 321{,}461 \times 0.12 = 38{,}575 \text{ kWh}$$

If the monthly power consumption of one household is 300kWh and the daily power consumption of one household is 10kWh, 38,575kWh is equivalent to the daily power consumption of about 3800 households. Therefore, an improvement in prediction accuracy of 6% is equivalent to the daily power consumption of 22,800 households, and the economic operation of thermal power generation can be improved.

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Detection and Parameter Extraction of Low Probability of Intercept Frequency Hopping Signals using the Spectrogram and the Reassigned Spectrogram

By Daniel L. Stevens

Abstract- Low probability of intercept radar signals, which are often problematic to detect and characterize, have as their goal 'to see and not be seen'. Digital intercept receivers are currently moving away from Fourier-based analysis and towards classical time-frequency analysis techniques for the purpose of analyzing these low probability of intercept radar signals. Although these classical time-frequency analysis techniques are an improvement over existing Fourier-based techniques, they still suffer from a lack of readability –which can be caused by poor time-frequency localization (such as the spectrogram), which may in turn lead to inaccurate detection and parameter extraction. In this study, the reassignment method, because of its ability to improve time-frequency localization, is proposed as an improved signal analysis technique to address the poor time-frequency localization deficiency of the spectrogram. This paper presents the novel approach of characterizing low probability of intercept frequency hopping radar signals through utilization and direct comparison of the spectrogram versus the reassigned spectrogram.

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Detection and Parameter Extraction of Low Probability of Intercept Frequency Hopping Signals using the Spectrogram and the Reassigned Spectrogram[1]

Daniel L. Stevens

Abstract- Low probability of intercept radar signals, which are often problematic to detect and characterize, have as their goal 'to see and not be seen'. Digital intercept receivers are currently moving away from Fourier-based analysis and towards classical time-frequency analysis techniques for the purpose of analyzing these low probability of intercept radar signals. Although these classical time-frequency analysis techniques are an improvement over existing Fourier-based techniques, they still suffer from a lack of readability –which can be caused by poor time-frequency localization (such as the spectrogram), which may in turn lead to inaccurate detection and parameter extraction. In this study, the reassignment method, because of its ability to improve time-frequency localization, is proposed as an improved signal analysis technique to address the poor time-frequency localization deficiency of the spectrogram. This paper presents the novel approach of characterizing low probability of intercept frequency hopping radar signals through utilization and direct comparison of the spectrogram versus the reassigned spectrogram. A 4 component frequency hopping low probability of intercept radar signal was analyzed. The following metrics were used for evaluation: average percent error of: carrier frequency, modulation bandwidth, modulation period, and time-frequency localization. Also used were averages: percent detection, lowest signal-to-noise ratio for signal detection, and plot (processing) time. Experimental results demonstrate that the 'squeezing' quality of the reassignment method produced an improved readability over the classical time-frequency analysis technique and consequently, the reassigned spectrogram produced more accurate characterization metrics than the spectrogram. An improvement in performance may well translate into saved equipment and lives.

I. Introduction

a) Frequency hopping techniques

A low probability of intercept (LPI) radar that uses frequency hopping techniques changes the transmitting frequency in time over a wide bandwidth in order to prevent an intercept receiver from intercepting the waveform. The frequency slots used are chosen from a frequency hopping sequence, and it is this unknown sequence that gives the radar the advantage over the intercept receiver in terms of processing gain. The frequency sequence appears random to the intercept receiver, and so the possibility of it following the changes in frequency is remote [PAC09]. This prevents a jammer from reactively jamming the transmitted frequency [ADA04]. Frequency hopping radar performance depends only slightly on the code used, given that certain properties are met. This allows for a larger variety of codes, making it more difficult to intercept[1].

b) Time-frequency signal analysis

Time-frequency signal analysis involves the analysis and processing of signals with time-varying frequency content. Such signals are best represented by a time-frequency distribution [PAP95], [HAN00], which is intended to show how the energy of the signal is distributed over the two-dimensional time-frequency plane [WEI03], [LIX08], [OZD03]. Processing of the signal may then exploit the features produced by the concentration of signal energy in two dimensions (time and frequency), instead of only one dimension (time or frequency) [BOA03], [LIY03]. Since noise tends to spread out evenly over the time-frequency domain, while signals concentrate their energies within limited time intervals and frequency bands; the local SNR of a noisy signal can be improved simply by using time-frequency analysis [XIA99]. Also, the intercept receiver can increase its processing gain by implementing time-frequency signal analysis [GUL08]. In addition, time-frequency distributions are useful for the visual interpretation of signal dynamics [RAN01]. An experienced operator can quickly detect a signal and extract the signal parameters by analyzing the time-frequency distribution [ANJ09].

Some of the more common classical time-frequency analysis techniques include the Wigner-Ville distribution (WVD), Choi-Williams distribution (CWD), spectrogram and scalogram. The WVD exhibits the highest signal energy concentration [PAC09], but has the worst cross-term interference, which can severely limit the readability of a time-frequency representation

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Global Journal of Researches in Engineering (F) Volume XX Issue IV Version I Year 2020

[GUL08], [BOA03]. The CWD is a member of Cohen's class, which adds a smoothing kernel to help reduce cross-term interference [BOA03]. The CWD, as with all members of Cohen's class, is faced with a trade-off between cross-term reduction and time-frequency localization. The spectrogram is the magnitude squared of the short-time Fourier transform (STFT) [HLA92], [MIT01]. It has poorer time-frequency localization but less cross-term interference than either the WVD or CWD, and its cross-terms are limited to regions where the signals overlap [BOA03]. The scalogram is the magnitude squared of the wavelet transform and can be used as a time-frequency distribution [COH02], [GAL05]. Like the spectrogram, the scalogram has cross-terms that are limited to regions where the signals overlap [BOA03], [HLA92].

Though classical time-frequency analysis techniques are a great improvement over Fourier analysis techniques, they may suffer from poor time-frequency localization, as described above. This may result in degraded readability of time-frequency representations, potentially leading to inaccurate LPI radar signal detection and parameter extraction metrics, and as such, can lead to decisions based on inaccurate information.

c) Reassignment method

A promising avenue for overcoming this deficiency is the utilization of the reassignment method. The reassignment method, which can be applied to most energy distributions [HIP00], has, in theory, a perfectly localized distribution for chirps, tones and impulses [BOA03], making it a good candidate for the analysis of certain LPI radar signals, such as the triangular modulated frequency modulated continuous wave (FMCW) (which can be viewed as back-to-back chirps) and the frequency shift keying (FSK) (which can be viewed as tones).

d) Spectrogram and reassigned spectrogram

The spectrogram is defined as the magnitude squared of the STFT [BOA03], [HIP00], [HLA92], [MIT01], [PAC09]. For non-stationary signals, the STFT is usually in the form of the spectrogram [GRI08].

The STFT of a signal $x(u)$is given in equation 2.5 as:

$$F_x(t,f;h) = \int_{-\infty}^{+\infty} x(u)h\,(ut)e^{-j2\pi fu}\,du \qquad (2.5)$$

Where $h(t)$ is a short time analysis window localized around $t = 0$ and $f = 0$. Because multiplication by the relatively short window $h(u-t)$ effectively suppresses the signal outside a neighborhood around the analysis point $u = t$, the STFT is a 'local' spectrum of the signal $x(u)$ around t. Think of the window $h(t)$ as sliding along the signal $x(u)$ and for each shift $h(u-t)$ we compute the usual Fourier transform of the product function $x(u)h(u-t)$. The observation window allows localization of the spectrum in time, but also smears the spectrum in frequency in accordance with the uncertainty principle, leading to a trade-off between time resolution and frequency resolution. In general, if the window is short, the time resolution is good, but the frequency resolution is poor, and if the window is long, the frequency resolution is good, but the time resolution is poor.

The STFT was the first tool devised for analyzing a signal in both time and frequency simultaneously. For analysis of human speech, the main method was, and still is, the STFT. In general, the STFT is still the most widely used method for studying non-stationary signals [COH95].

The spectrogram (the squared modulus of the STFT) is given by equation 2.6 as:

$$S_x(t,f) = \left|\int_{-\infty}^{+\infty} x(u)\,h(u-t)e^{-j2\pi fu}\,du\right|^2 \qquad (2.6)$$

The spectrogram is a real-valued and non-negative distribution. Since the window h of the STFT is assumed of unit energy, the spectrogram satisfies the global energy distribution property. Thus we can interpret the spectrogram as a measure of the energy of the signal contained in the time-frequency domain centered on the point (t, f) and whose shape is independent of this localization.

Here are some properties of the spectrogram: 1) time and frequency covariance - the spectrogram preserves time and frequency shifts, thus the spectrogram is an element of the class of quadratic time-frequency distributions that are covariant by translation in time and in frequency (i.e. Cohen's class); 2) time-frequency resolution - the time-frequency resolution of the spectrogram is limited exactly as it is for the STFT; there is a trade-off between time resolution and frequency resolution. This poor resolution is the main drawback of this representation; 3) interference structure - as it is a quadratic (or bilinear) representation, the spectrogram of the sum of two signals is not the sum of the two spectrograms (quadratic superposition principle); there is a cross-spectrogram part and a real part. Thus, as for every quadratic distribution, the spectrogram presents interference terms; however, those interference terms are restricted to those regions of the time-frequency plane where the signals overlap. Thus if the signal components are sufficiently distant so that their spectrograms do not overlap significantly, then the interference term will nearly be identically zero [COH95], [HLA92], [ISI96].

The original idea of reassignment was introduced in an attempt to improve the spectrogram [OZD03]. As with any other bilinear energy distribution, the spectrogram is faced with an unavoidable trade-off between the reduction of misleading interference terms and a sharp localization of the signal components.

Global Journal of Researches in Engineering (F) Volume XX Issue IV Version I Year 2020
12

We can define the spectrogram as a two-dimensional convolution of the WVD of the signal by the WVD of the analysis window, as in equation 2.9:

$$S_x(t,f;h) = \iint_{-\infty}^{+\infty} W_x(s,\xi) W_h(t-s, f-\xi) ds\, d\xi \quad (2.9)$$

Therefore, the distribution reduces the interference terms of the signal's WVD, but at the expense of time and frequency localization. However, a closer look at equation 2.9 shows that $W_h(t-s, f-\xi)$ delimits a time-frequency domain at the vicinity of the (t,f) point, inside which a weighted average of the signal's WVD values is performed. The key point of the reassignment principle is that these values have no reason to be symmetrically distributed around (t,f), which is the geometrical center of this domain. Therefore, their average should not be assigned at this point, but rather at the center of gravity of this domain, which is much more representative of the local energy distribution of the signal [BOA03]. Reasoning with a mechanical analogy, the local energy distribution $W_h(t-s, f-\xi)W_x(s,\xi)$ (as a function of s and ξ) can be considered as a mass distribution, and it is much more accurate to assign the total mass (i.e. the spectrogram value) to the center of gravity of the domain rather than to its geometrical center. Another way to look at it is this: the total mass of an object is assigned to its geometrical center, an arbitrary point which except in the very specific case of a homogeneous distribution, has no reason to suit the actual distribution. A much more meaningful choice is to assign the total mass of an object, as well as the spectrogram value, to the center of gravity of their respective distribution [BOA03].

This is exactly how the reassignment method proceeds: it moves each value of the spectrogram computed at any point (t,f) to another point $(\hat{t},\hat{f})$ which is the center of gravity of the signal energy distribution around (t,f) (see equations 2.10 and 2.11) [LIX08]:

$$\hat{t}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} s\, W_h(t-s,f-\xi)W_x(s,\xi)ds\, d\xi}{\iint_{-\infty}^{+\infty} W_h(t-s,f-\xi)W_x(s,\xi)ds\, d\xi} \quad (2.10)$$

$$\hat{f}(x;t,f) = \frac{\iint_{-\infty}^{+\infty} \xi\, W_h(t-s,f-\xi)W_x(s,\xi)ds\, d\xi}{\iint_{-\infty}^{+\infty} W_h(t-s,f-\xi)W_x(s,\xi)ds\, d\xi} \quad (2.11)$$

and thus leads to a reassigned spectrogram (equation (2.12)), whose value at any point (t',f') is the sum of all the spectrogram values reassigned to this point:

$$S_x^{(r)}(t',f';h) = \iint_{-\infty}^{+\infty} S_x(t,f;h)\delta(t' - \hat{t}(x;t,f))\delta\left(f' - \hat{f}(x;t,f)\right) dt\, df \quad (2.12)$$

One of the most interesting properties of this new distribution is that it also uses the phase information of the STFT, and not only its squared modulus as in the spectrogram. It uses this information from the phase spectrum to sharpen the amplitude estimates in time and frequency. This can be seen from the following expressions of the reassignment operators:

$$\hat{t}(x;t,f) = -\frac{d\Phi_x(t,f;h)}{df} \quad (2.13)$$

$$\hat{f}(x;t,f) = f + \frac{d\Phi_x(t,f;h)}{dt} \quad (2.14)$$

where $\Phi_x(t,f;h)$ is the phase of the STFT of x : $\Phi_x(t,f;h) = \arg(F_x$ (t, f; h)). However, these expressions (equations 2.13 and 2.14) do not lead to an efficient implementation, and have to be replaced by equations 2.15 (local group delay) and 2.16 (local instantaneous frequency):

$$\hat{t}(x;t,f) = t - \Re\left\{\frac{F_x(t,f;T_h)F_x^*(t,f;h)}{\left|F_{x(t,f;h)}\right|^2}\right\} \quad (2.15)$$

$$\hat{f}(x;t,f) = f - \Im\left\{\frac{F_x(t,f;D_h)F_x^*(t,f;h)}{\left|F_{x(t,f;h)}\right|^2}\right\} \quad (2.16)$$

where $T_h(t) = t \times h(t)$ and $D_h(t) = \frac{dh}{dt}(t)$. This leads to an efficient implementation for the reassigned spectrogram without explicitly computing the partial derivatives of phase. The reassigned spectrogram may thus be computed by using 3 STFTs, each having a different window (the window function h; the same window with a weighted time ramp t*h; the derivative of the window function h with respect to time (dh/dt)). Reassigned spectrograms are therefore very easy to implement, and do not require a drastic increase in computational complexity.

