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AN OPTIMAL CONTROL WITH DISTURBANCE ESTIMATION FOR THE EMERGENCY VENTILATION OF A LONGITUDINALLY VENTILATED ROAD TUNNEL

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ABSTRACT

Road tunnels are usually ventilated in order to dilute pollution. Recent trend of the road tunnel ventilation system in Japan is longitudinal one, which is superior to transverse system from the viewpoint of economy. When a fire breaks out in a longitudinally ventilated tunnel for two-way traffic, it is desirable to reduce wind velocity so that safe circumstance for refuge action is ensured in both sides of the fire point. There are several tunnels in which this kind of control system is installed, but the concept and the method of emergency control is not established yet. In the present paper, the author proposes an optimal control with disturbance estimation which gives instruction on jet fan operation at each control period, with which wind velocity in the tunnel would reduce to zero quickly. The new control method is confirmed by numerical simulation which showed that it is more excellent in rapidity and stability in comparison with the privailed PID control.

1. INTRODUCTION

The highway network in Japan has been remarkably developed, up to about 5,000 km of the total length. Many of the recent routes runs across mountainous area resulting in more proportion of tunnel. It is now well accepted in Japan to adopt a longitudinal ventilation system for a long tunnel instead of transverse one, mainly from the viewpoint of simplicity and economy. The Kan-etsu tunnel(10,965m) and the Ena-san tunnel (the second shaft: 8,625m) are typical examples of the application of longitudinal system to long tunnels. They are ventilated by jet fans, electorstatic precipitator stations and vertical shafts.

It is often the case that a single shaft is used for two-way traffic for several years for the tunnels in a local area. For these tunnels it is important to prepare the emergency operation, with which a safe evacuation environment is ensured in case of fire. According to the experience such as for the Kan-etsu tunnel, it turned out to be effective to control jet fans by feed back to suppress the air flow velocity in the tunnel[1],[2]. It was, however, a rather primitive control, and there has been some instability in performance[3]. Moreover, for the tunnels with the length of 2 to 4 km, efficient and stable countermeasure is not yet established.

In the present work, a new control algorythm for emergency operation is proposed and tested by means of numerical simulation. It is based on the concept of optimal control accompanied by the estimation of disturbance. The object tunnel is supposed to be 3,000m of the length equipped with 33 reversible jet fans, used for two-way traffic. The air flow velocity is affected strongly by imbalance of traffic force and by natural wind. Ordinary PID control of jet fans can achieve good result in reducing the air flow in the tunnel, although there exists overshoot or deviation from the target value. On the other hand it is clearly shown that the performance by the proposed optimal control is far better in that quick and stable suppression of wind is attained.

2. NOMENCLATURE

A_r [m^2] : Air flow velocity in the tunnel.
A_t [m^2] : Mean projection area of vehicle.
D_r [m] : Reference diameter of the tunnel cross section.
F_j [N] : The force driven by the jet fans.
F_r [N] : The force by friction.
F_t [N] : The force by vehicles.
F_T [N] : The overall force ancting on the air column in the tunnel.
F_w [N] : The force by natural wind.

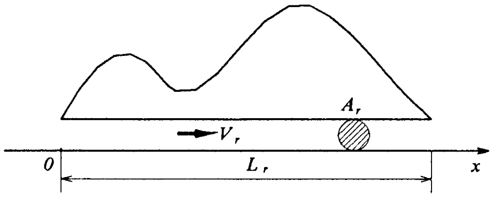


Fig. 1 Model of a longitudinally ventilated tunnel.

K_j [-] : Coefficient of pressure rise by jet fans.
K_p [(jet fans)/(m/s)] : Proportional gain.
K'_p [N/(m/s)] : Proportional gain.
L_r [m] : Length of the tunnel.
m [kg] : Mass of air in the tunnel.
$n, n-1$: time step of control period.
n_j [-] : Number of jet fans in operation.
n_t [-] : Number of vehicles existing in the tunnel.
t [s] : time.
T [s] : Period of control.
V_j [m/s] : Velocity of jet fan discharge. (Absolute value)
V_n [m/s] : Natural wind velocity.
V_r [m/s] : Air flow velocity in the tunnel.
V_t [m/s] : Speed of vehicles.
V_0 [m/s] : Target value of V_r.
x [m] : Coordinate along the tunnel axis.
λ_r [-] : Coefficient of pipe friction loss.
ρ [kg/m^3]: Density of air.
ζ_e [-] : Coefficient of entrance loss.

