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Designing Emergency Mechanical Ventilator

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Abstract - *This paper represents the required calculative measures that are essential in the design process and working of an Emergency Mechanical ventilator (EMV) to provide the right amount of pressure flow into the patient's lung by evaluating the three main inputs namely Tidal Volume, Breath Rate, and IE ratio along with automatic Bag Value Mask (AMBU Bag) compression system driven by motor and lead screw mechanics. Thus, eliminating the traditional manual ventilator method. The Emergency Mechanical Ventilator has a backup battery pack in the event of mains failure along with an alarm system whenever the ventilator operation fails at any instant of time including the max pressure exceed failure (Pmax >40 cm h20) and for all the other respiratory ventilation processes.*

Key Words: Calculative, AMBU bag, Tidal Volume, Leadscrew, Pressure

1.INTRODUCTION

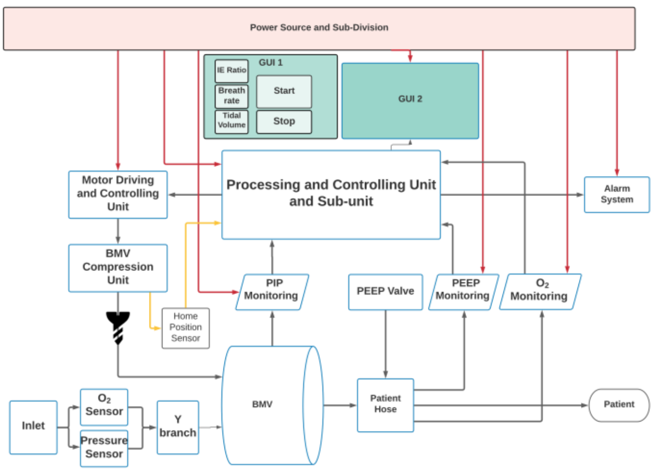

Fig - 1: Block Diagram

A Mechanical Ventilator is a machine that helps a patient breathe when the patients are unable to breathe on their own. With a rapidly growing rate of COVID-19, it has become a global pandemic causing the increasing demand for ventilators required in the assisted breathing, eventually resulting in the shortage of ventilators. The proposed system helps to connect the gap between the increasing demand for Mechanical ventilators and the traditional manual ventilator system. Mechanical Ventilators are also required for patients suffering from injuries such as chronic respiratory ailments, anaphylaxis, etc. The morality of patients going through ventilation is 31-37% [1]. From Fig – 1 the working of the Mechanical Ventilator can be determined by the following parameters. Starting with IE Ratio, which is the ratio between inspiration time and expiratory time, and in normal spontaneous breathing, the expiratory time is about twice as long as the inspiration time thus giving an IE ratio of 1:2 and is read "one to two" [2]. IE ratios used in this Mechanical Ventilator are 1:1, 1:2, 2:1. The next parameter is Tidal Volume (T_V) which is delivered air volume to the lungs along with each breath. Tidal Volumes used in this Mechanical Ventilator are 250 mL, 350mL, 450mL, 550mL, 650mL, 750mL. The next parameter is Breath Rate (BR) which is the set rate for delivering breaths per minute. Breath rates used in this Mechanical Ventilator are 12, 16, 18, 20. For example, if the Breath Rate is 12 then the delivery of breath can be given as 1 breath every 5 seconds. The next parameter is Peak inspiratory pressure (PIP), which is the highest level of pressure applied to the lungs during inhalation and should not exceed more than 40 cm H_2O. The next parameter is plateau pressure ($P_{plateau}$) which is the pressure that is measured with an inspiratory hold during the inhale process, the plateau pressure hold time T_h is 0.5 to 1 second and the pressure should not exceed more than 30 cm H_2O. The next parameter is Positive End Expiratory Pressure (PEEP), the PEEP is positive pressure that will remain in the airway at the end of the exhaling process. The most important parameter In the Mechanical Ventilator is the AMBU bag. AMBU bag is a silicon resuscitator in an oval shape that is used to provide ventilation to the patients. The AMBU bag used in this Mechanical Ventilator has a width of 127mm and a total volume capacity of 1475 mL [3]. The designed Mechanical Ventilator is equipped with 2 pressure sensors for monitoring different pressures during the ventilation process, three adjustable knobs for setting the IE, Breath Rate, and Tidal Volume values. The home position sensor is used to drive the motor to its initial '0' position after the completion of every cycle and after every system failure. The AMBU Bag compression unit is driven by a DC Hub motor to compress the AMBU bag linearly by the leadscrew unit from either side of the AMBU bag. The Mechanical Ventilator was designed to work in Volume control mode