One of the most important properties of the reassignment method is that the application of the reassignment process to any distribution of Cohen's class theoretically yields perfectly localized distributions for chirp signals, frequency tones, and impulses, since the WVD does so also. As mentioned earlier, this is one of the reasons that the reassignment method can be chosen as a signal process analysis tool for analyzing LPI radar waveforms such as triangular modulated FMCW waveforms (which can be viewed as back-to-back chirps) and FSK waveforms (which can be viewed as frequency tones).

The reassignment method provides readability improvement. The components are much better localized and very concentrated. In order to rectify the classical time-frequency analysis deficiency of poor time-frequency localization, there needs to be a method that produces more concentrated distributions, which the reassignment method does. This squeezing quality of the reassignment method lead to improved readability - which leads to more accurate metrics extracted – which in turn, creates a more informed and safer intercept receiver environment.

II. Methodology

The methodologies detailed in this section describe the processes involved in obtaining and comparing metrics between the classical time-frequency analysis technique of the spectrogram vs. the reassigned spectrogram, for the detection and characterization of low probability of intercept frequency hopping radar signals.

The tools used for this testing were: MATLAB (version 8.3), Signal Processing Toolbox (version 6.21), Wavelet Toolbox (version 4.13), Image Processing Toolbox (version 9.0), Time-Frequency Toolbox (version 1.0) (http://tftb.nongnu.org/).

All testing was accomplished on a desktop computer (Dell Precision T1700; Processor - Intel Xeon CPU E3-1226 v3 3.30GHz; Installed RAM - 32.0GB; System type - 64-bit operating system, x64-based processor).

Testing was performed for the 4 component frequency hopping waveform, whose parameters were chosen for academic validation of signal processing techniques. Due to computer processing resources they were not meant to represent real-world values. The number of samples for each test was chosen to be 512, which seemed to be the optimum size for the desktop computer. Testing was performed at three different SNR levels: 10dB, 0dB, and the lowest SNR at which the signal could be detected. The noise added was white Gaussian noise, which best reflects the thermal noise present in the IF section of an intercept receiver [PAC09]. Kaiser windowing was used, when windowing was applicable. 100 runs were performed for each test, for statistical purposes. The plots included in this paper were done at a threshold of 5% of the maximum intensity and were linear scale (not dB) of analytic (complex) signals; the color bar represented intensity. The signal processing tools used for each task were the spectrogram and the reassigned spectrogram.

The 4 component frequency hopping signal (prevalent in the LPI arena [AMS09]) had the following parameters: sampling frequency=5KHz; carrier frequencies=1KHz, 1.75KHz, 0.75KHz, 1.25KHz; modulation bandwidth=1KHz; modulation period=.025sec.

After each particular run of each test, metrics were extracted from the time-frequency representation. The different metrics extracted were as follows:

Plot (processing) time: Time required for plot to be displayed.

Percent detection: Percent of time signal was detected - signal was declared a detection if any portion of each of the signal components (4 signal components for frequency hopping) exceeded a set threshold (a certain percentage of the maximum intensity of the time-frequency representation).

Threshold percentages were determined based on visual detections of low SNR signals (lowest SNR at which the signal could be visually detected in the time-frequency representation) (see Figure 1).

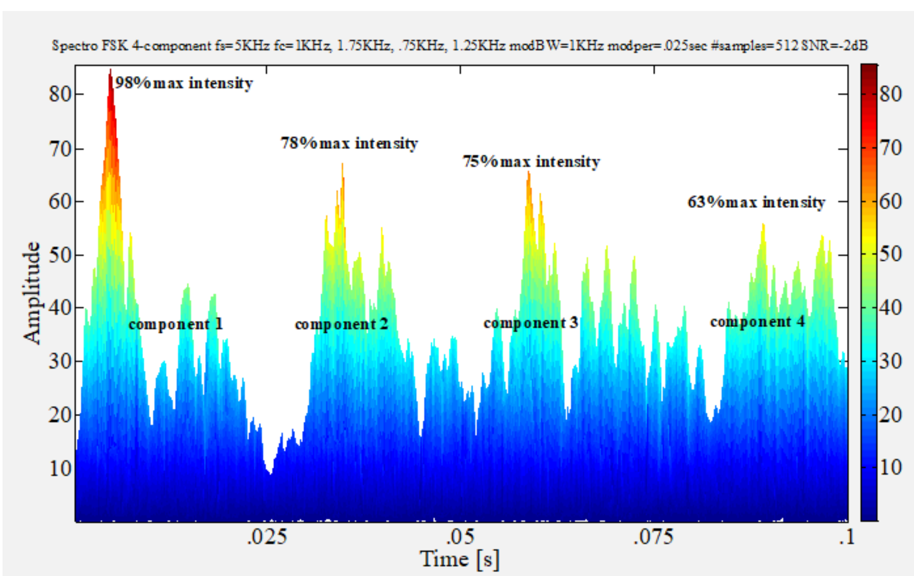

Figure 1: Threshold percentage determination. This plot is an amplitude vs. time (x-z view) of the spectrogram of a frequency hopping 4 component signal (512 samples, SNR= -2dB). For visually detected low SNR plots (like this one), the percent of max intensity for the peak z-value of each of the signal components was noted (here 98%, 78%, 75%, 63%), and the lowest of these 4 values was recorded (63%). Ten test runs were performed for both time-frequency analysis tools (spectrogram and reassigned spectrogram) for this waveform. The average of these recorded low values was determined and then assigned as the threshold for that particular time-frequency analysis tool. Note - the threshold value assigned for the spectrogram was 60%.

Thresholds were assigned as follows: spectrogram (60%); reassigned spectrogram (50%).

For percent detection determination, these threshold values were included in the time-frequency plot algorithms so that the thresholds could be applied automatically during the plotting process. From the threshold plot, the signal was declared a detection if any portion of each of the signal components was visible (see Figure 2).

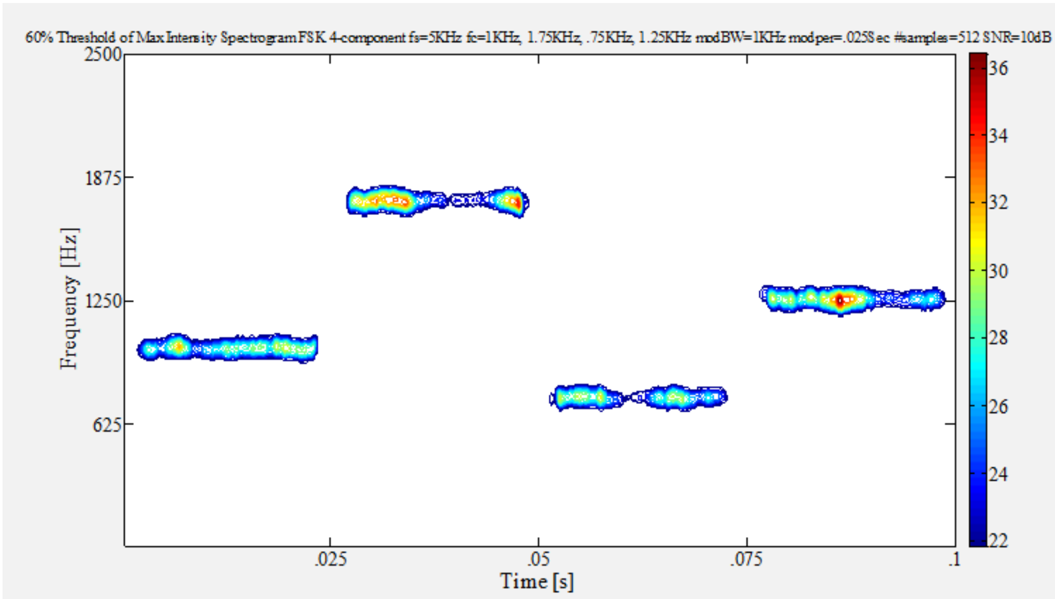

Figure 2: Percent detection (time-frequency). This plot is a time vs. frequency (x-y view) of the spectrogram of a 4 component frequency hopping signal (512 samples, SNR=10dB) with threshold value automatically set to 60%. From this threshold plot, the signal was declared a (visual) detection because at least a portion of each of the 4 FSK signal components was visible.

Carrier frequency: The frequency corresponding to the maximum intensity of the time-frequency representation (there are multiple carrier frequencies (4 ea) for the 4 component frequency hopping waveform) (see Figure 3).

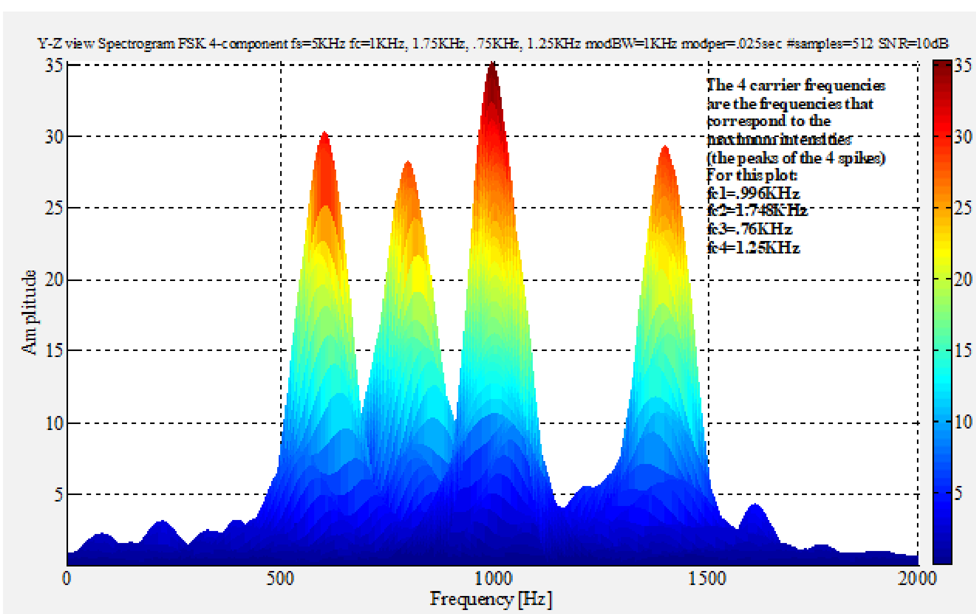

Figure 3: Determination of carrier frequency. Spectrogram of a 4 component frequency hopping signal (512 samples, SNR=10dB). From the frequency-intensity (y-z) view, the 4 maximum intensity values (1 for each carrier frequency) are manually determined. The frequencies corresponding to those 4 max intensity values are the 4 carrier frequencies (for this plot fc1=996 Hz, fc2=1748Hz, fc3=760Hz, fc4=1250Hz).

Modulation bandwidth: Distance from highest frequency value of signal (at a threshold of 20% maximum intensity) to lowest frequency value of signal (at same threshold) in Y-direction (frequency).

The threshold percentage was determined based on manual measurement of the modulation bandwidth of the signal in the time-frequency representation. This was accomplished for ten test runs of each time-frequency analysis tool (spectrogram and reassigned spectrogram), for the 4 component frequency hopping waveform. During each manual measurement, the max intensity of the high and low measuring points was recorded. The average of the max intensity values for these test runs was 20%. This was adopted as the threshold value, and is representative of what is obtained when performing manual measurements. This 20% threshold was also implemented for determining the modulation period and the time-frequency localization (both are described below).

For modulation bandwidth determination, the 20% threshold value was included in the time-frequency plot algorithms so that the threshold could be applied automatically during the plotting process. From the threshold plot, the modulation bandwidth was manually measured (see Figure 4).

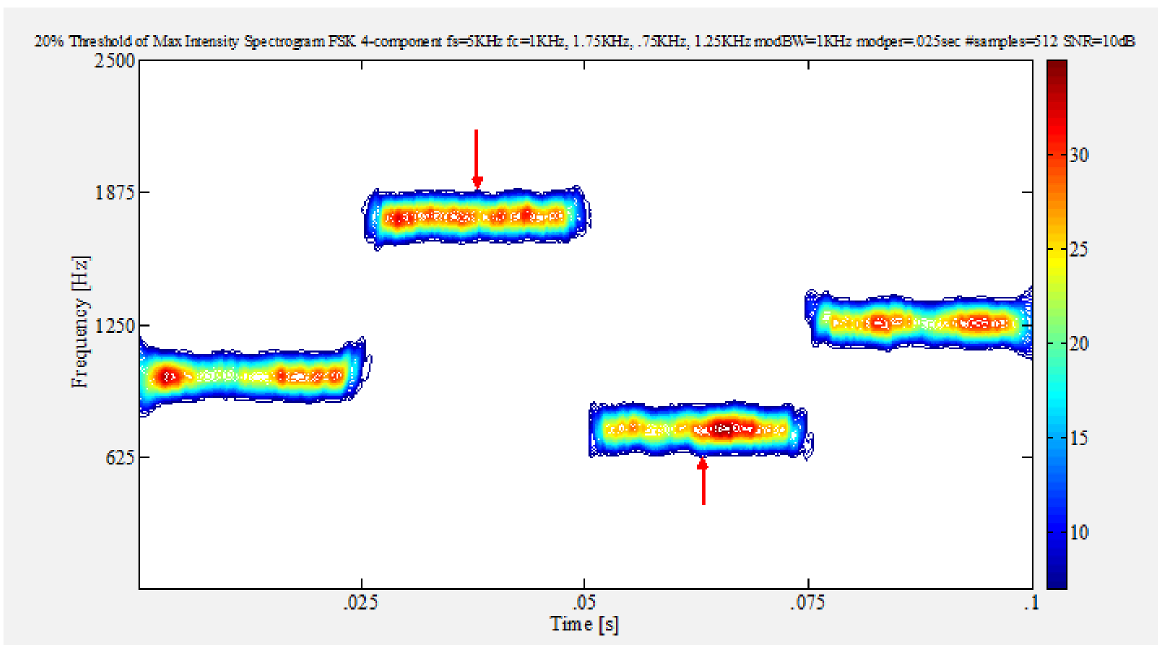

Figure 4: Modulation bandwidth determination. This plot is a time vs. frequency (x-y view) of the spectrogram of a 4 component frequency hopping signal (512 samples, SNR=10dB) with threshold value automatically set to 20%. From this threshold plot, the modulation bandwidth was measured manually from the highest frequency value of the signal (top red arrow) to the lowest frequency value of the signal (bottom red arrow) in the y-direction (frequency).