Suffix
$+, -$: denote the value to be in positive/negative direction.

3. THE SIMULATION MODEL FOR TUNNEL VENTILATION

A model tunnel with a longitudinal ventilation system is treated, as in fig. 1. The variables concerning velocity or force are defined to be positive in the direction of x coordinate. The aerodynamics of the air column in the tunnel is considered to follow the Newton's second law of motion,

$$m\frac{dV_r}{dt} = F_T, \tag{1}$$

where F_T is the overall force acting on the air, and it will be broken down in the next equation. In eq.(1) compressibility is neglected for simplicity. According to the experience of the numerical simulation for the Kan-etsu tunnel[4], this assumption was shown to be valid, and it was later confirmed by the comparison with the experiments[3].

The forces acting on the air column in the tunnel are described as

$$F_T = F_r + F_w + F_t + F_j, \tag{2}$$

for the tunnel with a longitudinal ventilation system driven only by jet fans. The resistance force due to pipe friction is

$$F_r = -\left(1 + \zeta_e + \lambda_r\frac{L_r}{D_r}\right)\frac{\rho}{2}A_r V_r\left|V_r\right|, \tag{3}$$

whereas the force caused by natural wind is described as

$$F_w = \left(1 + \zeta_e + \lambda_r\frac{L_r}{D_r}\right)\frac{\rho}{2}A_r V_n\left|V_n\right|, \tag{4}$$

where V_n is the air flow velocity which would have occured if there were no disturbances by vehicles and ventilators. It is considered that the natural wind velocity is caused by the pressure difference at both portals of the tunnel due to meteorological condition.

The traffic force in both directions can be summarized as

$$\begin{aligned} F_t = \frac{\rho}{2}A_t\{\, & n_{t+}\left(V_{t+} - V_r\right)\left|V_{t+} - V_r\right| \\ & + n_{t-}\left(V_{t-} - V_r\right)\left|V_{t-} - V_r\right|\}. \end{aligned} \tag{5}$$

Here, n_{t+} and n_{t-} are the number of vehicles existing in the tunnel toward each direction respectively. V_{t+} and V_{t-} are the velocities of vehicles with different signs. The thrust force by the jet fans is

$$F_j = n_j K_j \rho A_j V_j\left(V_j \mp V_r\right) \quad \begin{cases} - \text{ for } n_j \geq 0 \\ + \text{ for } n_j < 0. \end{cases} \tag{6}$$

V_j is absolute value of the jet fan exhaust, while n_j takes negative value when the jet fans are operated reversely. V_r can be positive or negative.

4. THE HYPOTHESIZED CONDITIONS FOR THE SIMULATION

The hypothesized conditions for the numerical simulation are given in this section. The parameters with regard to the model tunnel are

Tunnel length	3,000 m
Cross sectional area	55.5 m^2
Equivalent diameter	7.6 m
Friction coefficient	0.025
Coefficient of entrance loss	0.6
Density of air	1.20 kg/m^3

The ventilator (jet fan) specifications are

Number of jet fans	33
Size of jet fans	1250 mm in diameter
Outlet velocity of jet fans	30 m/s
Coefficient of pressure rise by jet fans	1.0

Traffic conditions are supposed as

Traffic density	2020 vehicles/h
Directional ratio	50:50
Natural wind velocity	± 2.5 m/s, 0.0 m/s

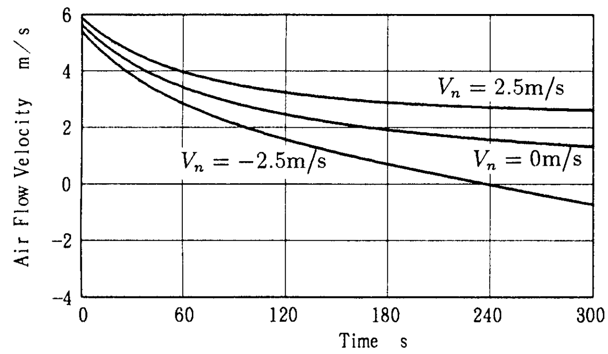


Fig. 2 Dynamic characteristic of the air flow velocity in the tunnel. (Influence of natural wind velocity)

