Journal of Engineering and Applied Sciences

MEDWELL PUBLICATIONS SINCE 2000

Design and Performance Investigation of a Low Cost Portable Ventilator for COVID-19 Patients

Mustefa Jibril, Messay Tadese and Nuriye Hassen
School of Electrical and Computer Engineering, Dire Dawa Institute of Technology, Dire Dawa, Ethiopia

Key words: Ventilator, COVID-19, DC motor, proportional integral derivative, full state feedback H_2 controller

Corresponding Author:
Mustefa Jibril
School of Electrical and Computer Engineering, Dire Dawa Institute of Technology, Dire Dawa, Ethiopia

Page No.: 239-244
Volume: 16, Issue 07, 2021
ISSN: 1816-949x
Journal of Engineering and Applied Sciences

Abstract: In this study, the design of a low cost portable ventilator with performance analysis have been done to solve the scarcity of respiratory ventilators for COVID-19 patients. The materials used to build the system are: DC motor, rotating disc and pneumatic piston. The system input is the patient heart beat and the output is volume of air to the patient lung with adjusted breathing rate. This ventilator adjusts the breathing rate to the patient depending on his heart beat rate. The performance analysis of this system have been done using Proportional Integral Derivative (PID) and Full State Feedback H_2 controllers. Comparison of the system with the proposed controllers have been done using a step change and a random change of the patient heart beat and a promising result have been analyzed successfully.

INTRODUCTION

A ventilator is a machine that provides mechanical ventilation by stirring breathable air into and out of the lungs to deliver air to a patient who is physically unable to breathe, or breathing insufficiently. Modern respirator are computerized microprocessor-controlled systems but patients can also be ventilated with a simple, hand-operated bag valve mask. Ventilators are chiefly used in intensive-care medicine, abode care and emergency medication (as standalone units) and in anesthesiology (as a component of an anesthesia systems). Ventilators are sometimes called “respirators”, a term commonly used for them in the 1950s (particularly the “Bird respirator”). However, contemporary hospital and medical dictionary uses the phrase “respirator” to refer to a protective face-mask.Modern respirator are electronically controlled by a small embedded design to allow exact rendering of weight and flow timber to an individual patient's needs. Fine-tuned respirator settings also serve to make freshening more tolerable and comfortable for the patient[1].

MATERIALS AND METHODS

Mathematical modeling of the ventilator: The design of the simple ventilator is shown in Fig. 1. The DC motor rotates the disc at angular displacement theta and this angle is converted to a linear displacement x. This displacement pushes the piston back and forth, so that, the air will be entered to lung and gets out[2].

The mathematical modeling system is shown. The DC motor transfer function between the input voltage and the angular displacement output is simply:

$$G_m(s) = \frac{\theta(s)}{E(s)} = \frac{K_T}{JL_a s^3 + (R_a J + L_a B)s^2 + (R_a B + K_b K_T)s} \quad (1)$$

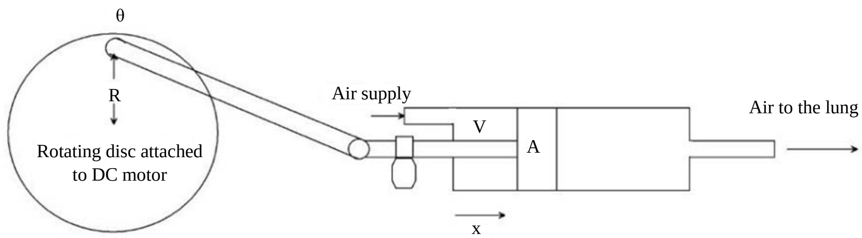

Fig. 1: Respiratory ventilator system design

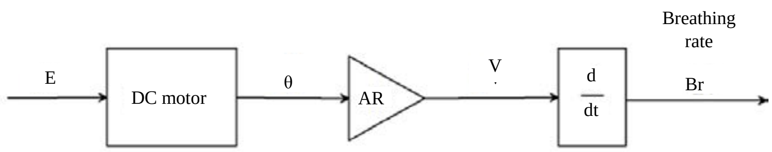

Fig. 2: Block diagram of the ventilator

Where:

K_t = Torque constant of the motor having units Nm/A
J = Total inertia of the motor
B = Damping coefficient of the motor
K_b = Voltage constant of the motor
R_a = Armature resistance
L_a = Armature inductance

The displacement that the piston moves is simply:

$$X(s) = R\theta(s) \tag{2}$$

The volume of air enters to the patient lung is simply the area of the piston A multiplied by the piston displacement x[3]:

$$V(s) = X(s)A \tag{3}$$

The rate of volume enters to the patient lung is the derivative of the volume of the piston:

$$Br(s) = sV(s) \tag{4}$$

March 27, 2021Substituting Eq.1-4 yields[4:

$$Br(s) = sRA\theta(s) \tag{5}$$

Substituting (Eq. 5) into (Eq. 1) yields to the transfer function between the motor voltage input to the breathing rate output as:

$$\frac{B_r(s)}{E(s)} = \frac{RK_TA}{JL_as^2+(R_aJ+L_aB)s+(R_aB+K_bK_T)}$$

The block diagram of the ventilator is shown in Fig. 2. The parameters of the ventilator are shown in Table 1. The transfer function becomes:

Table 1: System parameters

Parameters	Symbol	Values
Torque constant of the motor	K_T	20 Nm/A
total inertia of the motor	J	1.25 Kgm^2/sec^2
damping coefficient of the motor	B	2.5 Nms
voltage constant of the motor	K_b	0.8 $V.rad/sec^2$
Armature resistance	R_a	50 Ω
Armature inductance	L_a	6.25 H
Disc length	R	0.3 m
Piston area	A	0.4 m^2

$$\frac{B_r(s)}{E(s)} = \frac{2.4}{7.8s^2+78.2s+141}$$

With state space representation:

$$\dot{x} = \begin{pmatrix} -10.0256 & -18.0769 \\ 1 & 0 \end{pmatrix} x + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u$$
$$y = \begin{pmatrix} 0 & 0.3077 \end{pmatrix} x$$

The closed loop system block diagram is shown in Fig. 3. The normal heart beat of an adult person is[5:

$$H_B = 1.2\frac{\text{Beats}}{s}$$

The average normal breath rate of an adult person is:

$$B_R = 0.25\frac{\text{Breath}}{s}$$

Table 2 shows the heart beat rate and breathing rate of an adult human being before and after activity. Assuming the heart beat rate and breathing rate relation is linear, the transfer function between the input heart beat rates to the output breathing rate output becomes:

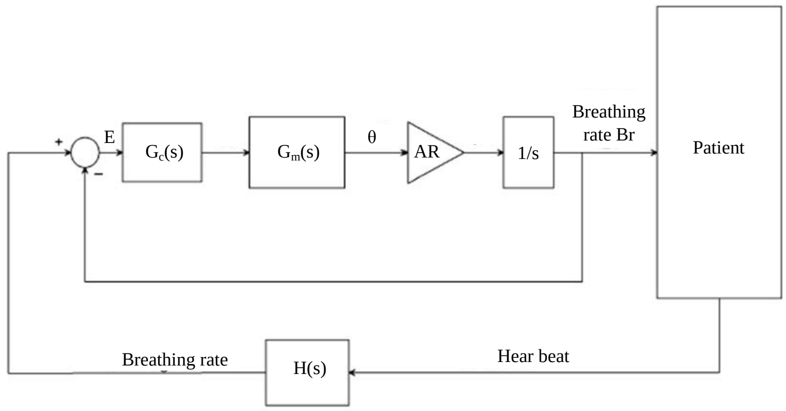

Fig. 3: Closed loop system block diagram

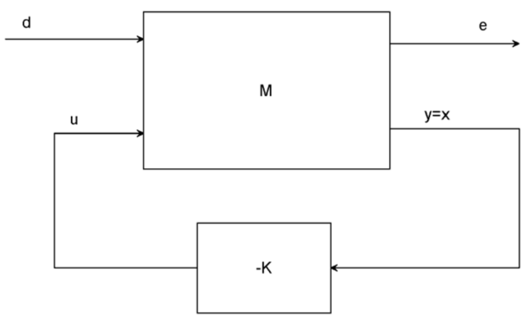

Fig. 4: A full state feedback system

Table 2: Heart beat rate and breathing rate of an adult human being

Activity	Heart beat rate (Beats/sec)	Breathing rate (m^3/sec)
Before activity	1.73	0.000467
After activity	2.13	0.0006
Average	1.93	0.0005335

$$H(s) = \frac{B_r(s)}{HB_r(s)} = K_r = \frac{0.0005335}{1.93} = 0.000276$$

The proposed controllers design

Full state feedback H_2 controller design: Consider Figure 4 and assume that:

$$M = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & 0 & D_{12} \\ I & 0 & 0 \end{bmatrix} \tag{6}$$

From Eq. 6:

$$\dot{x} = Ax + B_1 d(t) + B_2 u(t) \tag{7}$$

$$e(t) = C_1 x(t) + D_{12} u(t) \tag{8}$$

$$y(t) = x(t) \tag{9}$$

Assuming that d(t) is the white noise vector with unit intensity:

$$\left\|T_{ed}(s)\right\|_{H_2}^2 = E\left(e^T(t)e(t)\right) \tag{10}$$

Where:

$$e^T e = x^T C_1^T C_1 x + 2x^T C_1^T D_{12} u + u^T D_{12}^T D_{12} u \tag{11}$$

With Eq. 7 and 10, the minimization of $||T_{ed}(s)||H_2$ is equivalent to the solution of the stochastic regulator problem. Setting:

$$Q_f = C_1^T C_1,\ N_f = C_1^T D_{12} \text{ and } R_f = D_{12}^T D_{12} \tag{12}$$

the optimal state feedback law is given by:

$$u = -Kx \tag{13}$$

Where:

$$K = R_f^{-1}\left(PB_2 + N_f\right)^T \tag{14}$$

And:

$$\begin{aligned} &P\left(A - B_2 R_f^{-1} N_f^T\right) + \left(A - B_2 R_f^{-1} N_f^T\right)^T \\ &P - PB_2 R_f^{-1} B_a^T P + Q_f - N_f R_f^{-1} N_f^T = 0 \end{aligned} \tag{15}$$

It should be noted that the gain K is independent of the matrix B1. For this system the full state feedback gain matrix becomes (Fig. 5 and 6)[6]:

$$K = (0.0431 \quad 0.0227)$$

PID controller: A proportional-integral-derivative controller (PID controller) is a control system loop feedback mechanism (controller) widely used in industrial control systems. A PID controller attempts to correct the incorrectness between a measured variable and a desired set point by counting and then outputting a corrective demand that can adjust the currents accordingly and rapidl, to maintenance the erroneousness minimal.