Modulation period: From Figure 5 (which is at a threshold of 20% maximum intensity), the modulation period is the manual measurement of the width of each of the 4 frequency hopping signals in the x-direction (time), and then the average of the 4 signals is calculated.

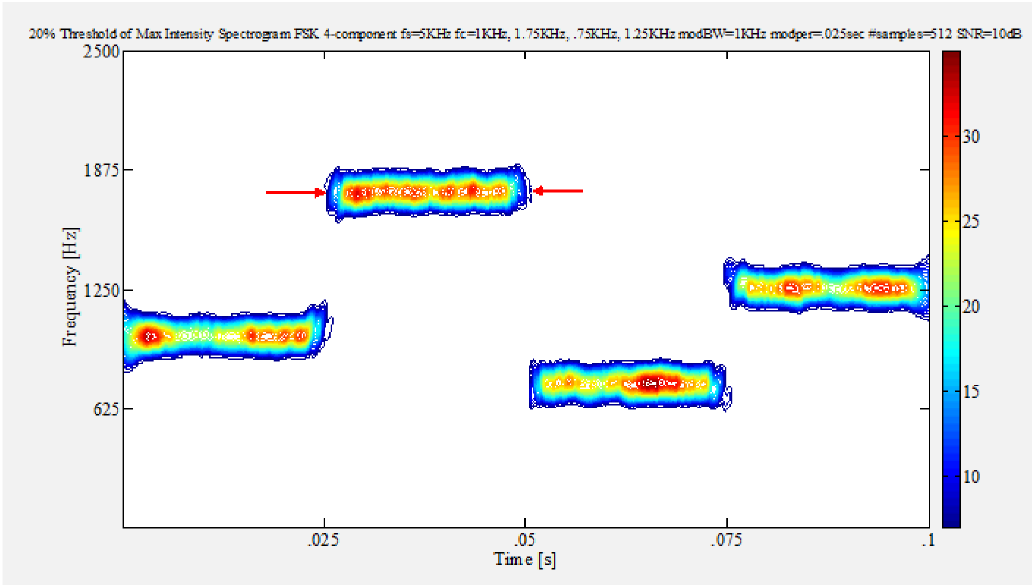

Figure 5: Modulation period determination. This plot is a time vs. frequency (x-y view) of the spectrogram of a 4 component frequency hopping signal (512 samples, SNR=10dB) with threshold value automatically set to 20%. From this threshold plot, the modulation period was measured manually from the left side of the signal (left red arrow) to the right side of the signal (right red arrow) in the x-direction (time). This was done for all 4 signal components, and the average value was determined.

Time-frequency localization: From Figure 6, the time-frequency localization is a manual measurement (at a threshold of 20% maximum intensity) of the 'thickness' (in the y-direction) of the center of each of the 4 frequency hopping signal components, and then the average of the 4 values are determined. The average frequency 'thickness' is then converted to: percent of the entire y-axis.

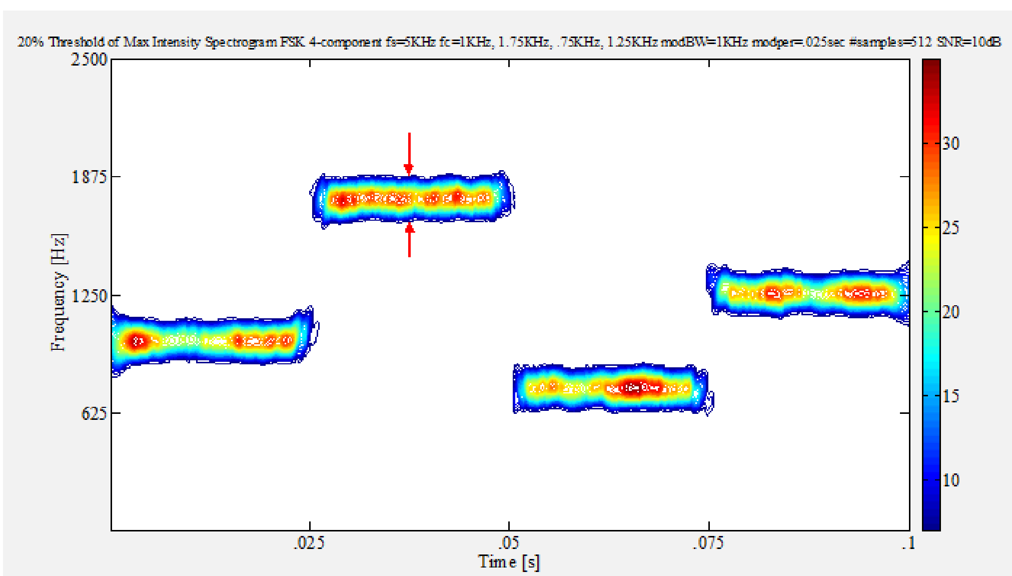

Figure 6: Time-frequency localization determination. This plot is a time vs. frequency (x-y view) for the spectrogram of a 4 component frequency hopping signal (512 samples, SNR=10dB) with threshold value automatically set to 20%. From this threshold plot, the time-frequency localization was measured manually from the top of the signal (top red arrow) to the bottom of the signal (bottom red arrow) in the y-direction (frequency). This frequency 'thickness' value was then converted to: % of entire y-axis.

Lowest detectable SNR: The lowest SNR level at which at least a portion of each of the signal components exceeded the set threshold listed in the percent detection section above.

For lowest detectable SNR determination, these threshold values were included in the time-frequency plot algorithms so that the thresholds could be applied automatically during the plotting process. From the threshold plot, the signal was declared a detection if any portion of each of the signal components was visible. The lowest SNR level for which the signal was declared a detection is the lowest detectable SNR (see Figure 7).

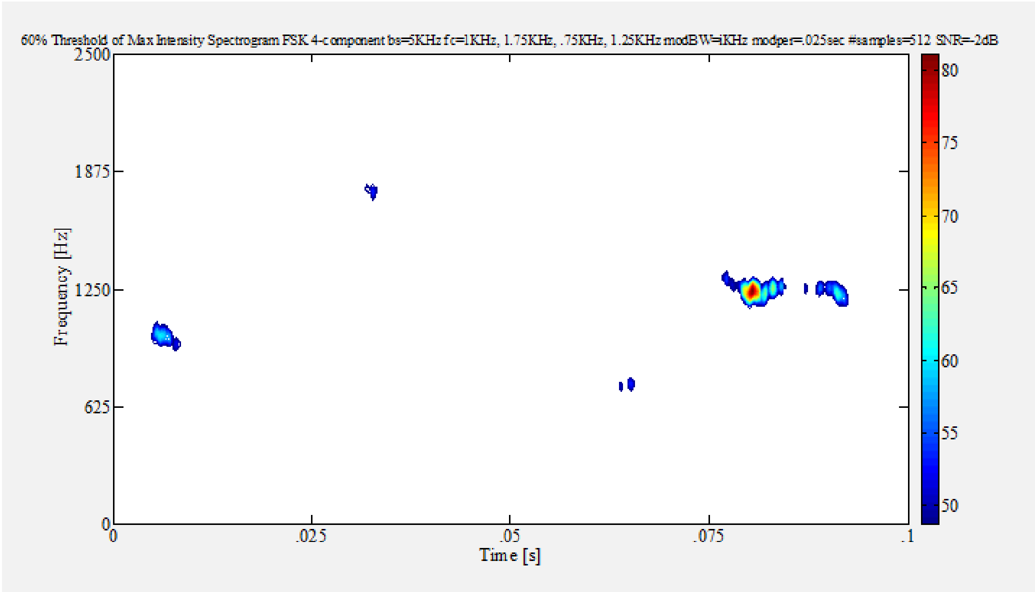

Figure 7: Lowest detectable SNR. This plot is a time vs. frequency (x-y view) of the spectrogram of a 4 component frequency hopping signal (512 samples, SNR=-2dB) with threshold value automatically set to 60%. From this threshold plot, the signal was declared a (visual) detection because at least a portion of each of the 4 frequency hopping signal components was visible. Note that the average lowest detectable SNR for the spectrogram was determined to be -2.7dB. Compare to Figure 2, which is the same plot, except that it has an SNR level equal to 10dB.

The data from all 100 runs for each test was used to produce the actual, error, and percent error for each of these metrics listed above.

The metrics from the spectrogram were then compared to the metrics from the reassigned spectrogram. By and large, the reassigned spectrogram outperformed the spectrogram, as will be shown in the results section.

III. Results

Table 1 presents the overall test metrics for the signal processing analysis techniques used in this testing (spectrogram versusre assigned spectrogram).

Table 1: Overall test metrics (average percent error: carrier frequency, modulation bandwidth, modulation period, time-frequency localization-y; average: percent detection, lowest detectable snr, plot time) for spectrogram versusreassigned spectrogram.

Parameters	Spectrogram	Reassigned spectrogram
carrier frequency	0.93%	0.74%
modulation bandwidth	25.70%	10.82%
modulation period	11.84%	9.30%
time-frequency localization-y	9.09%	4.05%
percent detection	67.24%	86.84%
lowest detectable snr	-2.7db	-3.5db
plottime	4.72s	7.62s

From Table 1, the reassigned spectrogram outperformed the spectrogram in average percent error: carrier frequency (0.74% vs. 0.93%), modulation bandwidth (10.82% vs. 25.70%), modulation period (9.30% vs. 11.84%), and time-frequency localization (y-direction) (4.05% vs. 9.09%);and in average: percent detection (86.84% vs. 67.24%), and lowest detectable SNR (-3.5db vs. -2.7db), while the spectrogram outperformed the reassigned spectrogram in average plot time (4.72s vs. 7.62s).

Figure 8 shows comparative plots of the spectrogram vs. the reassigned spectrogram (4 component frequency hopping) at SNRs of 10dB (top), 0dB (middle), and -3dB (bottom).

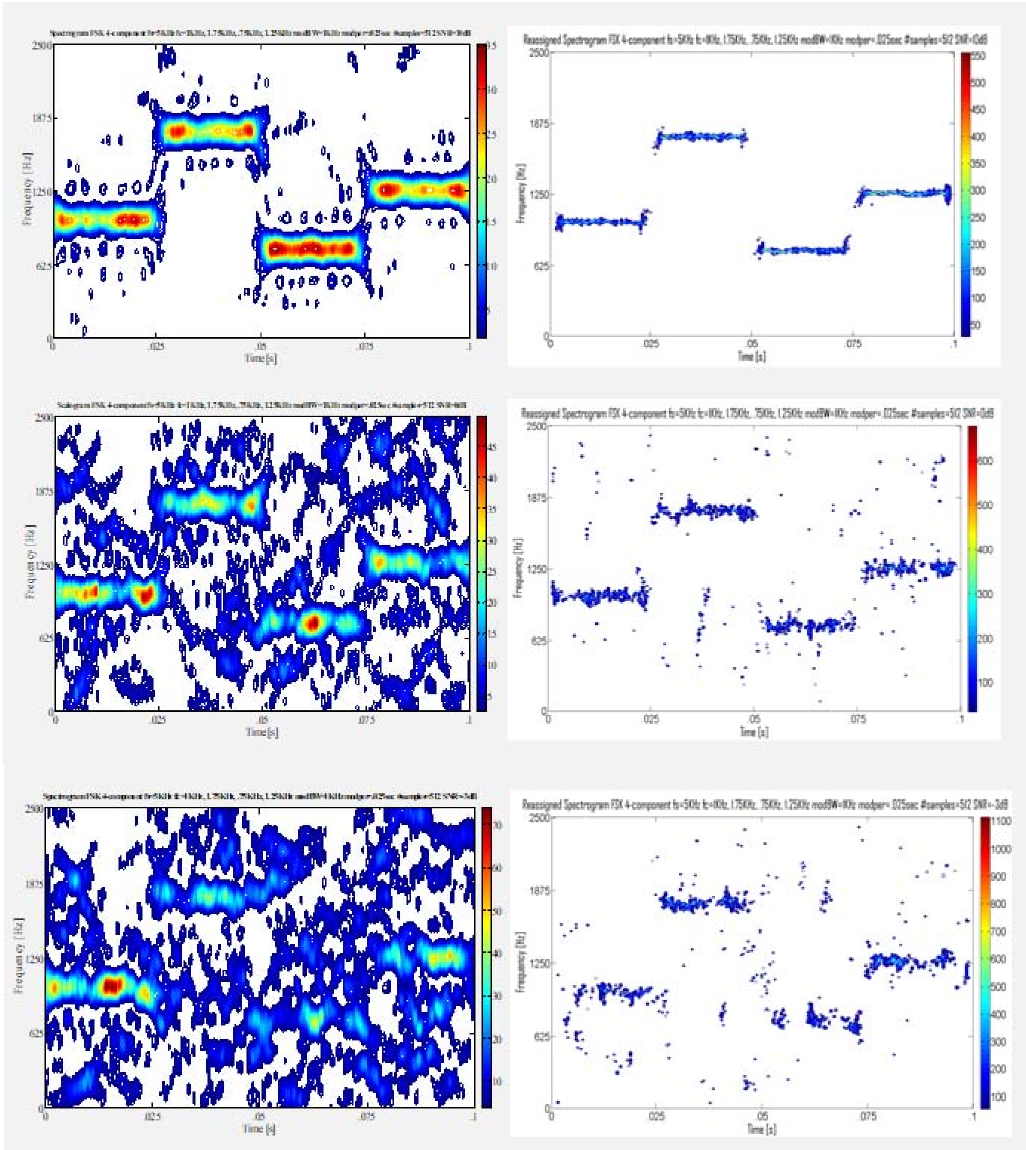

Figure 8: Comparative plots of the 4 component frequency hopping low probability of intercept radar signals (spectrogram (left-hand side) vs. the reassigned spectrogram (right-hand side)). The SNR for the top row is 10dB, for the middle row is 0dB, and for the bottom row is -3dB. In general, the reassigned spectrogram signals appear more localized ('thinner') than do the spectrogram signals. In addition, the reassigned spectrogram signals appear more readable than the spectrogram signals at every SNR level.

IV. Discussion

This section will elaborate on the results from the previous section.

From Table 1, the performance of the spectrogram and the reassigned spectrogram will be summarized, including strengths, weaknesses, and generic scenarios in which each particular signal analysis tool might be used.