Before the accident at the time $t = 0$, the traffic and the ventilation are normal under above mentioned condition. As soon as the accident occurs, it is supposed to break out a fire. Then all the traffic toward the accident stop at once, while the vehicles leaving from the fire point are not disturbed at all, causing large imbalance of traffic force, when the fire point is near one of the portals. For example, if the point of fire is near the left hand side of the tunnel, the vehicles in the positive direction keep running until they go out of the tunnel, while the vehicles in the opposite direction are supposed to stop immediately. This leads to the oveall traffic force to take large positive value for several minutes. The traffic model is thus a rough one, which however gives reasonable characteristic as a whole. At $t = 0$ the emergency control mode is evoked.

5. THE DYNAMIC CHARACTERISTICS OF THE AIR FLOW VELOCITY IN THE TUNNEL

According to the above mentioned situation, typical dynamic characteristics of the air flow velocity in the tunnel is simulated. It is supposed that the traffic force diminishes after the accident at $t = 0$, then the air flow velocity depends solely on natural wind and friction. The mass of air being extremely large, however, it takes much time in damping of the air flow velocity (fig. 2). Especially, when the natural wind is positive, the reduction of the wind is slow. In this case, the velocity is more than 2 m/s even 5 minutes after the break out of the fire. Fig. 3 shows the variation of dynamic characteristics under combined conditions of traffic force and natural wind. Negative traffic imbalance comes from the supposition of the accident at $x = 0$, while positive one is at $x = L_r$. From these preliminary simulations, it is easily understood that the air flow velocity after the accident does not always reduce, due to disturbances by traffic and natural wind, if the ventilator operation is simply shut down. This is why a more sophisticated operation strategy is required.

6. EMERGENCY VENTILATION OPERATION BY OPTIMAL CONTROL WITH DISTURBANCE ESTIMATION

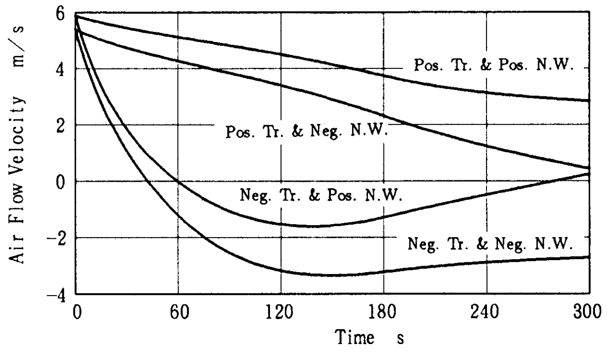


Fig. 3 Dynamic characteristic of the air flow velocity in the tunnel.
(Combined influence of natural wind velocity and traffic force)

6-1 Emergency Ventilation Control by Conventional Concept In a rather long tunnel with a longitudinal ventilation system, served for two-way traffic, the behavior of the smoke emerged from fire is a serious problem. Nevertheless, it is a pretty new concept to control air flow velocity in order to ensure a favorable refuge circumstance. The author proposed the necessity to equip a control system for the Kan-etsu Tunnel some ten years ago in order to reduce the air flow velocity quickly in case of emergency[1]. The system was installed in the actual tunnel, and it showed a satisfactory performance in damping the wind to within 2 m/s in less than 3 minutes[3]. But there existed perturbations ranging 1 to 2 m/s. The control algorythm for the Kan-etsu Tunnel is based on the PID, which is usually applied to a linear system. Because of its strong non-linearity, the control of tunnel ventilation is more or less unstable if it is controlled by the conventional PID concept. Figs. 4 and 5 are the results of the PID control. The figures above are the air flow velocity, while the jet fan operations are illustrated below. Under both situations for the positive worst case, and corresponding negative counterpart, overshoot occurs, although a rather quick reduction of the flow is achieved.