and only for adults. Guidelines by MHRA UK were referred for the manufacturing process [4].

Fig - 2: Proposed CAD Design [Courtesy Robonist Tech Solutions PVT.LTD]

2. Control Mode

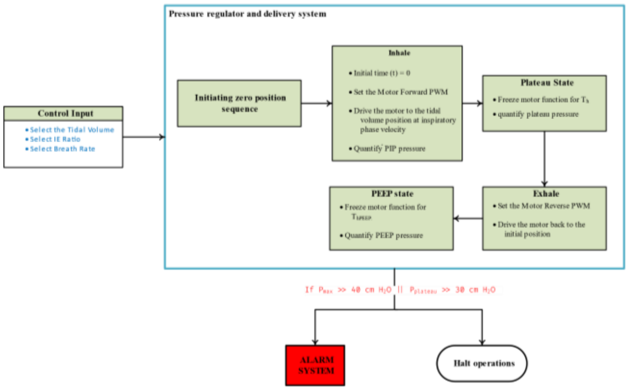

Fig - 3: Mode of Operation

The volume-controlled Mechanical Ventilator works by setting the fixed amount of Tidal Volume to be delivered at a set interval of time while the airway pressure is variable resulting in adaptive and more stable minute ventilation. The flow of operation is quite self-explanatory and is being divided into three main sections. The first section is the input section where the doctor/physician sets the required tidal volume along with the breath cycle timing. Once the input parameters are set, the motor is commanded to drive to the zero position thus by maintaining the travel distance graph incorporated with every combination of inputs. The zero position of the motor is maintained by the proximity sensor working in a counter-loop, which is reset to 0 after the completion of every cycle. The next main section is the pressure regulator and delivery section. It delivers the required tidal volume by maintaining the pressure criteria discussed in the introductory part.

During the inhale stage, timer t is set to 0. Where timer t = T_{total} and $0 \le t \le T_{in}$. Then the motor is commanded to travel to the tidal volume position (T_V) along with calculating the motor forward PWM (F_{PWM}), thus compressing the AMBU bag. Simultaneously, the system keeps checking the PIP value and raises an alarm if the PIP value exceeds 40 cm H_20. After reaching the PIP stage, the motor function is frozen for T_h time, where $T_{in} \le t \le T_{in} + T_h$. Simultaneously, the system keeps checking the pressure $P_{plateau}$ and raises an alarm if the $P_{plateau}$ value exceeds 30 cm H_2O.

During the exhale stage, the motor is commanded to travel back to the '0' position, allowing the AMBU bag to decompress. After the exhale stage, the motor function is frozen for T_{hPEEP}.

If any of the mentioned pressure values exceed the desired values, all the system functions of the Mechanical Ventilator are halted.

3. Calculating Pressure wave

A single cycle of the pressure wave is the total time required for a single breath to be completed. The pressure wave consists of three main parameters. Namely, inhale period, hold period and exhale period. Where total inspiration time is the sum of inhale period and hold period, where the expiration time is equal to exhale period. The inspiratory hold manoeuvre on the mechanical ventilator is 0.5 to 1 second [5].