The spectrogram outperformed the reassigned spectrogram in average plot time (4.72s vs 7.62s). However, the spectrogram was outperformed by the reassigned spectrogram in every other category. The spectrogram's extreme reduction of cross-term interference is grounds for its good plot time, but at the expense of signal localization (i.e. it produces a 'thicker' signal (as is seen in Figure 8) – due to the trade-off between cross-term interference and signal localization). This poor signal localization ('thicker' signal), coupled with the reassigned spectrogram's 'squeezing' quality, can account for the spectrogram being outperformed by the reassigned spectrogram in the areas of: average percent error of modulation bandwidth, modulation period, time-frequency localization (y-direction), lowest detectable SNR, and percent detection. Note that average percent detection and lowest detectable SNR are both based on visual detection in the time-frequency representation. Figure 8 clearly shows that the signals in the reassigned spectrogram plots are more readable than those in the spectrogram plots, which accounts for the reassigned spectrogram's better average percent detection and lowest detectable SNR. The spectrogram might be used in a scenario where a short plot time is necessary, but where accurate parameters are not as vital. Such a scenario might be a 'quick and dirty' check to see if a signal is present, without accurate extraction of its parameters. The reassigned spectrogram might be used in a scenario where you need accurate parameters, in a low SNR environment, in a quick time frame.

V. Conclusions

Digital intercept receivers, whose main job is to detect and extract parameters from low probability of intercept radar signals, are currently moving away from Fourier-based analysis and towards classical time-frequency analysis techniques, such as the spectrogram, for the purpose of analyzing low probability of intercept radar signals. Based on the research performed for this paper (the novel direct comparison of the spectrogram versus the reassigned spectrogram for the signal analysis of low probability of intercept frequency hopping radar signals) it was shown that the reassigned spectrogram by-and-large outperformed the spectrogram in analyzing these low probability of intercept radar signals - for reasons brought out in the discussion section above. More accurate characterization metrics could well translate into saved equipment and lives.

Future plans include analysis of additional low probability of intercept radar waveforms, using additional time-frequency analysis and reassignment method techniques.

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A Signal Conditioner System for Mems based Magnetic Field Sensors using Arduino

By Enoch Tetteh Amoatey, Henry Kwame Atiglah & Daniel Krah
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Abstract- Sensors have become useful in many areas of our contemporary lives and also in industries, where they are largely used for measuring physical quantities for the purposes of analysis or control. The use of sensors is essential in areas such as industrial automation, robotics, environmental control, household appliances, agriculture, medicine, among other areas. Magnetic fields generated by the brain or heart are very useful in clinical diagnoses, so the magnetic signals produced by others Organs are also of great interest hence the need to condition the measured output of magnetic field sensors. The objective of this work is to realize a signal conditioning system for a magnetic field sensor based on MEMS technology. We achieve this by feeding sinusoidal signals to the magnetic field sensor using the Arduino system to obtain a linear response. The linear response is then conditioned by a MEMS signal conditioning system. We finally transmit the conditioned signal to a system receiver wirelessly, which will be visualized.

Keywords: *magnetic field sensors, MEMS, arduino, linear response and signal conditioning.*

GJRE-F Classification: *FOR Code: 090699*

ASIGNALCONDITIONERSYSTEMFORMEMSBASEDMAGNETICFIELDSENSORSUSINGARDUINO

A Signal Conditioner System for Mems based Magnetic Field Sensors using Arduino

Enoch Tetteh Amoatey [α], Henry Kwame Atiglah [σ] & Daniel Krah [ρ]

Abstract- Sensors have become useful in many areas of our contemporary lives and also in industries, where they are largely used for measuring physical quantities for the purposes of analysis or control. The use of sensors is essential in areas such as industrial automation, robotics, environmental control, household appliances, agriculture, medicine, among other areas. Magnetic fields generated by the brain or heart are very useful in clinical diagnoses, so the magnetic signals produced by others Organs are also of great interest hence the need to condition the measured output of magnetic field sensors. The objective of this work is to realize a signal conditioning system for a magnetic field sensor based on MEMS technology. We achieve this by feeding sinusoidal signals to the magnetic field sensor using the Arduino system to obtain a linear response. The linear response is then conditioned by a MEMS signal conditioning system. We finally transmit the conditioned signal to a system receiver wirelessly, which will be visualized.

Keywords: magnetic field sensors, MEMS, arduino, linear response and signal conditioning.

I. Introduction

A measurement or control system is made up of the acquisition of information gathered by a sensor or transducer, the processing of the said information and presentation of results, so that they can be perceived and interpreted by the human observer [1]. There are generally six types of signals in the field of engineering namely mechanical, thermal, magnetic, electrical, optical and molecular (chemical). In this paper, signal measurements are made using a MEMS (Microelectromechanical Systems) based magnetic field sensor. Magnetic field sensors are used in areas of medicine, telephony mobile, steel industry, automotive industry, GPS navigation, among other areas. A Microelectromechanical System (MEMS) is a device with dimensions of small microns that incorporate electrical and mechanical components. Hence, MEMS are used to reduce size, save energy consumption and decrease the cost of magnetic field sensors [2].

In this paper we analyze and test a magnetic field sensor based on MEMS technology with an Arduino board which will be used to power and acquire the signal generated by the sensor along with an electronic system designed to condition the acquired signal so that it can be measured linearly. The Transmission of the conditioned signal will be carried out wirelessly.

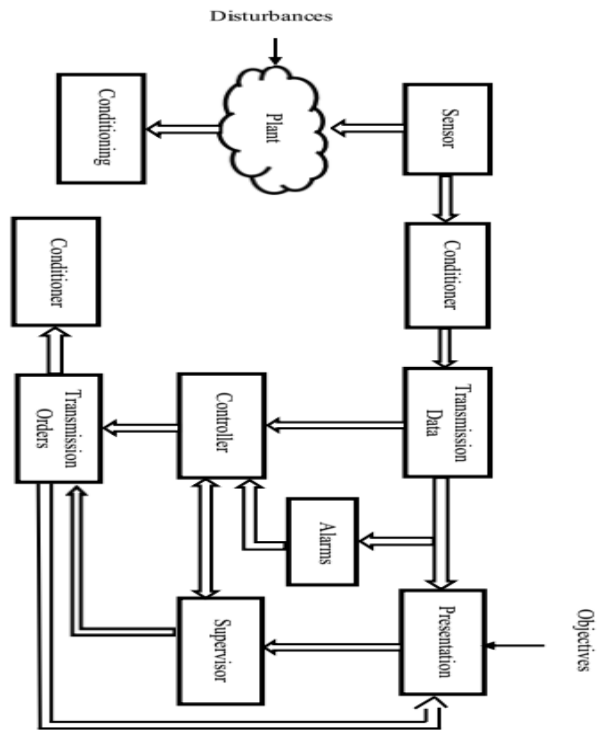

Fig. 1: General structure of a measurement and control system [1]

II. Magnetic Field Sensors

Magnetic field sensors are devices in which a physical quantity can produce an alteration of a magnetic field or an electric field, without a change in inductance or capacitance. These sensors detect magnetic fields caused by magnets or electrical currents.

The strength of a magnetic field can be measured using different types of techniques with each technique having unique properties that make it more suitable for specific applications. These applications can range from sensing the presence of any change in the magnetic field, to accurately measure the scalar and vector properties of a magnetic field. Magnetic field sensors can be divided into two types:

- Vector component.
- Scalar Magnitude.

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Vector type sensors can be divided into sensors that are used to measure Low Field (< 1mT) and High Field (> 1mT). The instruments that measure low fields are commonly known as magnetometers, and Instruments that measure high fields are usually referred to as Gaussimeters.

a) MEMS Technology Based Sensor

The MEMS sensor detects the flux density of a magnetic field using the Lorentz force as shown in Figure 2. It has a resonant structure of 700 x 600 x 5 μm, with a rectangular circuit, four flexible silicon beams and an arrangement of longitudinal and transverse silicon beams. The resonant structure is attached to a silicon substrate through two beams of torsion (60 x 40 x 5 μm). The MEMS sensor also contains a jumper Wheatstone bridge with four p-type piezoresistors, two of them are positioned on flexible beams and the other two on the surface of the silicon substrate [3]. The MEMS sensor operates with the Lorentz force, which is generated by the interaction between a magnetic flux density and an excitation current sinusoidal through an aluminum circuit, as shown in Figure 3. The magnetic flux density is applied in the longitudinal direction of the resonant structure [3]. The Lorentz force is amplified when the resonant structure operates at its first resonant frequency. This causes a longitudinal deformation in the two piezoresistors located on the flexible beams, causing the initial resistances to change. This generates a variation in the voltage output of the Wheatstone bridge. Consequently, the electrical voltage signal from the bridge becomes proportional to the magnetic flux density applied to the MEMS sensor [4].

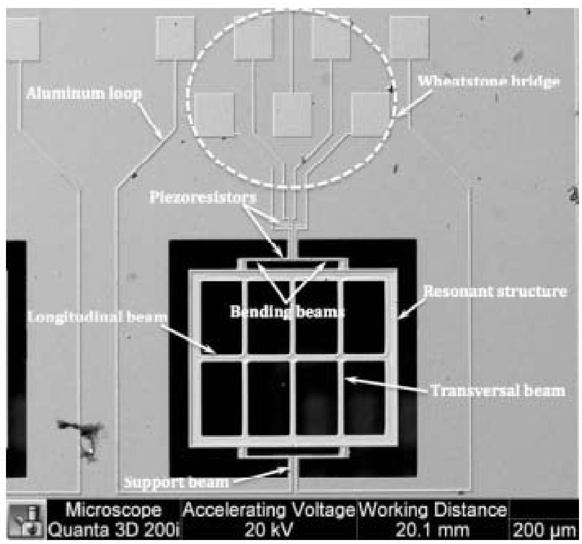

Fig. 2: MEMS magnetic field sensor

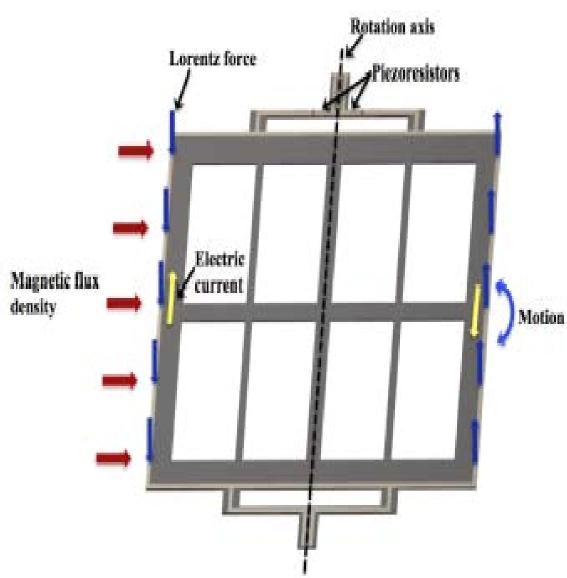

Fig. 3: Main operation of the MEMS magnetic field sensor [3]

b) Sensor Signal Conditioning

Signal conditioners are measuring elements that offer from an output signal of an electrical sensor, a signal suitable for displayed or used in a later process. The functions of signal conditioners are: filtering, amplification, modulation and demodulation, and impedance matching.

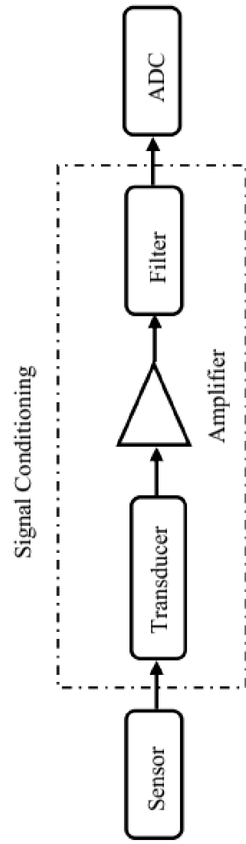

Fig. 4: Signal conditioning

A filter is a device that separates the signals according to their frequency or other criteria. The filter can be located at the input or intermediate stage. When the filter is located in the input stage, it can be of electrical, mechanical, pneumatic, thermal, or electromagnetic type. When the filter is located in an intermediate stage, it is normally of the electrical type.

An amplifier is a device that, by using energy, magnifies the amplitude of a phenomenon. For this purpose, amplifiers used are mainly operational amplifiers with some key characteristics such as:

- High input resistance (hundreds of MΩ).
- Low output resistance (below 1Ω).
- Large open loop gain (104 to 106).
- Large CMRR (common mode rejection ratio) (Gd / Gc).
- Good range of operating frequencies.
- Low sensitivity to variations in the power supply.
- Great stability at ambient temperature change.

Modulation is a set of techniques for transporting information over a carrier wave, normally sine. This allows for a better use of the communication channel transmitting more information simultaneously and protecting it from noise and interference.

Demodulation as its name indicates, is the reverse of modulation. It is the set of techniques to recover the information carried on a carrier wave. So in any telecommunication there will always be at least one modulator-demodulator pair.

The objective of impedance matching is for maximum transfer of power to exist so that all the energy sent by the source are received by powered devices. If the source has an impedance less than connected device, it is required to place resistance equal to the impedance of the source in parallel with the high impedance device.

III. System Design

a) Sensor Feed

The sensor is powered by two signals, one with a frequency of 1 KHz and the other with a frequency of 14.376 KHz. At these frequencies, the sensor has a response with a linear behavior within a range of 40 μT to 2000 μT. To generate these signals, the Arduino Nano

Global Journal of Researches in Engineering (F) Volume XX Issue IV Version I Year 2020

board is used. Arduino is selected mainly because it works with a quartz crystal, which has a great advantage of stability in frequency and phase.

The Arduino Nano board has 6 pins that provide PWM (Pulse-width modulation) output. PWM or pulse width modulation is a technique that is used to simulate a variable analog output to obtain a digital output. The resulting signal is a square wave, and its great feature is that the duration can be varied with a pulse when it is positive or 5 volts. However, this variation does not affect the duration between each pulse and cycle, which means that the signal frequency remains the same. Figure 5 shows the general PWM representation scheme. The importance of PWM in this work is fundamental, since using this technique seeks to generate the square and sinusoidal signals required by the MEMS sensor. The Arduino Nano is initially programmed to generate the PWM signal at a frequency of 490Hz. It is generated at this frequency because it is the default frequency for PWM on pin D9 of the Arduino. The signal generation is done using software through the programming of the ATMega328 chip incorporated in the Arduino Nano board.