6-2 Optimal Control with Disturbance Estimation If the object of control is the position of a large amount of mass, it easily overshoots due to inertia, when the negative force continues until it arrives at the target point(Fig. 6(a)). On the other hand, when the velocity is the subject of control, it is easy in that the external force is to be removed just at the time it reaches at the target value(Fig. 6(b)). The velocity remains at the value so long as no force is applied; it is the Newton's first law of motion.

One of the typical performance according to this concept is demonstrated in fig. 7. In this case it is hypothesized that no disturbance exists after emergency control starts at $t = 0$. The proportional term is activated with an extremely large gain, while the integral and differential term is suppressed;

$$n_j = -K_p(V_r - V_0). \tag{7}$$

As the result, all of the jet fans are reversely operated during the first 22 seconds, and the air flow reduces quickly. Once the

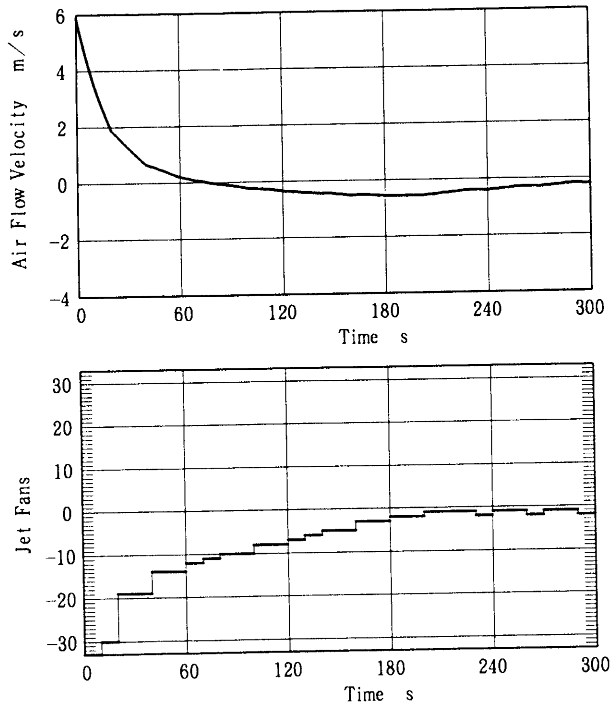
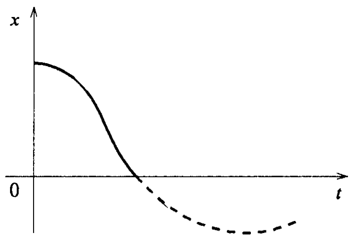
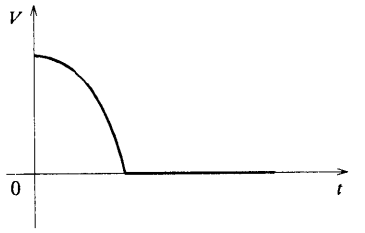


Fig. 4 Air flow velocity controlled by PID control sequence. (Case for positive traffic and positive natural wind)



(a) Control of position.



(b) Control of velocity.

Fig. 6 Control of position and of velocity.

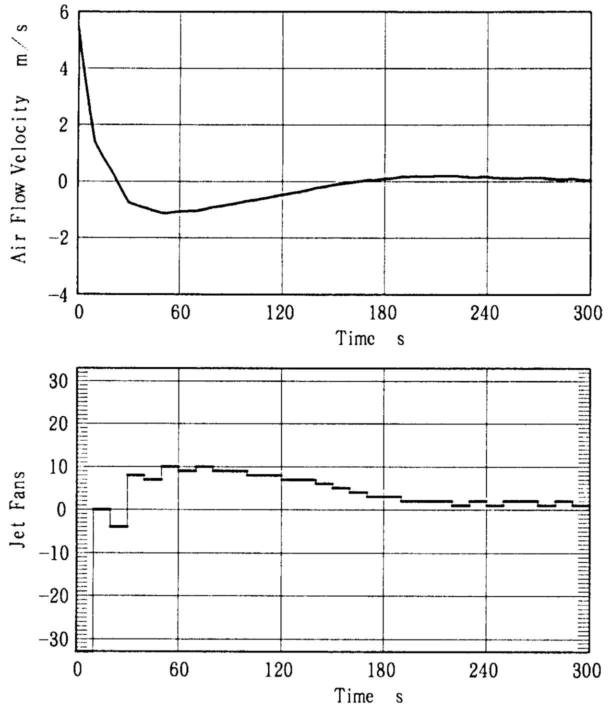


Fig. 5 Air flow velocity controlled by PID control sequence. (Case for negative traffic and negative natural wind)

