

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 H₂ 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

Copy Right: Medwell Publications

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 H₂ 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:

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

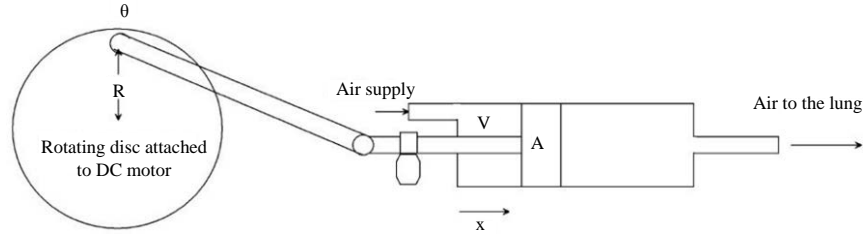


Fig. 1: Respiratory ventilator system design

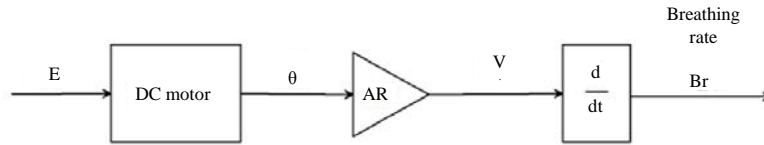


Fig. 2: Block diagram of the ventilator

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:

$$X(s) = R\theta(s) \quad (2)$$

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

$$V(s) = X(s)A \quad (3)$$

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

$$Br(s) = sV(s) \quad (4)$$

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

$$Br(s) = sRA\theta(s) \quad (5)$$

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 Kg m^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:

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

$$y = (0 \quad 0.3077)x$$

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:

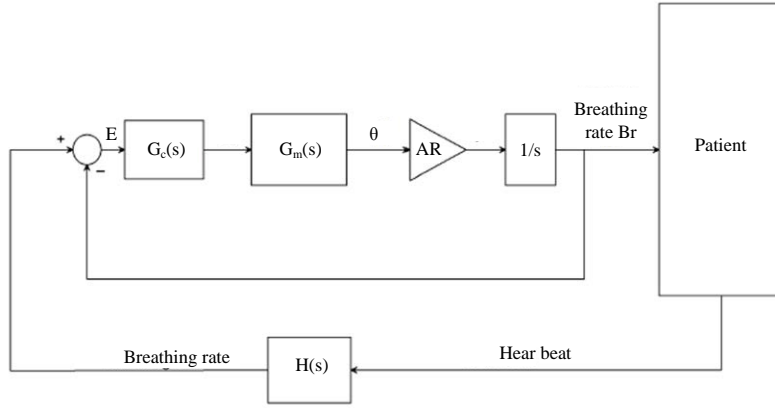


Fig. 3: Closed loop system block diagram

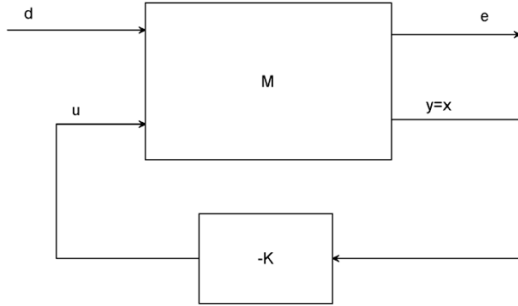


Fig. 4: A full state feedback system

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 H₂ controller design: Consider Figure 4 and assume that:

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

From Eq. 6:

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

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

$$y(t) = x(t) \quad (9)$$

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

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

Where:

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

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

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

the optimal state feedback law is given by:

$$u = -Kx \quad (13)$$

Where:

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

And:

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

It should be noted that the gain K is independent of the matrix B_1 . 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 rapidly, to maintenance the erroneousess minimal.