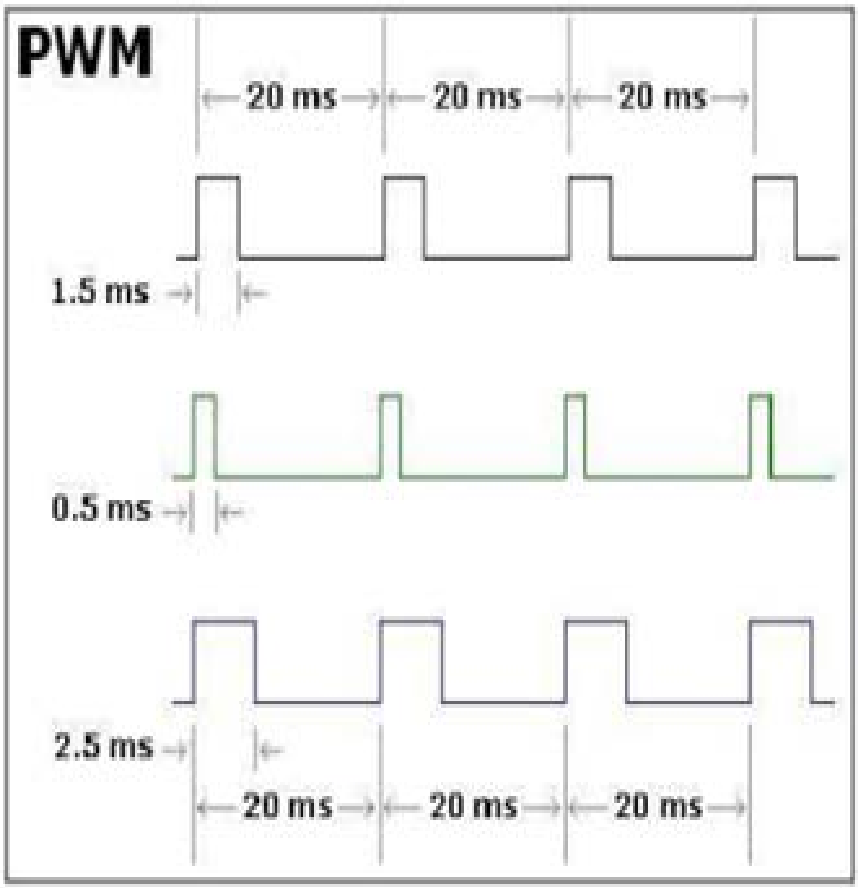

Fig. 5: PWM (Instructable) General Representation

b) Arduino Connection to Mems Sensor

In comparing the sinusoidal and square signals, a better resolution and precision is observed in square signals, as they are closer to the desired frequencies and in this case, they do not have distortion like the sinusoidal signals. Taking this into account, the MEMS sensor is powered with the 1 KHz and 14.376 KHz square signals. The Arduino output pins for the 1 KHz and 14.376 KHz signals are the pins 6 and 12 respectively. The 1 KHz signal connects to the MEMS sensor on pin 4 and the 14.376 KHz signal connects on pin 5. The connection of the Arduino to the MEMS sensor is shown in Figure 6. The output signal from the MEMS sensor is in the order microvolts therefore we use an amplifier to obtain a signal in the order of millivolts.

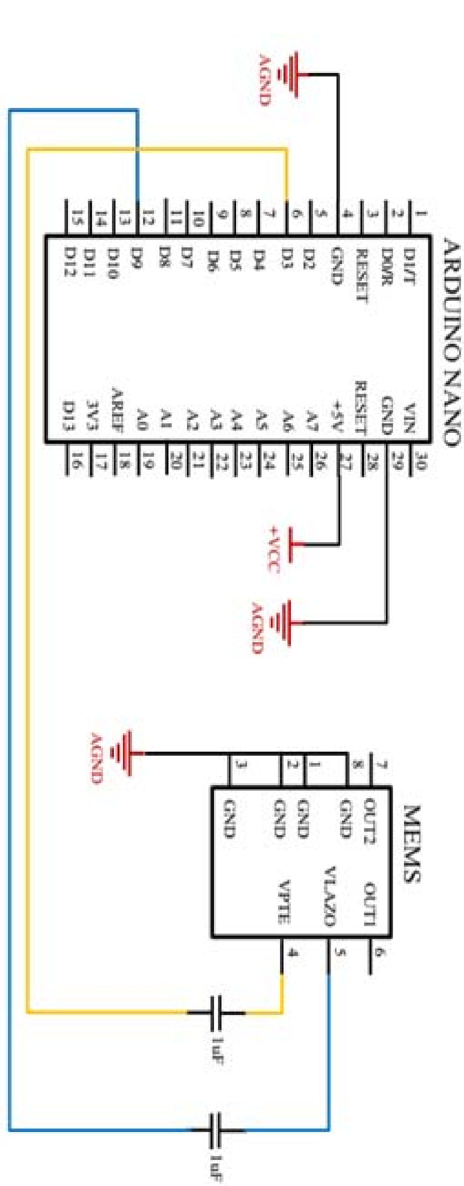

Fig. 6: Connection diagram for signal amplification of the MEMS sensor

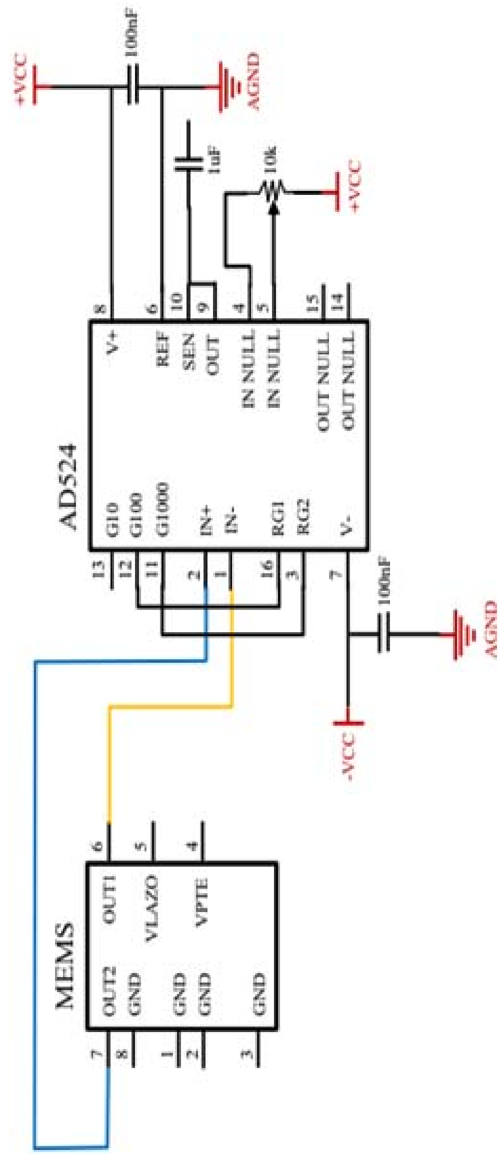

Fig. 7: Connection diagram for signal amplification of the MEMS sensor

c) *Amplification of the Mems Sensor Signal*

For the amplification stage of the output signal of the MEMS sensor, the AD524 integrated circuit, which is an instrumentation amplifier designed for high precision data acquisition applications is used. This amplifier has three programmable gain pins of 10, 100, and 1000. It operates with a supply voltage range of ± 6V to ± 18V. The frequency of operation is 25MHz so the output signal is not distorted with respect to the input signal. The programmable pins of the amplifier are 13, 12 and 11 for gains of 10, 100 and 1000 respectively. For the amplification of the MEMS sensor signal a gain of 1000 is needed per what pin 11 of the amplifier is used. The circuit connection of the amplification of the MEMS sensor signal is shown in Figure 7.

d) *Demodulation of the Amplified Signal*

To demodulate the signal generated by the instrumentation amplifier, the AD630 integrated circuit is used. This integrated circuit allows demodulation of a signal at a high speed and precision. The AD630 operates with a supply voltage range of ± 5V to ± 18V. The frequency of operation is approximately 350 KHz, hence the signal output is not distorted with respect to the input signal. The connection scheme for the demodulation of the amplified sensor signal MEMS is shown in Figure 8.

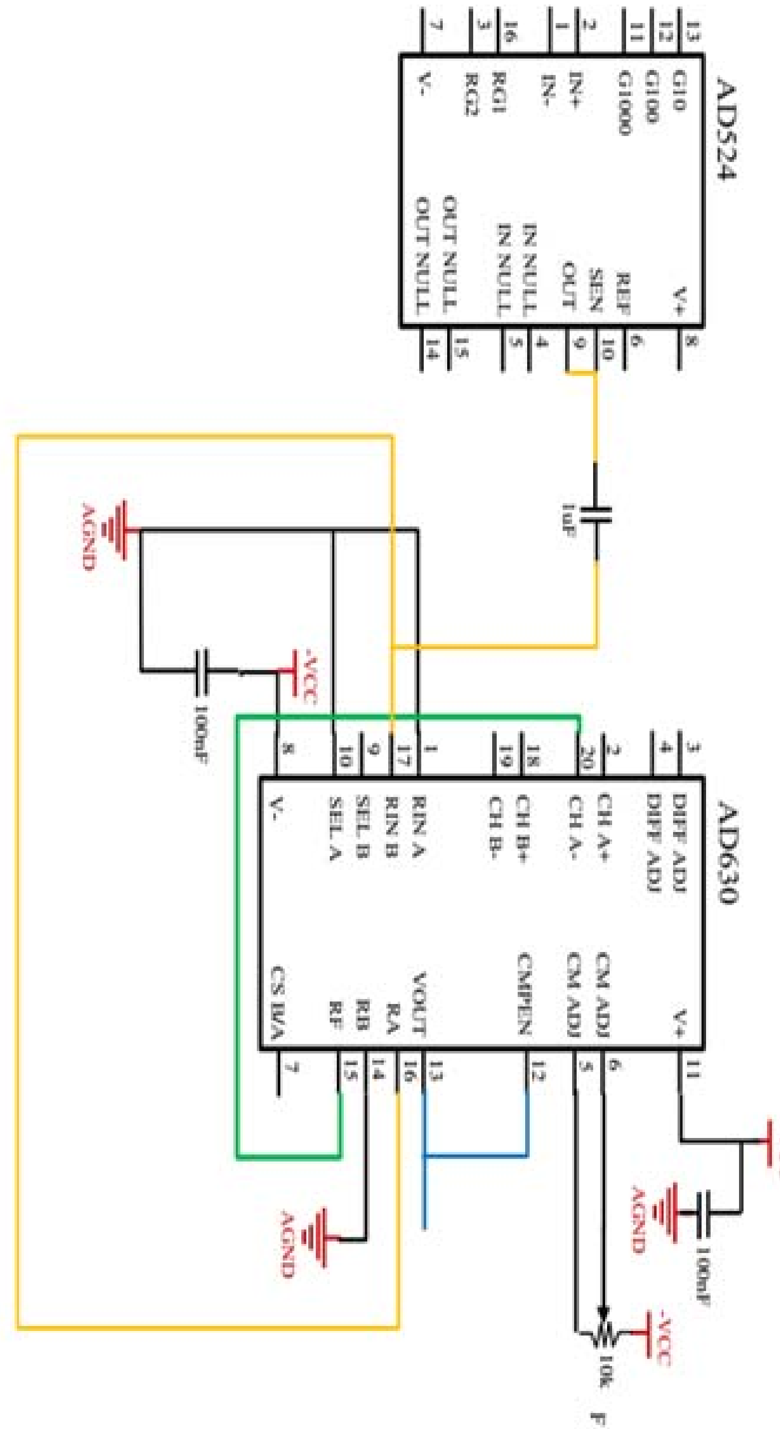

Fig. 8: AD630 Amplifier Connection Diagram

e) Filtering the Demodulated Signal

The AD630's output signal connects to a third-order low-pass filter to eliminate noise in the signal, leaving the connection diagram as shown in Figure 9. The output from the third order low pass filter is the ultimate signal of the system and the desired signal to be visualized and analyzed with a computer.

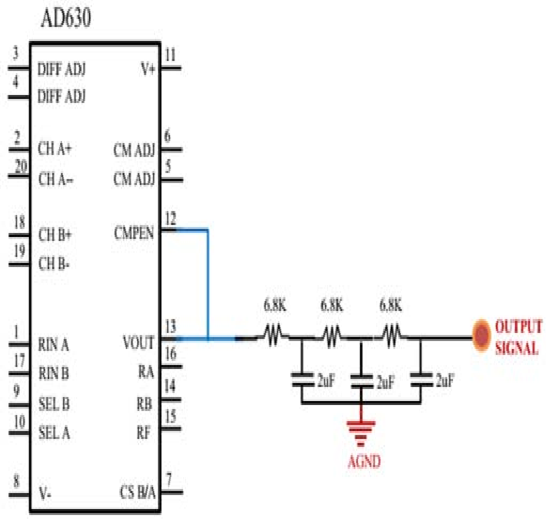

Fig. 9: Filter circuit of demodulated signal

IV. Results

Figure 10 shows the experimental setup used for the characterization of the signal conditioning system inside an environmental chamber along with the virtual instrument, which can be run on a computer connected to the PCI-DAS6031 data acquisition card.

Fig. 10: Experimental Test

The electrical response of the sensor to atmospheric pressure is obtained experimentally using a Helmholtz coil to apply magnetic densities of -150 μT to +150 μT. For this test the signal conditioning system of the magnetic field sensor is inserted into an environmental chamber in order to maintain a controlled temperature of 26 °C. The sensor is placed in the center of the Helmholtz coil, where the magnetic field density is homogeneous. The bridge Wheat stone's sensor is powered with 1 kHz signal and aluminum loop with 14.376 signal is fed at a current of 20mA. From the virtual instrument the output voltage of the system could be measured electronically using the data acquisition card.