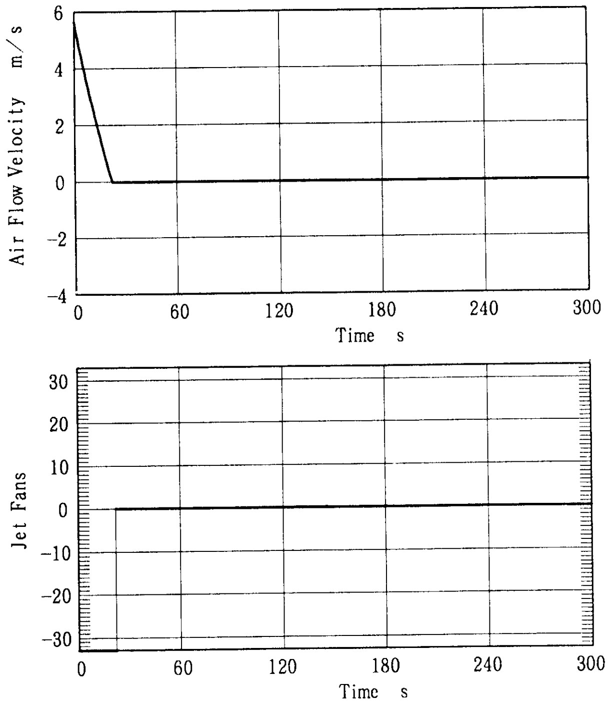


Fig. 7 Optimal control of the air flow velocity without disturbance.

velocity comes to zero, the jet fans are shut down, then the air flow remains non-existent so long as therer is no disturbance. This control is considered to be an optimal control in that the operation is done in the bang-bang manner.

In the actual system, however, enormous extent of disturbance exists, mainly due to traffic force, which will disturb such an ideal performance. It is therefore desirable that the disturbance force can be estimated, and be taken into the control algorithm. At first, the overall force acting on the air column is divided into two terms; F_j: the force driven by jet fans and F_{res}: the force other than the former one,

$$F_T = F_j + F_{res}. \tag{8}$$

As the first term on the right hand side is possible to be estimated in a rather higher accuracy by eq. (6), F_{res} can be obtaind if F_T is known. On the other hand, from the consideration of the acceleration of the air flow velocity between time step $(n-1)$ and n,

$$F_T = m\frac{V_r^n - V_r^{n-1}}{T} \tag{9}$$

where both V_r^n and V_r^{n-1} are known as measured values. T is the control period which is assumed to be around 10 seconds. Once the residual force F_{res} in the last control period is thus obtained from eqs. (8) and (9), one can expect that the value does not change largely in the next control period. The target values for the next period, shown with an asterisk, is calculated as follows: Let K_p' be a sufficiently large proportional gain,

$$F_T^* = -K_p'(V_r^n - V_0) \tag{10}$$

gives a desirable value of the total force, which leads the target force by jet fans

$$F_j^* = F_T^* - F_{res}. \tag{11}$$

Thus the number of jet fans to be operated in the next period is given by

$$n_j^* = \frac{F_j^*}{K_j \rho A_j V_j (V_j \mp V_r)} \quad \left\{ \begin{array}{l} - \text{ for } F_j^* \geq 0 \\ + \text{ for } F_j^* < 0. \end{array} \right. \tag{12}$$

As a jet fan is operated with On-Off, n_j^* is rounded to an integer.