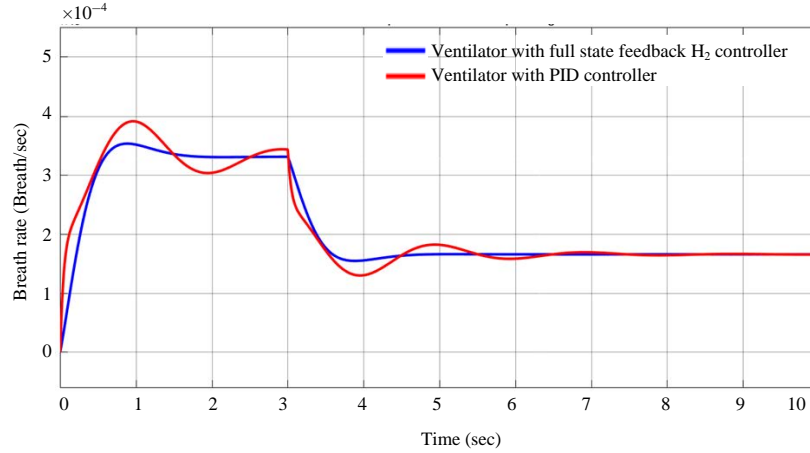


Fig. 5: Step response

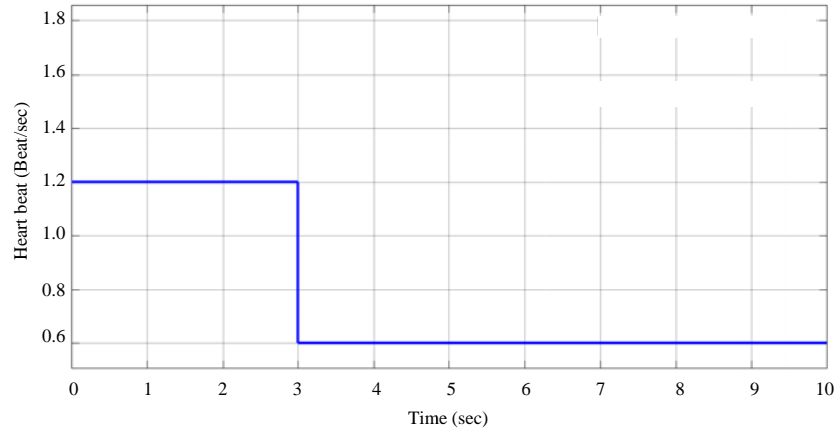


Fig. 6: Heart beat input

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 erroneous 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:

$$K_p = 86.3241 \quad K_i = 759.4440 \quad K_d = 42.7091$$

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

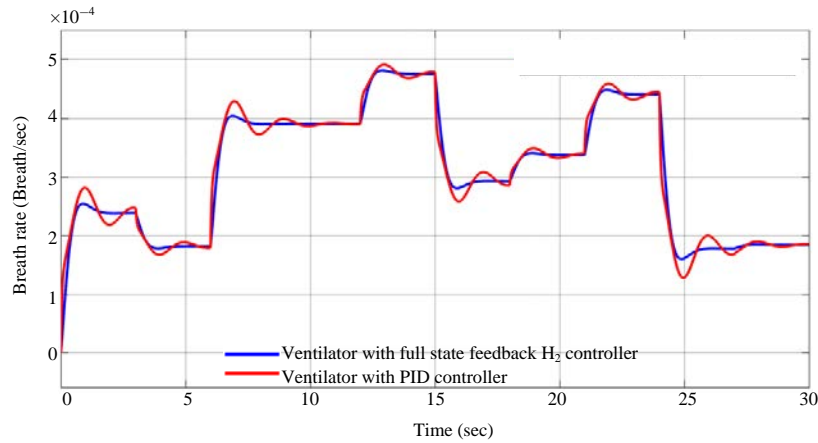


Fig. 7: Random response

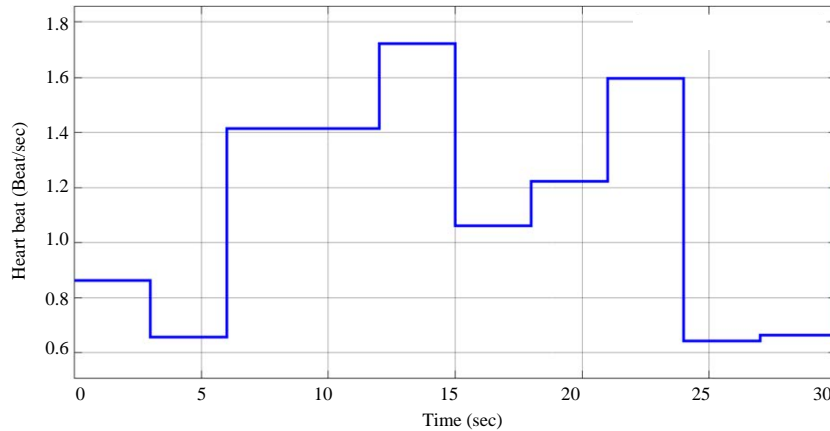


Fig. 8: Heart beat input

Table 3: Step response data

| Performance data | Full state feedback H ₂ 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 H₂ 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 H₂ 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 H₂ 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 H₂ controller improves the performance of the system by minimizing the percentage overshoot and settling time.

REFERENCES

01. Al Hussein, 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 Rehabilitation*, 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.