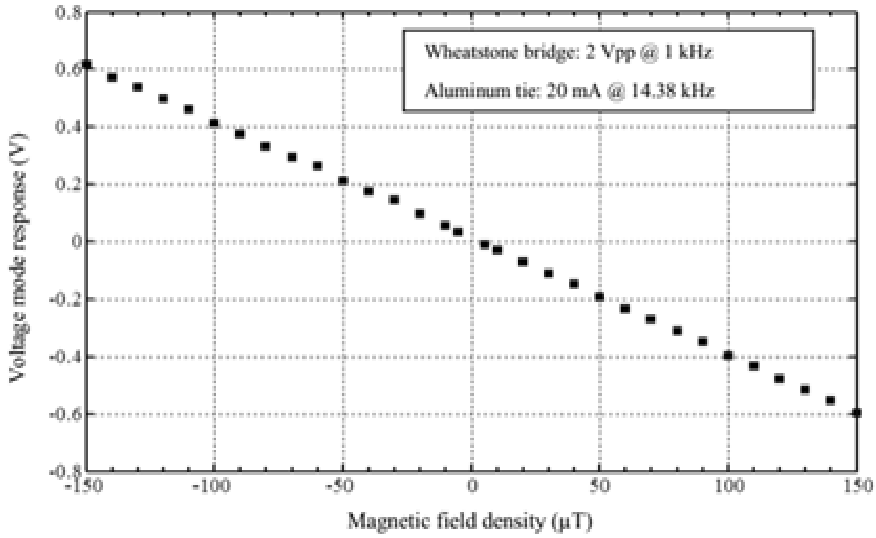

Fig. 11: Graph of the output signal

V. Conclusion

Because the MEMS sensor generates a very small output signal, in the microvolt scale, it is necessary to amplify this signal to obtain one that is on the millivolt scale. For this stage of amplification, we search an amplifier that works with a supply voltage of 9volts to use a single power supply for the entire electronic system. The signal amplified by the AD524 is a modulated signal, so it is necessary to undertake a signal demodulation step to recover the source signal from the amplified signal. For this, a demodulator is sought, like the other devices which operates on a 9volt supply voltage. When testing the demodulator, it is observed that there was curl in the demodulated signal. Due to this, a further stage of filtering the signal to eliminate noise in it becomes necessary. For the filtering stage, a third order low pass filter was designed. When passing the signal demodulated by this filter the unwanted ripple in the signal is removed, obtaining an expected analog signal.

As can be seen in the previous points, an improvement in the design of the signal acquisition system of a magnetic field sensor based on MEMS technology has been successful by a decrease in electronic components on the motherboard, as well as lower consumption of energy, changing the 15volts power supply for a 9volts is enough to power the Arduino board and other components.

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Grey Wolf Optimizer Applied to Dynamic Economic Dispatch Incorporating Wind Power

By Hardiansyah Hardiansyah
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Keywords: gray wolf optimizer, dynamic economic dispatch, wind power, ramp rate limits, valve-point effects.

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I. Introduction

The electric power system is one of the most vital needs in human life. The demand for electricity continues to increase causing electricity to be supplied by power plants to be very large. On the other hand renewable energy sources are the deciding factors in industrial development that can improve people's living standards. In addition, technological advances and developments have also contributed greatly to increasing electricity demand. Power system planning, power system management, and distribution of power system are required to meet consumer demand for an increase in the quantity and quality of electric power produced. Improving the quality of electric power is also very influential in increasing the efficiency and reliability of the system. Optimization of generator scheduling in the electric power system is very necessary, because the generation and distribution process in the electric power system requires a very large cost. Coordination between power plants is needed in an effort to optimize generator scheduling to get the minimum cost. Dynamic economic dispatch (DED) is the change in real-time load on an electric power system. The DED is a development of conventional ED involving ramp rate parameters. DED is used to determine the economic distribution of generating units within a certain timeframe of the generating units. The parameter to be considered is transmission losses. In fact, the distribution of electrical power to the load always causes power losses on the transmission line, therefore, transmission losses need to be calculated so that the generator can generate power that can meet the load requirements by considering the transmission loss. In general, the cost function for each generator is represented by a quadratic function, and the valve-point effect is ignored in solving the DED problem. If the DED problem includes the valve-point effect, then the problem becomes a non-convex optimization problem with non-convex characteristics, which introduces difficulties in finding global optimal solutions [1-3].

Renewable energy is energy resource that comes from sustainable natural processes, such as energy from wind energy, solar energy, hydropower, biomass and geothermal energy. Renewable energy began to attract the attention of people and policy makers as an alternative energy resource after the world oil crisis in 1973. The use of renewable energy then rapidly developed when the United Nations Framework Convention on Climate Change (UNFCCC) was formed by the United Nations as a movement to reduce gas greenhouse. This institution continues to consistently voice the shift towards environmentally friendly energy through the Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs) issued by the United Nations. Climate change is currently a major concern of the world community due to its effect which causes an unnatural rise in world temperatures. The main cause of climate change is electricity production activities which are dominated by coal-fired power plants and natural gas power plants which account for around 30% of total gas emissions that cause global warming. Wind energy is a clean and rapidly growing renewable energy resources. They have shown great prospects in decreasing fuel consumption as well as reducing pollutants emission. However, the expected wind power is difficult to predict accurately, primarily due to the intermittent nature of the wind speed, coupled with the highly non-linear wind energy conversion. In order to adjust unforeseeable nature of the wind power, planned productions and uses in electricity market must be improved during the real operation of the power system. Due to the intermittent

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characteristic of wind power, DED is very suited for formulate the problem of optimal scheduling of generating units by including wind power. Several related studies have been conducted to overcome the problem of ED and DED by including renewable energy sources to the power system [4-11].

Over the past few years, a number of approaches have been developed to solve this DED problem using mathematical programming, namely, the lambda iteration method, linear programming, quadratic programming and the gradient projection method [12-14]. Most of the methods that have been applied do not apply to non-convex or non-smooth cost functions. Many heuristic optimization techniques known such as genetic algorithms (GA), simulated annealing (SA), differential evolution (DE), particle swarm optimization (PSO), artificial bee colony (ABC) algorithm, hybrid evolutionary programming (EP) and sequential quadratic programming (SQP), deterministically guided PSO, hybrid PSO and SQP, hybrid seeker optimization algorithm and sequential quadratic programming (SOA-SQP), imperialist competitive algorithm (ICA), hybrid harmony search (HHS) algorithm, artificial immune system (AIS), and glowworm swarm optimization (GSO) have been successfully used to solve the DED problems [15-28].

More recently, a new meta-heuristic search algorithm, called Gray Wolf Optimizer (GWO) [29], has no affinity for sticking to local optimal points in complex multimodal optimization problems and which provides a more diverse search of space the solution. The GWO is based on gray wolf behavior. Better optimal solutions with lower computational loads can be found at GWO compared to the stochastic search techniques mentioned above. In this paper, the GWO algorithm has been applied to solve the DED problem considering wind power. The performance of the proposed approach has been demonstrated in the 5-unit and 10-unit generating systems. The results obtained from the proposed algorithm are compared with other optimization results reported in the literature. The comparison shows that the proposed GWO-based approach provides the best solution in terms of minimum production cost and power loss.

II. Problem Formulation

The objective of DED problem is to find the optimal schedule of output powers of online generating units with predicted power demands over a certain period of time to meet the power demand at minimum operating cost.

The objective function of the DED problem is,

$$F_T = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{i,t}(P_{i,t}) = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i\right) \quad (1)$$

$$\text{for } i = 1,2,\cdots,N;\ t = 1,2,\ldots,T$$

where $F_{i,t}$ (in \$/h) is the operating cost of ith unit at time interval t, a_i, b_i, and c_i are the cost coefficients of generating ith unit, $P_{i,t}$ (in MW) is the real power output of generating ith unit at time period t, and N is the number of generators. T is the total number of hours in the operating horizon. The fuel cost function of ith unit with valve-point effects is represented as follows [9, 21, 22]:

$$F_T = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(\begin{array}{l}(a_i P_{i,t}^2 + b_i P_{i,t} + c_i) + \\ \left|e_i \times \sin\left(f_i \times \left(P_{i,\min} - P_{i,t}\right)\right)\right|\end{array}\right) \quad (2)$$

where F_T (in \$/h) is total operating cost of generation including valve point loading, e_i and f_i are fuel cost coefficients of ith unit reflecting valve-point effects.

The fuel cost is minimized subjected to the following constraints:

a) Power Balance

For power balance, an equality constraint should be satisfied. The total generated power should be the same as total load demand plus the total line loss.

$$\sum_{i=1}^{N}\left(P_{i,t} + P_{w,t}\right) = P_{D,t} + P_{L,t} \quad (3)$$

where $P_{w,t}$ is power output of wind farm at time interval t; $P_{D,t}$ is the load demand at time interval t; $P_{L,t}$ is the transmission loss at time interval t that can be represented using the B-coefficients:

$$P_{L,t} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{i,t} B_{ij} P_{j,t} \quad (4)$$

where B_{ij}, is the loss-coefficient matrix.

b) Generation Limits

Generation output of each generator should lie between minimum and maximum limits. The corresponding inequality constraint for each generator is

$$P_{i,\min} \le P_{i,t} \le P_{i,\max} \quad (5)$$

where $P_{i,\,min}$ and $P_{i,\,max}$ are the minimum and maximum capacity of unit i, respectively.

c) Ramp Rate Limits

The actual operating ranges of all on-line units are restricted by their corresponding ramp rate limits. The ramp-up and ramp-down constraints can be written as (6) and (7), respectively.

$$P_{i,t} - P_{i,t-1} \le R_{i,up} \quad (6)$$

$$P_{i,t-1} - P_{i,t} \le R_{i,down} \quad (7)$$

where $P_{i,t}$ and $P_{i,t-1}$ are the present and previous power outputs, respectively. $R_{i,up}$ and $R_{i,down}$ are the ramp-up and ramp-down limits of unit i.

To consider the ramp rate limits and power output limits constraints at the same time, therefore, equations (5), (6) and (7) can be rewritten as follows:

$$\max\{P_{i,\min}, P_{i,t-1} - R_{i,down}\} \le P_{i,t} \le \min\{P_{i,\max}, P_{i,t-1} + R_{i,up}\} \tag{8}$$

III. Grey Wolf Optimizer

Grey Wolf Optimizer (GWO) is a new population based meta-heuristic algorithm proposed by Mirjalili et al. in 2014 [29]. The grey wolves mostly like to live in a pack and one of the most important features is their very strict social hierarchy. The main leader of the pack is called alpha. The alpha wolf is the most predominant wolf in the pack as his/her orders were followed by rest of the pack. The alpha wolf is one of the most important members in terms of managing the pack.

The second important one is called beta. They are also known as sub-ordinate wolves as they help alpha in their respective work. They act as advisor to alpha and commander to the rest of the wolves in the pack. The third one are called delta. They submitted themselves to the alphas and betas but dominate the omegas. The fourth one which are lower ranking wolves are called omega. They have to submit themselves to all other members in the pack.

In another important thing among the grey wolves is their hunting mechanism which includes tracking, chasing, encircling and harassing the prey until they stop moving. Then they attack the prey. The mathematical model of this model is discussed as following.

a) Social Hierarchy

In order to mathematically model the social hierarchy of wolves when designing GWO that would consider the first fitness solution as alpha (α), the second best solution as beta (β), and the third best solution as delta (δ). The rest of the solutions are assumed as omega (ω). The hunting mechanism is decided by α, β, and δ, and the ω wolves have to follow them.

b) Encircling Prey

As the grey wolves encircle prey during the hunt, so their mathematical model which represents their encircling behavior is discussed as below:

$$\vec{D} = \left|\vec{C}\cdot\vec{X}_p(t) - \vec{X}_w(t)\right| \tag{9}$$

$$\vec{X}_w(t+1) = \vec{X}_p - \vec{A}\cdot\vec{D} \tag{10}$$

where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_p$ is the position of prey and $\vec{X}_w$ is the position of grey wolf.

The vector $\vec{A}$ and $\vec{C}$ are given as:

$$\vec{A} = 2\vec{a}\cdot\vec{r}_1 - \vec{a} \tag{11}$$

$$\vec{C} = 2\vec{r}_2 \tag{12}$$

where $\vec{r}_1$, $\vec{r}_2$ are random vector between 0 to 1, and value of $\vec{a}$ is linearly decreased from 2 to 0. The grey wolf can update their position according to equation (9) and (10).

c) Hunting

As we know that the grey wolf firstly recognizes the prey and then encircles them to hunt. The hunt is usually decided by alpha and beta, delta also participate in hunting occasion. So mathematically in the hunting procedure we take alpha, beta and delta as the best candidate solution and omega have to update its position according to the best search agent. The mathematical model for hunting is shown below:

$$\vec{D}_\alpha = \left|\vec{C}_1\cdot\vec{X}_\alpha - \vec{X}(t)\right| \tag{13}$$

$$\vec{D}_\beta = \left|\vec{C}_2\cdot\vec{X}_\beta - \vec{X}(t)\right| \tag{14}$$

$$\vec{D}_\delta = \left|\vec{C}_3\cdot\vec{X}_\delta - \vec{X}(t)\right| \tag{15}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1\cdot\vec{D}_\alpha \tag{16}$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2\cdot\vec{D}_\beta \tag{17}$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3\cdot\vec{D}_\delta \tag{18}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{19}$$

where $\vec{X}_\alpha$ is the position of the alpha, $\vec{X}_\beta$ is the position of the beta, $\vec{X}_\delta$ is the position of the delta, $\vec{C}_1, \vec{C}_2, \vec{C}_3$, $\vec{A}_1$, $\vec{A}_2$, and $\vec{A}_3$ are all random vectors, $\vec{X}$ is the position of the current solution, and t is the iteration number.

d) Search for Prey

As we know that the grey wolves finishes their hunt by attacking the prey. In mathematical model we have $\vec{A}$ is a random variable having values in the interval [-2*a*, 2*a*] where *a* is decreased from 2 to 0 over the course of iterations. When the random value of $\vec{A}$ are in [-1, 1] then the next position of search agent is between its current position and position of prey. The pseudo code of the GWO algorithm is presented in Figure 1.

```
Initialize the grey wolf population X_i (i=1, 2, ..., n)
Initialize a, A, and C
Calculate the fitness of each search agent
X_α = the best search agent
X_β = the second best search agent
X_δ = the third best search agent
while (t < Max number of iterations)
    for each search agent
        Update the position of the current search agent by equation (19)
    end for
    Update a, A, and C
    Calculate the fitness of all search agents
    Update X_α, X_β, and X_δ
    t=t+1
end while
Return X_α
```

Fig. 1: Pseudo code of GWO algorithm [29]

IV. Simulation Results

In order to demonstrate the performance of the GWO algorithm, two testing systems consisting of a 5-unit and 10-unit generating system with non-smooth cost functions are taken into account. The GWO algorithm is implemented in MATLAB 2016a on a Pentium IV personal computer with a processor speed of 3.6 GHz and 4 GB RAM. The time horizon for scheduling is one day divided into 24 periods every one hour. The iteration performed for each test case is 1000 for the 5-unit system and 500 for the 10-unit system; and the number of search agents (population) taken in both test cases is 30.

a) Test System 1

In this section a 5-unit system is tested considering the valve-point effects, the ramp rate limits, and transmission losses. All technical data generating units are given in Appendix, which is taken from [16]. The optimal dispatch of real power for the given scheduling horizon using the proposed GWO algorithm is given in Table 1. Figure 2 shows the convergence characteristic of GWO technique for DED problem. The comparison results between the proposed GWO algorithm and other methods are shown in Table 2. It is clear that the proposed GWO algorithm has achieved lower minimum production cost.