6-3 Numerical Simulation for the Demonstration of the Current Control Sequence The performance of the above mentioned control algorythm is numerically simulated. In fig. 8 and fig. 9, the optimal control with disturbance estimation is executed under harsh conditions as in the case for figs. 5 and 6. The former is the one for the positive traffic and positive natural wind forces; while the latter is for both forces being negative. Both results show that quick and stable reduction of the air flow velocity is achieved. Here, proportional gain K_p is 10 [jet fans/(m/s)].

It often occurs that only a few number of jet fans are possible to start in a certain period of time due to limited capacity of electric facilities. In fig. 10, it is supposed that only four jet fans can be started in each control period, and that maximum

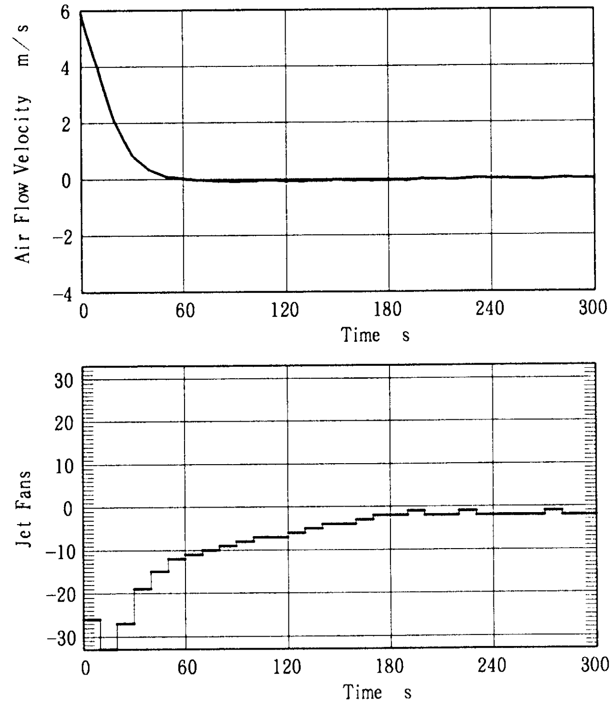


Fig. 8 Air flow velocity controlled by optimal control sequence with disturbance estimation.
(Case for positive traffic and positive natural wind)

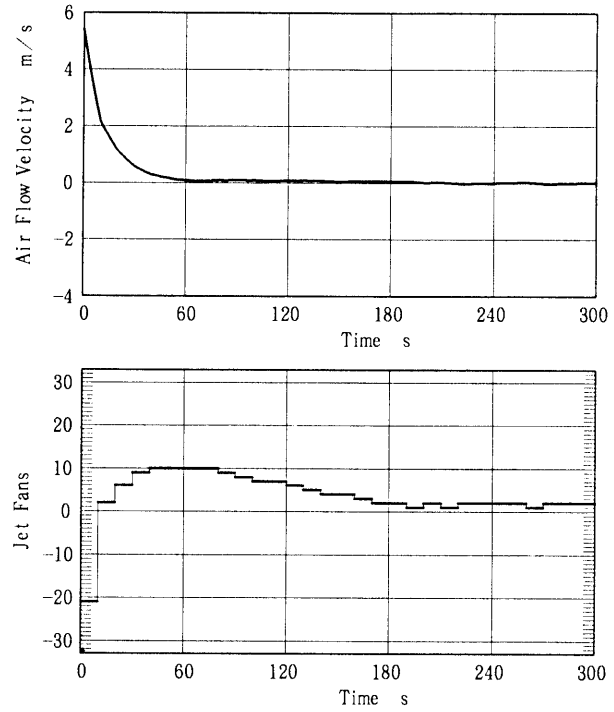


Fig. 9 Air flow velocity controlled by optimal control sequence with disturbance estimation.
(Case for negative traffic and negative natural wind)