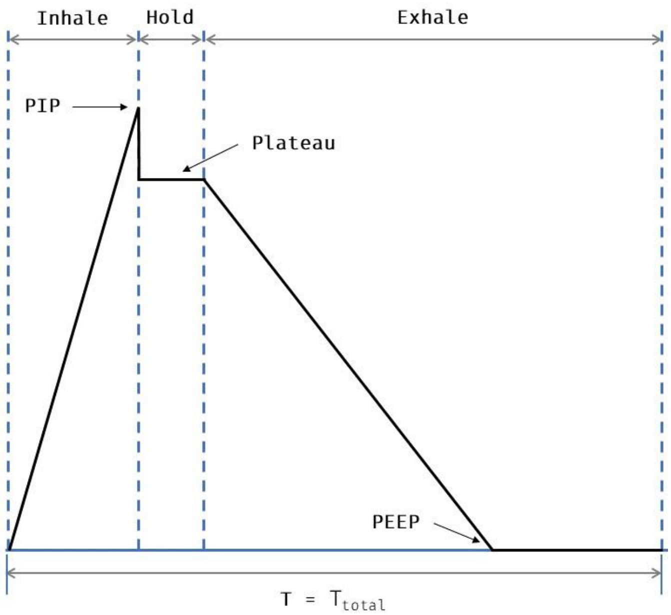

Fig - 4: pressure wave

The same can be given and calculated by mathematical expressions as below:

$$T_{total} = \frac{60}{BR} \qquad \text{i}$$

where,

T_{total} is measured in seconds.

BR= Breath Rate

The total time required for inhaling is given by -

$$T_{in} = \frac{T_{total}}{1 + IE} - T_h \qquad \text{ii}$$

where,

T_{in} = total inhale period in seconds
IE = Inhale Exhale ratio

T_h = hold period in seconds

The exhale period is calculated as:

$$T_{ex} = T_{total} - (T_{in} + T_h) \quad \text{iii}$$

Thus, T_{total} can also be given as

$$T_{total} = T_{in} + T_h + T_{ex} \quad \text{iv}$$

With the help of aforesaid formulas, with IE = 1:2 and breath rate = 12 and T_h = 0.5 sec,

Table -1: Inhale and exhale time calculation

Output Parameters			
T_{in}	1.2 sec	Tex	3.3 sec

Based on the above output parameters, the sequential breath cycles for 1 minute can be given as –

Table - 2: Sequential breath cycle

Cycle Number	T_{in} period	Hold period	T_{ex} period
1	1.2 sec	1.7 sec	5.0 sec
2	6.2 sec	6.7 sec	10.0 sec
3	11.2 sec	11.7 sec	15.0 sec
4	16.2 sec	16.7 sec	20.0 sec
5	21.2 sec	21.7 sec	25.0 sec
6	26.2 sec	26.7 sec	30.0 sec
7	31.2 sec	31.7 sec	35.0 sec
8	36.2 sec	36.7 sec	40.0 sec
9	41.2 sec	41.7 sec	45.0 sec
10	46.2 sec	46.7 sec	50.0 sec
11	51.2 sec	51.7 sec	55.0 sec
12	56.2 sec	56.7 sec	60.0 sec

4. Leadscrew Mechanism

A leadscrew is a linking screw in a machine that converts the rotational motion into linear motion

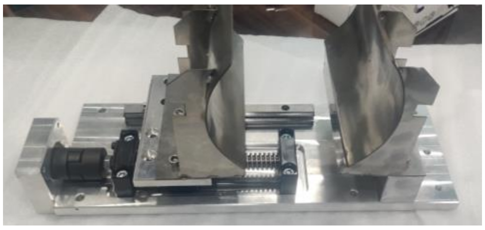

Fig - 5: Lead Screw Ambu Bag Compression Mechanism [Courtesy Robonist Tech Solutions PVT.LTD]

4.1 Calculating leadscrew parameters

The rotational motion from the motor is transformed into transitional motion using a lead screw, resulting in the shaft being subject to the loads. While selecting the right leadscrew for the desired application, the following parameters need to be considered and calculated.