Table 1: Optimal scheduling of 5-unit systems obtained from GWO

H	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	Cost ($)	Ploss (MW)
1	27.4519	98.5642	112.6621	124.9061	50.0400	1290.9632	3.6243
2	40.8780	20.6864	112.6565	124.8953	139.7611	1377.0230	3.8773
3	10.0011	93.0222	112.4978	124.6033	139.6305	1390.6017	4.7549
4	60.1566	98.3944	112.6397	124.8896	139.7547	1585.5829	5.8351
5	10.0244	88.7822	112.0767	124.8338	228.9681	1617.1250	6.6853
6	50.1727	98.5283	112.7020	124.9175	229.5269	1781.1620	7.8474
7	73.6823	98.4360	112.6268	209.7858	139.7856	1784.5556	8.3165
8	12.3970	98.7988	112.6697	209.8054	229.5890	1798.0200	9.2598
9	49.5491	98.5680	112.6757	209.7783	229.5974	1978.6326	10.1685
10	72.2391	20.0936	112.6555	209.8019	300.0000	2135.0457	10.7901
11	74.9901	22.4924	123.6426	210.0779	300.0000	2244.7025	11.2030
12	74.9978	124.6737	112.6965	209.7741	229.5776	2180.7454	11.7197
13	64.1287	98.5337	112.5886	209.8145	229.4943	1997.0867	10.5597
14	49.6763	98.5417	112.6029	209.7535	229.5338	1978.2501	10.1681
15	12.4498	98.6583	112.8169	209.8146	229.5189	1797.7365	9.2584
16	21.4368	98.5737	112.7391	124.9316	229.5195	1654.7180	7.2007
17	11.9769	83.8383	30.9181	208.9142	229.6487	1660.5675	7.2962
18	42.6229	21.2725	112.7108	209.8011	229.5037	1797.6510	7.9110
19	12.5602	98.5976	112.7763	209.8092	229.5146	1797.6550	9.2580
20	64.1452	98.4801	112.6121	209.8090	229.5131	1997.1149	10.5595
21	54.9786	20.3704	174.9802	209.8063	229.4998	2086.0725	9.6354
22	47.2316	98.4822	112.6528	124.8810	229.5265	1773.6759	7.7741
23	56.9070	98.5339	112.6500	124.9057	139.7739	1581.7362	5.7705
24	10.0019	80.8739	112.2489	124.8239	139.5408	1423.0320	4.4894
Total cost & losses						42709.4563	193.9628

Table 2: Comparative results for 5-unit test system

Method	Fuel cost ($)	Method	Fuel cost ($)
SA [16]	47356	APSO [25]	44678
DE [17]	43213	ICA [25]	43117.05
PSO [19]	50124	HHS [26]	43154.8554
ABC [20]	44045.83	GSO [28]	43414.12
AIS [25]	44385.43	GWO	42709.4563

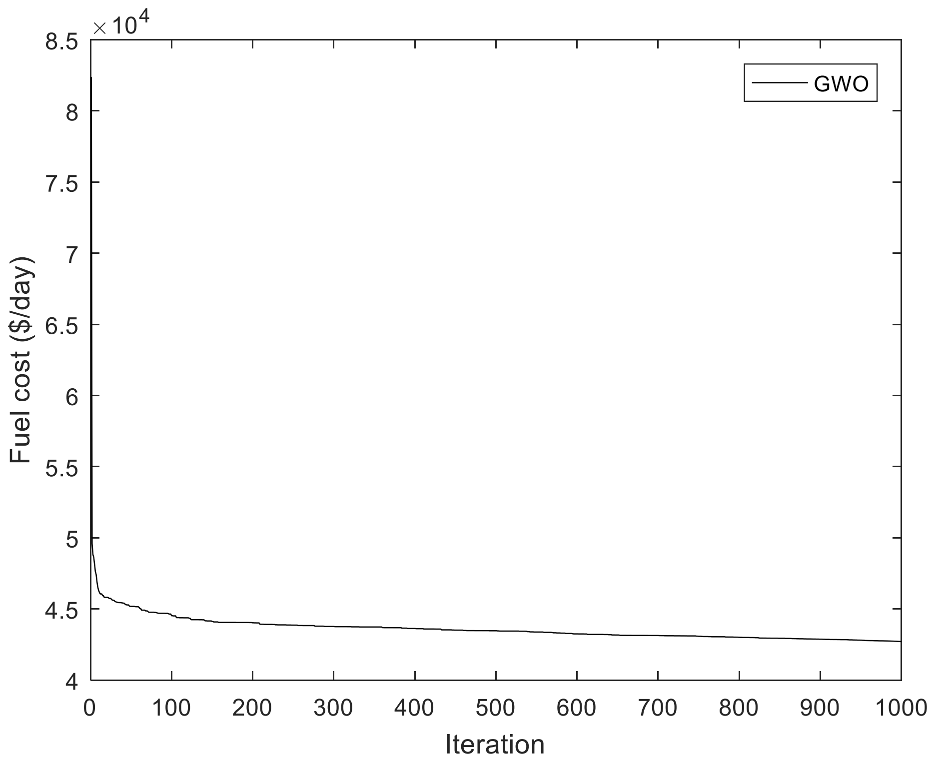

Fig. 2: Cost convergence characteristics of GWO for 5-unit test system

b) Test System 2

In this section a 10-unit system is tested considering the valve-point effects, the ramp rate limits, and transmission losses. All technical data generating units are adopted from [30], as given in Appendix. The optimal dispatch of real power for the given scheduling horizon using proposed GWO algorithm is given in Table 3. Table 4 shows hourly production cost and power loss obtained from GWO algorithm. Figure 3 shows the cost convergence characteristic of GWO technique for 10-unit system. The comparison of different methods with the proposed GWO algorithm in terms of the best cost is given in Table 5. Clearly from the results, the proposed GWO algorithm produces a higher quality solution in terms of minimum production costs.

Table 3: Optimal scheduling of 10-unit systems obtained from GWO

H	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6 (MW)	P7 (MW)	P8 (MW)	P9 (MW)	P10 (MW)
1	150.0153	135.1646	81.6951	78.1106	171.7151	157.6784	130.0000	120.0000	21.1887	10.0431
2	150.0339	135.0000	88.1448	99.2764	210.5885	159.5589	130.0000	120.0000	21.5715	18.2262
3	150.0220	135.4325	145.4896	143.4040	242.7314	160.0000	130.0000	120.0000	48.7274	10.6402
4	150.0218	136.1829	226.6413	212.9782	243.0000	160.0000	130.0000	120.0000	39.1587	23.4546
5	150.0237	138.2234	262.7324	217.9014	242.8597	160.0000	129.9846	119.7323	75.2897	22.6374
6	150.1772	137.9471	320.9046	288.3540	243.0000	160.0000	129.9051	119.9520	77.8772	47.9230
7	150.3891	176.5578	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
8	180.7688	225.6316	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
9	248.3704	318.1951	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
10	312.8586	415.6121	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
11	350.0713	460.0000	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
12	432.0750	460.0000	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000

13	314.6123	413.8516	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
14	247.1493	319.4191	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
15	182.6077	223.7909	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
16	150.1035	137.3010	286.1571	251.9220	243.0000	160.0000	130.0000	119.8981	77.9175	41.2532
17	150.1917	137.3060	250.0038	231.4954	243.0000	159.6602	130.0000	120.0000	74.2053	23.4837
18	150.0677	135.7610	309.1457	297.1537	242.6610	160.0000	130.0000	120.0000	77.0148	54.2051
19	181.5973	224.8022	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
20	311.5092	416.9671	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
21	247.4667	319.1009	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
22	150.0866	135.3409	325.0350	279.1528	243.0000	160.0000	130.0000	120.0000	79.0925	54.3389
23	150.0059	135.6498	181.6116	171.6901	241.5650	160.0000	130.0000	120.0000	53.0420	20.2331
24	150.0738	135.9606	115.9187	113.7158	238.7687	132.5843	130.0000	119.9900	43.2199	29.2336
Total cost ($) = 2463046.3595; Total losses (MW) = 1314.9416										

Table 4: Hourly production cost and power loss obtained from GWO

H	Cost ($)	Ploss (MW)	H	Cost ($)	Ploss (MW)
1	60618.6976	19.6109	13	141137.7122	84.4640
2	64038.9120	22.4001	14	121076.9722	70.5684
3	71273.7775	28.4469	15	104451.0947	58.3985
4	79124.4204	35.4374	16	87490.3301	43.5525
5	83318.3071	39.3846	17	83283.8259	39.3461
6	91979.1098	48.0402	18	91920.5131	48.0091
7	97395.8194	52.9469	19	104451.0565	58.3995
8	104451.4185	58.4004	20	141139.6650	84.4762
9	121076.9983	70.5655	21	121076.9045	70.5676
10	141138.1957	84.4707	22	91902.9362	48.0466
11	152498.7538	92.0713	23	75066.7055	31.7975
12	165433.1451	100.0750	24	67701.0884	25.4654

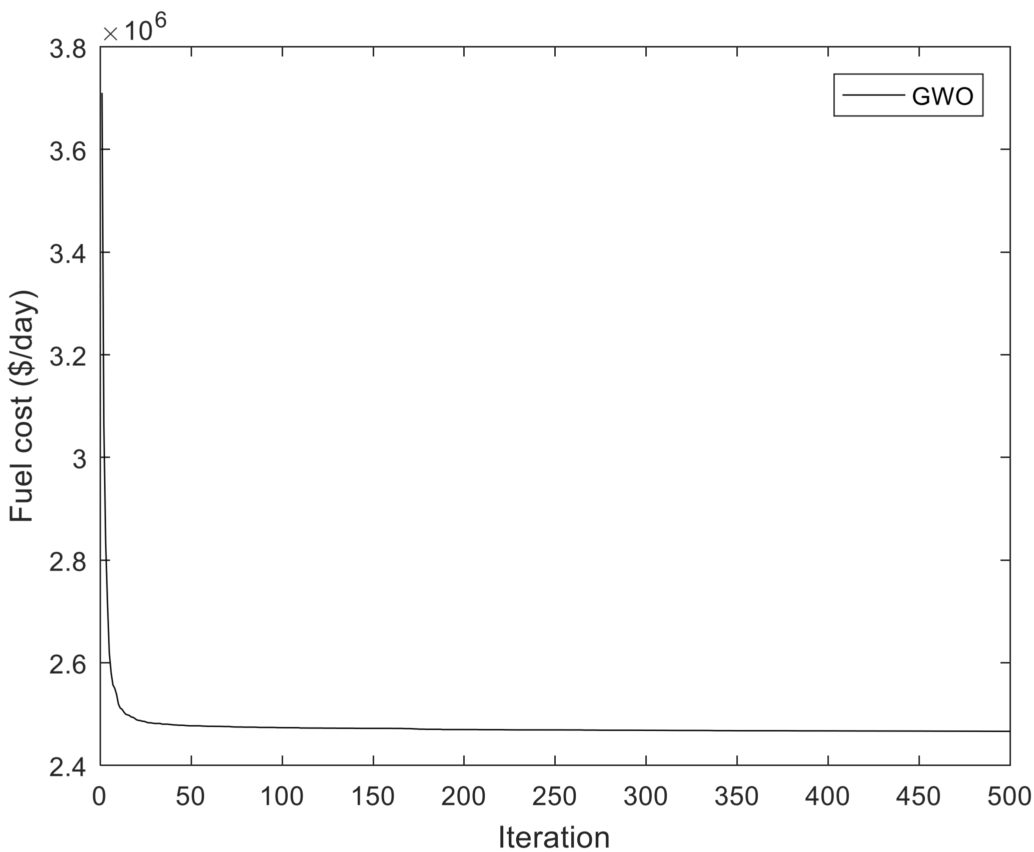

Fig. 3: Cost convergence characteristics of GWO for 10-unit test system

Table 5: Comparative results for 10-unit test system

Method	Fuel cost ($)
GA [27]	2596847.38
PSO [27]	2580148.25
MBFA [27]	2544523.21
AIS [27]	2500684.32
GWO	2463046.3595

c) DED with wind power

In testing the following system, wind power connected to the network is considered. The total installed capacity of wind power connected to the network is 100 MW, with a total of 50 wind turbines [11]. The best results obtained from the proposed GWO technique for the DED model without and with wind power are summarized in Table 6. The cost convergence characteristics of the DED model with wind power for the two systems are shown in Figures 4 and 5, respectively.

To realize the rationality of the integration of wind power into the power system, the comparison results of the two DED models are presented in Table 6. From Table 6, it can be seen that when compared to the DED model without wind power for the 5-unit system, the savings in operating costs per day are obtained 2780.5154 $ and transmission losses reduced by 25.7935 MW (down 13.2982%). For the 10-unit system, the operating cost savings per day were 128069.3605 $ and transmission losses were reduced by 121.0233 MW (9.2037% decrease).