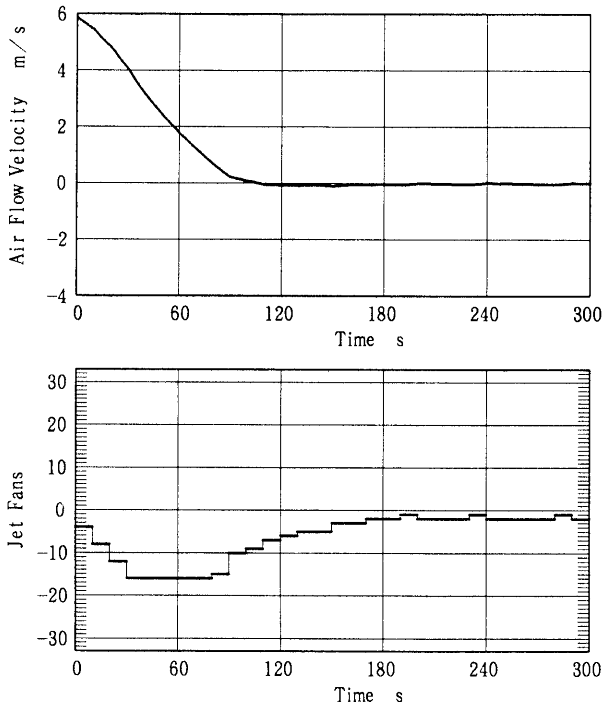


Fig. 10 Air flow velocity controlled by optimal control sequence with disturbance estimation.
(Under constraint of jet fan operation:
Case for positive traffic and positive natural wind)

number of jet fans is 16. This limit comes from the viewpoint of the safety near the fire point. The positive disturbance is supposed as in the case for fig. 9, and the same control parameter is used. Similar performance is achieved, although the damping of the wind velocity is slower, for which the control algorythm is not responsible. It is remarkable that there exists no sign of overshoot or vibratory phenomena under such severe restrictions.

Here the author would like to discuss about the upper limit of the control gain in the proposed algorythm. In the current system, it is possible to set a much larger gain compared to normal PID algorithm so that a quick reduction of the wind velocity is realized. But, for stability, the change of the wind velocity in a single control period should be less than the difference between the current value V_r and the target value V_0, or

$$|F_T^*| < m\frac{V_r - V_0}{T}. \qquad (13)$$

This leads the upper limit of the gain to be

$$K_p' < \frac{m}{T}. \qquad (14)$$

When the residual force is neglected and V_r is small enough, this relation can be roughly interpreted as

$$K_p < \frac{m}{\rho A_j V_j^2 T}. \qquad (15)$$

This means that a smaller control period enables a larger control gain.

7. TOWARD ACTUAL APPLICATION

For the application of the current algorythm to an actual system, there arises several items, described below, which must be carefully considered.

1) The start up time of the thrust of jet fans must be considered, while it is ignored in the simulation.

2) A proper control period must be selected, probably depending on the characteristics of the aerodynamics of the tunnel.

3) Sufficintly reliable parameters, such as pressure rise coefficient of the jet fans, or pipe friction coefficient and other fluid dynamic characteristics must be available.

4) A proper countermeasure must be prepared in case of failure of the control system.

5) Reliable and properly smoothed air flow velocity must be measured, and the sensors are properly installed for the purpose.

6) A computer system with the performance above certain level is to be equipped in order to realize the present system.

7) The jet fans must be durable for frequent switching to positive and negative rotation.

8) It is necessary to avoid the operation of jet fans near the fire point, which would disturb the evacuation circumstance.

8. CONCLUSION

The author has proposed an optimal control with disturbance estimation for the emergency operation of a longitudinally ventilated road tunnel. From the results of numerical simulations, it was shown that quick and stable reduction of longitudinal air flow was achieved by means of the present method. It became also clear that there arises no serious effect from that a jet fan has no control mechanism of blade angle nor rotational speed. Under the restriction of available jet fans and the number of start-up fans, the proposed system also showed a good performance. For the actual application of the system, possible problems to be solved are listed up. Main results can be summarized as follows.

1) When a 3 km tunnel is controlled by the optimal control with disturbance estimation, the wind velocity reduces to zero within a minuite. It is not dependent on the control parameter for a rather wide range.

2) When the tunnel is controlled by the PID, the performance is not desirable as that overshoot is observed even if the control parameters are carefully adjusted.

3) The possible maximum value of proportion gain is obtained in terms of the tunnel parameters and the control period.

4) The current simulator is available for various tunnels if the specification of the tunnel and its ventilation system is given.

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