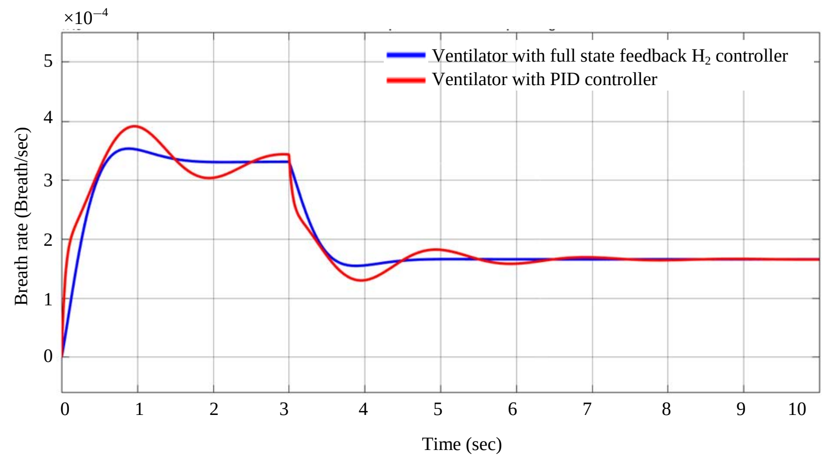

Fig. 5: Step response

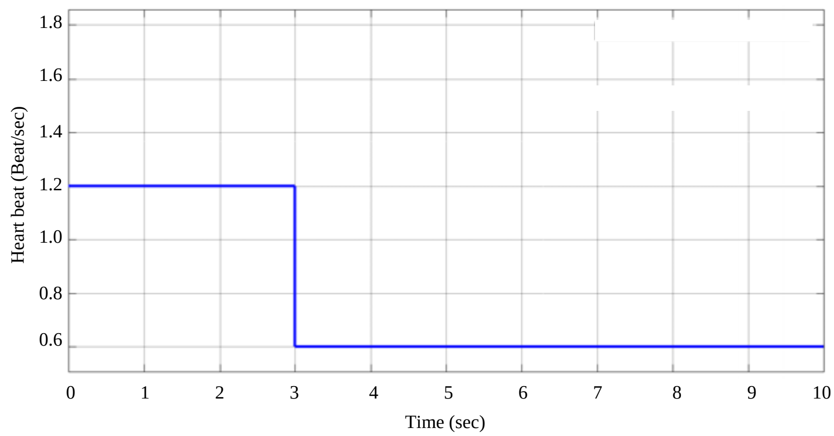

Fig. 6: Heart beat input

The PID controller planning (algorithm) involves three separate parameters; the proportional, the integral and derivative values. The proportional value determines the reaction to the current error, the integral value determines the response based on the sum of recent errors, and the derivative value determines the response based on the rate at which the erroneousness has been changing. The weighted sum of these three effect is used to adjust the system output via a control element such as the position of a DC motor.

The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining u(t) as the controller output, the final term of the PID controller is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (16)$$

Using Ziegler-Nichols tuning method the value of the PID controller are:

$$K_P = 86.3241 \;\; K_I = 759.4440 \;\; K_D = 42.7091$$

RESULTS AND DISCUSSION

Comparison of the portable ventilator with full state feedback H_2 and PID controllers for step change in heart beat: The comparison simulation of the portable ventilator with full state feedback H_2 and PID controllers for a step change from (1.2-0.6) beats per second is shown in Fig. 5 and 6.

The data of the rise time, percentage overshoot, settling time and peak value is shown in Table 3. As Table 3 shows that the portable ventilator with full state feedback H_2 controller improves the performance of the system by minimizing the percentage overshoot and settling time[7].

Comparison of the portable ventilator with full state feedback H_2 and PID controllers for random change in heart beat: The comparison simulation of the portable