1. Driving Torque to obtain thrust

$$T = \frac{F_a l}{2\pi\eta} \quad \text{v}$$

where,

T = Driving torque in Nm
F_a = Axial thrust force on the leadscrew
l = leadscrew length
η = Efficiency

While taking F_a = 20N, l = 140 mm and η = 95%, the required torque can be calculated as

$$T = \frac{20 \times 0.14}{2 \times \pi \times 0.95}$$

$$T = 0.4689\ Nm \cong 4.7814\ kg\ cm$$

2. Stresses from applied loads

While calculating stress, there are two stresses to be calculated, axial stress and torsional stress. The axial stress is mathematically given as –

$$\sigma_{axial} = \frac{F_a}{\pi r_{tr}^2} \quad \text{vi}$$

where,
F_a = Applied axial force in N
r_{tr} = rood radius in meter
T = applied torque

While taking F_a = 20 N and r_{tr} = 0.05, axial stress, σ_{axial} is calculated as-

$$\sigma_{axial} = \frac{20}{\pi \times 0.05^2}$$

$$\sigma_{axial} = 2547.771\ N/m^2$$

The torsional stress can be given as –

$$\tau_{torsional} = \frac{2T}{\pi r_{tr}^3} \quad \text{vii}$$

While taking T = 0.4689 Nm as calculated using equation v and r_{tr} = 0.05, $\tau_{torsional}$ can be calculated as –

$$\tau_{torsional} = \frac{2 \times 0.4689}{\pi \times 0.05^3}$$

$$\tau_{torsional} = 2389.3\ N/m^2$$

3. Compressive load

To avoid buckling, maximum compressive load needs to be calculated. The compressive load can be given as –

$$P_1 = \frac{\lambda \pi^2 EI}{l_b^2} \quad \text{viii}$$

where,
P_1 = Buckling load in N
l_b = Distance between mounting position in meters
E = Elastic modulus in Pascals
I = Second moment of inertia in m^4

λ = Support factor

while taking l_b = 140, E = 2.6 × 10⁵, I = 0.49 and λ = 4 P_1 can be calculated as –

$$P_1 = \frac{4 \times \pi^2 \times 2.6 \times 10^5 \times 490}{140^2}$$

$$P_1 = 2.56 \times 10^5\ N$$

4.2 Calculating leadscrew travel distance

As mentioned in the introductory part, the width of the AMBU bag is 127mm and the total volume capacity is 1475 mL. The rate of output volume per mm compressed is –

$$Output\ Rate = \frac{1475}{127}$$

$$Output\ Rate = 11.61\ mL/mm$$

The maximum tidal volume required is 750 mL. To achieve the maximum tidal volume, the required AMBU bag compression is 64.5 mm only out of its total width. To accomplish this, the AMBU bag is placed 64.5 mm inward from the farthest point of the leadscrew. The required travelling distance can be mathematically given by –

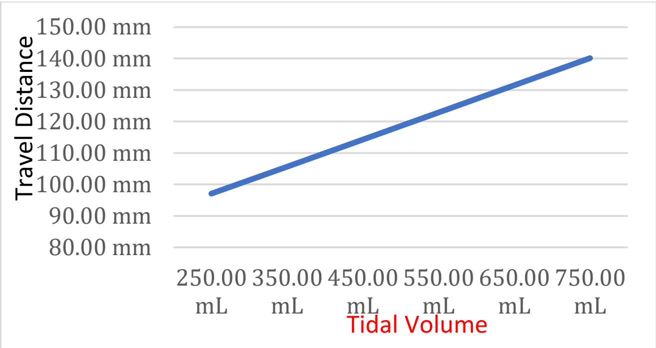

Chart - 1: Tidal Volume vs Leadscrew Travel Distance

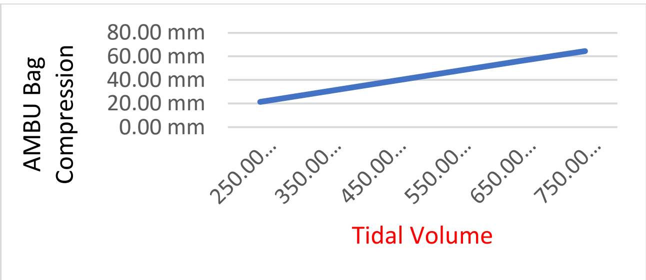

Chart - 2: Tidal Volume vs AMBU bag Compression

5. Calculating the Required PWM

Pulse width modulation is needed to be calculated to get the desired speed at which the motor shaft will rotate to achieve and match the input parameters set by the user such as IE ratio as well as Breath rate. The required PWM is calculated by the following method. While taking IE ratio=1:2, breath rate=12. First of all, the motor's revolution per second value is needed to be calculated and revolution per second is mathematically given as -