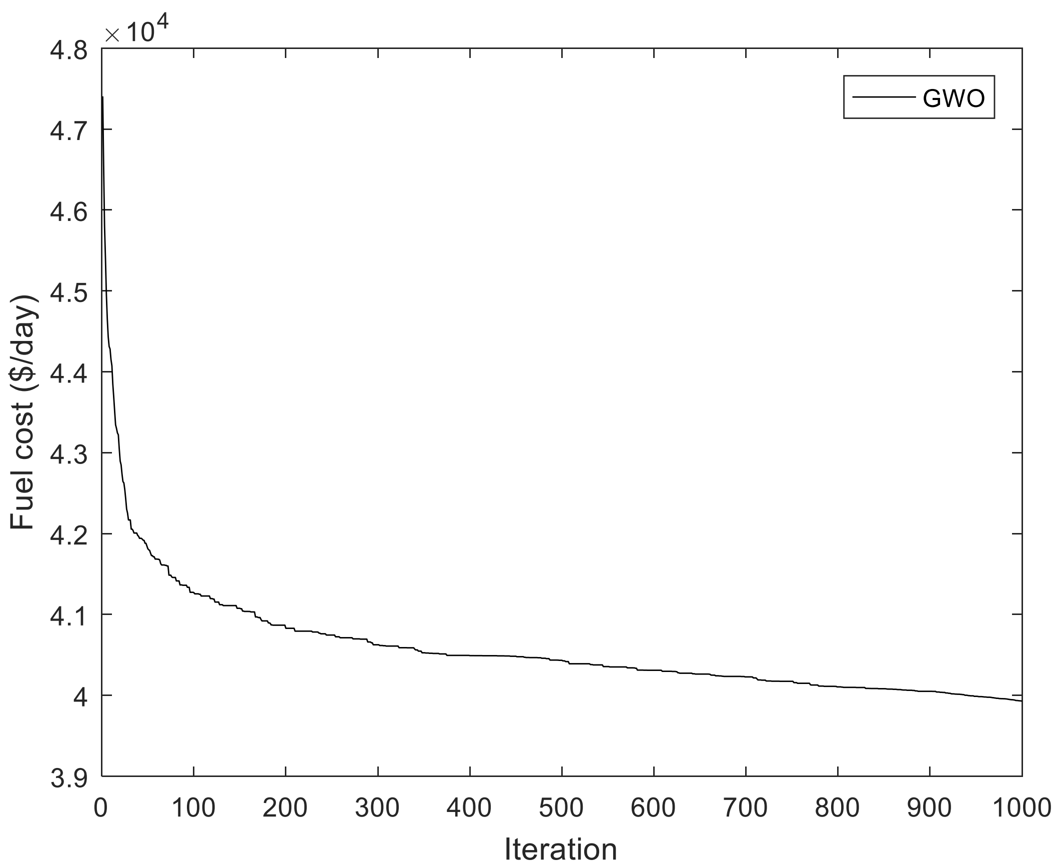

Fig. 4: Cost convergence characteristics of GWO for 5-unit test system with wind power

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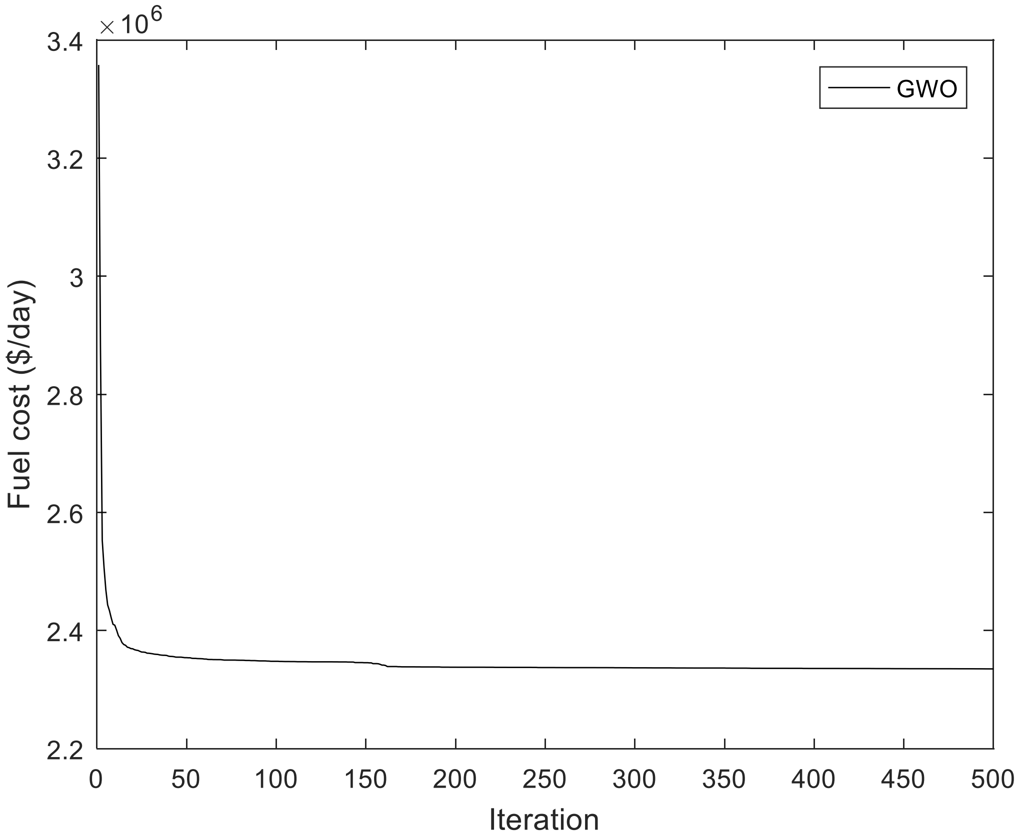

Fig. 5: Cost convergence characteristics of GWO for 10-unit test system with wind power

Table 6: Comparison results of two DED models

Models	5-unit system		10-unit system	
	Fuel cost ($)	Ploss (MW)	Fuel cost ($)	Ploss (MW)
DED without wind power	42709.4563	193.9628	2463046.3595	1314.9416
DED with wind power	39928.9419	168.1693	2334976.9990	1193.9183

V. Conclusion

This paper has successfully applied the GWO algorithm to solve the DED problem. Different constraints such as the valve-point effects, ramp rate limits, and transmission loss are taken into consideration to solve the DED problem without and with wind power. The feasibility of the proposed method was demonstrated with 5-unit and 10-unit generating system and compared with other optimization methods reported in the literature. The results obtained show that the GWO algorithm has a much better performance in terms of minimum production cost. The main advantage of the proposed GWO algorithm is the good ability to find the best solution.

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Appendix

Table A-1: Data for the 5-unit system

Unit	$P_{i,min}$ (MW)	$P_{i,max}$ (MW)	$R_{i,up}$ (MW/h)	$R_{i,down}$ (MW/h)	a_i ($/MW²hr)	b_i ($/MWhr)	c_i ($/hr)	e_i ($/hr)	f_i (rad/MW)
1	10	75	30	30	0.0080	2.0	25	100	0.042
2	20	125	30	30	0.0030	1.8	60	140	0.040
3	30	175	40	40	0.0012	2.1	100	160	0.038
4	40	250	50	50	0.0010	2.0	120	180	0.037
5	50	300	50	50	0.0015	1.8	40	200	0.035

Table A-2: B-loss coefficients (5-unit system)

$$B_{ij} = \begin{bmatrix} 0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000020 \\ 0.000014 & 0.000045 & 0.000016 & 0.000020 & 0.000018 \\ 0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 \\ 0.000015 & 0.000020 & 0.000010 & 0.000040 & 0.000014 \\ 0.000020 & 0.000018 & 0.000012 & 0.000014 & 0.000035 \end{bmatrix}$$

Table A-3: Load demand for 24 hours (5-unit system)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	410	7	626	13	704	19	654
2	435	8	654	14	690	20	704
3	475	9	690	15	654	21	680
4	530	10	704	16	580	22	605
5	558	11	720	17	558	23	527
6	608	12	740	18	608	24	463

Table A-4: Generating unit capacity and fuel cost coefficients (10-unit system)

Unit	$P_{i,min}$ (MW)	$P_{i,max}$ (MW)	$R_{i,up}$ (MW/h)	$R_{i,down}$ (MW/h)	a_i ($/MW²hr)	b_i ($/MWhr)	c_i ($/hr)	e_i ($/hr)	f_i (rad/MW)
1	150	470	80	80	0.1524	38.5397	786.7988	450	0.041
2	135	470	80	80	0.1058	46.1591	451.3251	600	0.036
3	73	340	80	80	0.0280	40.3965	1049.9977	320	0.028
4	60	300	50	50	0.0354	38.3055	1243.5311	260	0.052
5	73	243	50	50	0.0211	36.3278	1658.5692	280	0.063
6	57	160	50	50	0.0179	38.2704	1356.6592	310	0.048
7	20	130	30	30	0.0121	36.5104	1450.7045	300	0.086
8	47	120	30	30	0.0121	36.5104	1450.7045	340	0.082
9	20	80	30	30	0.1090	39.5804	1455.6056	270	0.098
10	10	55	30	30	0.1295	40.5407	1469.4026	380	0.094

Table A-5: Load demand for 24 hours (10-unit system)

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	1036	7	1702	13	2072	19	1776
2	1110	8	1776	14	1924	20	1972
3	1258	9	1924	15	1776	21	1924
4	1406	10	2022	16	1554	22	1628
5	1480	11	2106	17	1480	23	1332
6	1628	12	2150	18	1628	24	1184

Table A-6: Transmission loss coefficients (10-unit system) [xx]

$$B_{ij} = 10^{-5} \times \begin{bmatrix} 4.9 & 1.4 & 1.5 & 1.5 & 1.6 & 1.7 & 1.7 & 1.8 & 1.9 & 2.0 \\ 1.4 & 4.5 & 1.6 & 1.6 & 1.7 & 1.5 & 1.5 & 1.6 & 1.8 & 1.8 \\ 1.5 & 1.6 & 3.9 & 1.0 & 1.2 & 1.2 & 1.4 & 1.4 & 1.6 & 1.6 \\ 1.5 & 1.6 & 1.0 & 4.0 & 1.4 & 1.0 & 1.1 & 1.2 & 1.4 & 1.5 \\ 1.6 & 1.7 & 1.2 & 1.4 & 3.5 & 1.1 & 1.3 & 1.3 & 1.5 & 1.6 \\ 1.7 & 1.5 & 1.2 & 1.0 & 1.1 & 3.6 & 1.2 & 1.2 & 1.4 & 1.5 \\ 1.7 & 1.5 & 1.4 & 1.1 & 1.3 & 1.2 & 3.8 & 1.6 & 1.6 & 1.8 \\ 1.8 & 1.6 & 1.4 & 1.2 & 1.3 & 1.2 & 1.6 & 4.0 & 1.5 & 1.6 \\ 1.9 & 1.8 & 1.6 & 1.4 & 1.5 & 1.4 & 1.6 & 1.5 & 4.2 & 1.9 \\ 2.0 & 1.8 & 1.6 & 1.5 & 1.6 & 1.5 & 1.8 & 1.6 & 1.9 & 4.4 \end{bmatrix}$$

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Acknowledgments

Contributors to the research other than authors credited should be mentioned in Acknowledgments. The source of funding for the research can be included. Suppliers of resources may be mentioned along with their addresses.

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Authors can submit papers and articles in an acceptable file format: MS Word (doc, docx), LaTeX (.tex, .zip or .rar including all of your files), Adobe PDF (.pdf), rich text format (.rtf), simple text document (.txt), Open Document Text (.odt), and Apple Pages (.pages). Our professional layout editors will format the entire paper according to our official guidelines. This is one of the highlights of publishing with Global Journals—authors should not be concerned about the formatting of their paper. Global Journals accepts articles and manuscripts in every major language, be it Spanish, Chinese, Japanese, Portuguese, Russian, French, German, Dutch, Italian, Greek, or any other national language, but the title, subtitle, and abstract should be in English. This will facilitate indexing and the pre-peer review process.

The following is the official style and template developed for publication of a research paper. Authors are not required to follow this style during the submission of the paper. It is just for reference purposes.

Manuscript Style Instruction (Optional)

- Microsoft Word Document Setting Instructions.
- Font type of all text should be Swis721 Lt BT.
- Page size: 8.27" x 11'", left margin: 0.65, right margin: 0.65, bottom margin: 0.75.
- Paper title should be in one column of font size 24.
- Author name in font size of 11 in one column.
- Abstract: font size 9 with the word "Abstract" in bold italics.
- Main text: font size 10 with two justified columns.
- Two columns with equal column width of 3.38 and spacing of 0.2.
- First character must be three lines drop-capped.
- The paragraph before spacing of 1 pt and after of 0 pt.
- Line spacing of 1 pt.
- Large images must be in one column.
- The names of first main headings (Heading 1) must be in Roman font, capital letters, and font size of 10.
- The names of second main headings (Heading 2) must not include numbers and must be in italics with a font size of 10.

Structure and Format of Manuscript

The recommended size of an original research paper is under 15,000 words and review papers under 7,000 words. Research articles should be less than 10,000 words. Research papers are usually longer than review papers. Review papers are reports of significant research (typically less than 7,000 words, including tables, figures, and references)

A research paper must include:

a) A title which should be relevant to the theme of the paper.
b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper's subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

Authors should carefully consider the preparation of papers to ensure that they communicate effectively. Papers are much more likely to be accepted if they are carefully designed and laid out, contain few or no errors, are summarizing, and follow instructions. They will also be published with much fewer delays than those that require much technical and editorial correction.

The Editorial Board reserves the right to make literary corrections and suggestions to improve brevity.

Format Structure

It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.

All manuscripts submitted to Global Journals should include:

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The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

Author details

The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

Keywords

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

Numerical Methods

Numerical methods used should be transparent and, where appropriate, supported by references.

Abbreviations

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

Formulas and equations

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

Tables, Figures, and Figure Legends

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

Figures

Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

Preparation of Eletronic Figures for Publication

Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

For scanned images, the scanning resolution at final image size ought to be as follows to ensure good reproduction: line art: >650 dpi; halftones (including gel photographs): >350 dpi; figures containing both halftone and line images: >650 dpi.

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Tips for Writing a Good Quality Engineering Research Paper

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.

6. Bookmarks are useful: When you read any book or magazine, you generally use bookmarks, right? It is a good habit which helps to not lose your continuity. You should always use bookmarks while searching on the internet also, which will make your search easier.

7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

8. Make every effort: Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

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12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. Use good grammar: Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.

22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.

23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

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Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

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Mistakes to avoid:

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- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

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Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

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Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

INDEX

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