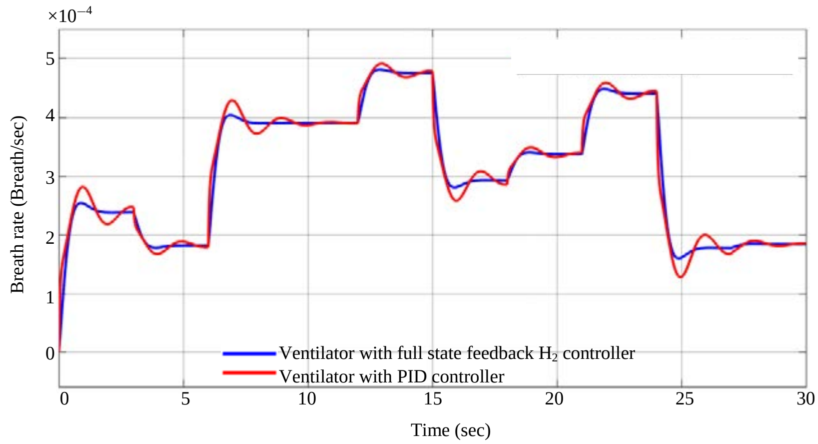

Fig. 7: Random response

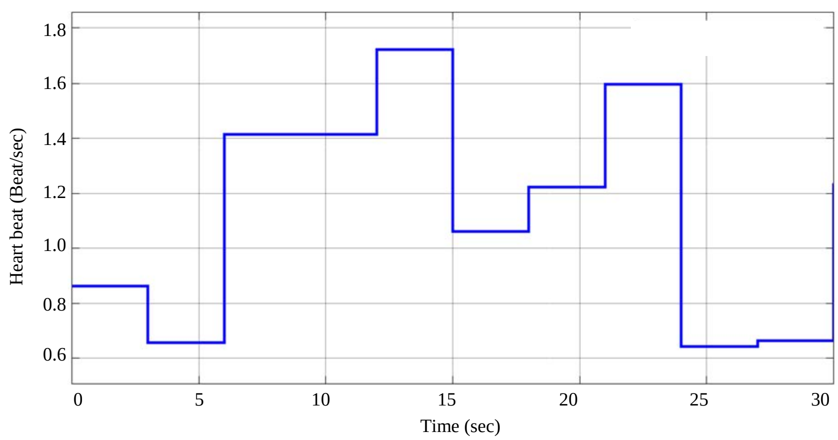

Fig. 8: Heart beat input

Table 3: Step response data

Performance data	Full state feedback H2 controller	PID controller
Rise time	0.4 (Sec)	0.15 (sec)
Per. overshoot	6 (%)	18.2 (%)
Settling time	4.3 sec	7.5 (sec)
Peak value	3.5 Beats per second	3.9 Beats per sec

ventilator with full state feedback H_2 and PID controllers for a random change from (0.6-1.8) beats per second is shown in Fig. 7 and 8.

As we seen from Fig. 7, the portable ventilator with full state feedback H_2 controller improves the performance of the system by minimizing the percentage overshoot and settling time.

CONCLUSION

In this study, designing and performance analysis of a low cost portable ventilator have been done for COVID-19 patients using MATLAB Toolbox successfully. This system senses the patient heart beat and delivers the exact amount of volume of air to the patient lung with adjusted breathing rate. In order to improve the performance of the system PID and Full State Feedback H_2 controllers have been used. The comparison simulation results of the system with the proposed controllers for a step change and a random change of the patient heart beat shows that the portable ventilator with full state feedback H_2 controller improves the performance of the system by minimizing the percentage overshoot and settling time.

REFERENCES

01. Al Husseini, A.M., H.J. Lee, J. Negrete, S. Powelson, A.T. Servi, A.H. Slocum and J. Saukkonen, 2010. Design and prototyping of a low-cost portable mechanical ventilator. J. Med. Devices, Vol. 4, No. 2.

02. El Majid, B., A. El Hammoumi, S. Motahhir, A. Lebbadi and A. El Ghzizal, 2020. Preliminary design of an innovative, simple and easy-to-build portable ventilator for COVID-19 patients. Euro-Mediterr. J. Environ. Integr., 5: 1-4.
03. Garmendia, O., M.A. Rodriguez-Lazaro, J. Otero, P. Phan and A. Stoyanova *et al*., 2020. Low-cost, easy-to-build noninvasive pressure support ventilator for under-resourced regions: Open source hardware description, performance and feasibility testing. Eur. Resp. J., Vol. 55, 10.1183/13993003.00846-2020
04. Heiselberg, P., 2016. Natural ventilation design. Int. J. Vent., 2: 295-312.
05. Krishna, B.S.P. and Y.B. Rao, 2020. Design and survey of a modular clinical application ventilator. Int. J. Psychosocial Rehabitation, 24: 5664-5670.
06. Pathak, P.A., T. Sonmez and M.U. Unver, 2020. Improving ventilator rationing through collaboration with experts on resource allocation. JAMA Network Open, 3: e2012838-e2012838.
07. Pearce, J.M., 2020. A review of open source ventilators for COVID-19 and future pandemics. F1000Research, Vol. 9, Issue 219.