$$R_{ps} = \frac{RPM_{base}}{T_{minute}} \qquad \text{ix}$$

where,
Rps = Revolution per second
RPM_{base} = Total RPM of the motor, which is 2750
T_{minute} = Time period of 1min $= 60 seconds$

$$R_{ps} = \frac{2750}{60}$$
$$R_{ps} \cong 46$$

Once R_{ps} is calculated, forward PWM and reverse PWM are calculated.

where,
F_{pwm} = Forward PWM
R_{pwm} = Reverse PWM

$$F_{pwm} = \frac{RPM_{base} \times T_{in}}{R_{ps}} \qquad \text{x}$$

T_{in} for the given IE ratio and breath rate can be calculated from equation ii, by taking the T_{in} value from table **Table -*1*:** Inhale and exhale time calculation.

$$F_{pwm} = \frac{2750 \times 1.2}{46}$$

$$F_{pwm} = 71.73$$

$$R_{pwm} = \frac{RPM_{base} \times T_{ex}}{R_{ps}} \qquad \text{xi}$$

T_{ex} for the given IE ration and breath rate can be calculated from equation iii, by taking T_{ex} value from table **Table -*1*:** Inhale and exhale time calculation.

$$R_{pwm} = \frac{2750 \times 3.3}{46}$$

$$R_{pwm} = 197.2$$

Similarly, PWM values for a different combination of an input parameter can be calculated.

6. Testing

To determine the veracity of all the mathematical functions, the flow rate, and delivered pressure, modelling simulation was carried out with different input parameters including Tidal Volume, IE ratio, Breath rate, etc. The simulated graph for the following can be observed as follow –

IE=1:1, Tidal Volume = 250, Breath Rate = 12

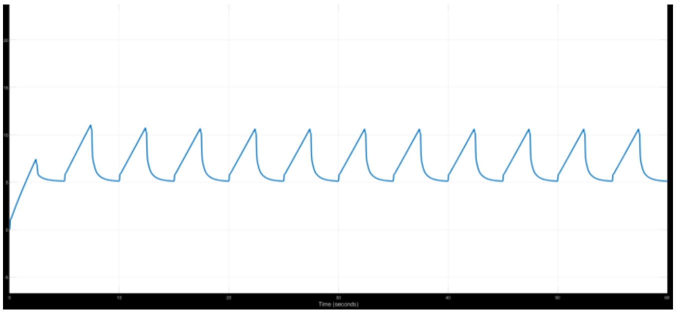

Fig - 6: Test 1

IE = 1:2, Tidal Volume = 350, Breath Rate = 14

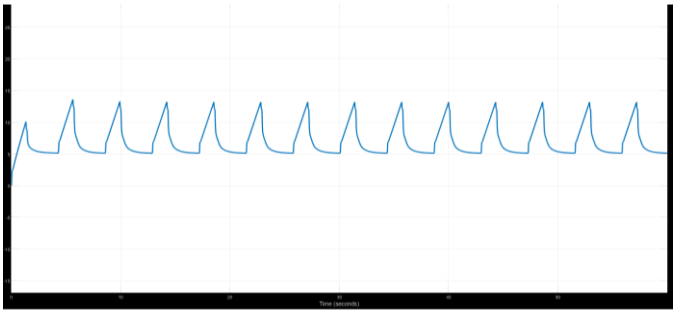

Fig - 7: Test 2

7. Conclusion

The Emergency Mechanical Ventilator was designed to overcome the shortage of rapid medical equipment in light of the current pandemic situation caused by COVID-19, this Emergency Mechanical Ventilator was designed as a rapid prototype only to be used in an emergency to replace the manually assisted ventilation and by maintaining the low-price segment. Several iterations were made to achieve the standards.

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