Dynamic Performance of Pneumatic Tube Type Heat Sensitive Fire Detectors

HEINZ O. LUCK and NORBERT DEFFTE
Duisburg University
Electrical and Electronic Engineering
Dept. of Communication Technology
Bismarckstr. 81; D-4100 Duisburg, FRG

ABSTRACT

Pneumatic tube type heat sensitive fire detectors are used in several different applications, e.g. the protection of road tunnels. Some quantitative knowledge in the dynamic performance of these systems is essential for the prediction of response times under different operating conditions or for the calculation of a suitable response threshold setting.

The paper discusses an approximative method to calculate the dynamic performance that takes into account the inherent nonlinearities of some system elements. The method is based on some simplifying assumptions and uses models for all system elements. The simplification results in an approximative overall model for the pneumatic system which can be described by a fairly simple nonlinear differential equation. This equation can be solved by using a suitable Runge-Kutta method and yields the pressure difference Δp at the pneumatic switch as a function of time. It is shown furthermore that this solution cannot be considered as valid in general but can be used as a calculation tool for response times and response behaviour of the system in the range of normally used response pressure thresholds with a suitable accuracy. So the method is simple enough and usable for practical purposes.

Keywords: Pneumatic tube type fire detectors, heat sensitive fire detectors, pneumatic models, nonlinear systems.

1. INTRODUCTION

Pneumatic tube type heat sensitive fire detectors are frequently applied for road tunnel protection. Several other applications are known /1/. The practical advantages of this type of fire detecting system are a robust installation that is insensitive against electromagnetic interference and a fairly good fire detection capability.

Several attempts have been made to calculate the dynamic performance of the underlying pneumatic system by using approximative models that apply methods known from linear electrical network analysis /1, 2/. Although the response time figures calculated from these models seem to be fairly close to those measured in some experiments the models themselves suffer from the fact that all the elements involved have to be modelled as linear elements. This is obviously not consistent with physical reality.

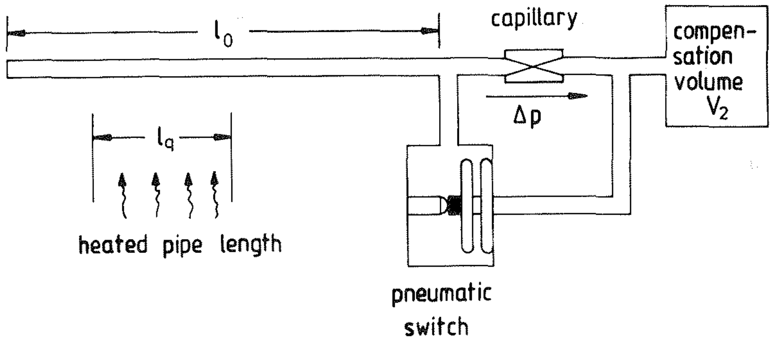


Fig. 1 Schematic sketch of a tube type fire detection system (SECURITON AG, Zollikofen, Switzerland)

The following article presents a method to calculate the dynamic performance that is approximative as well but takes nonlinearities into account where it seems to be necessary. The method has been developed using the characteristics and the essential parameters of the TRANSAFE fire detection system for road tunnels manufactured by the Securiton AG (Zollikofen, Switzerland).

2. BASIC MODELS FOR SYSTEM ELEMENTS

Fig. 1 shows a schematic sketch of the configuration used in the above mentioned tube type fire detection system. If a part of the pipe is heated a time varying pressure difference Δp will occur that operates a pneumatic switch.

The basic model that has been used in this study to calculate the dynamic performance is based on the following conditions:

(1.) The pressures and the fluid velocities within the pneumatic systems - except in the heated part of the sensor pipe - are small enough to assume that the specific air density ρ be a constant.
(2.) The flow resistances within the system - except that associated with the resistive capillary - are negligibly small.
(3.) The rate of change of all pneumatic values in the system is small enough to assume that dispersion within the system can be neglected. This assumption results in a model that considers a "system with concentrated elements" and there is no need to go back to the basic equations of gas dynamics (e.g. /3/ p. 182 or /4/).

Under the above conditions pressure variations in pneumatic subsystems can be described by associated variations in the mass flow to or out of the subsystems. Furthermore the model system itself can be described by using the so-called Kirchhoff-laws known from electrical network theory. The following is based on the equation for ideal gases

$$p\ V = \frac{R}{m} M\ T = \beta\ M\ T \qquad (2.1)$$

where p is the pressure and V an airfilled volume which e.g. is a part of the pneumatic sensor pipe. M is the total mass, T the absolute temperature and the

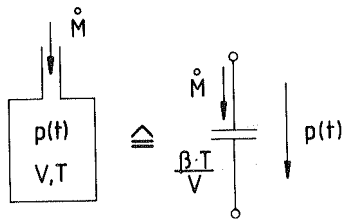


Fig. 2 Pneumatic capacity

constant β incorporates the gas-constant R and the molecular weight of the gas (air in this particular case). Introducing the specific air density $\rho = \frac{M_o}{V_o}$ at a known initial temperature T_o in the system, β can easily be calculated as follows using (2.1):

$$p_o = \beta \frac{M_o}{V_o} T_o = \beta \rho T_o \Rightarrow \beta = \frac{p_o}{\rho T_o}$$

In the following the system elements are discussed using the basic assumptions.

Airfilled Volumes at Constant Temperatures and with Time Varying Mass Flows

This model describes the constant temperature part of the sensor pipe of the length $l_o - l_g$ and the compensation vessel volume V_2 (see Fig. 1). Introducing the mass flow

$\mathring{M} = \frac{dM}{dt}$ we get

$$\mathring{p} V = \beta T \mathring{M} \quad \text{or} \quad \mathring{p} = \frac{\beta T}{V} \mathring{M} \qquad (2.2)$$

where $\frac{\beta T}{V}$ is a constant. (2.2) can be interpreted as a description of a pneumatic capacity, i.e. an element for potential energy storage, as shown in Fig. 2. From Fig. 1 it can easily be seen that the whole not heated part of the sensor pipe can be concentrated to one pneumatic capacity. Different elements of this kind can easily be connected in series as shown in Fig's. 3 and 4.

The Resistive Capillary

The capillary shown in Fig. 1 works as a flow resistive element. If friction within the flow is neglected and the flow is a laminar one the Bernoulli-law leads to

$$\Delta p = \text{const.}\ \mathring{M}_2 |\mathring{M}_2|$$

to describe the resistive behaviour of this element. Experimental results show on the other hand that the capillary flow is not laminar in the device under consideration and the best description for $\Delta p(\mathring{M}_2)$ is /5/

$$\Delta p = a\mathring{M}_2 + b\mathring{M}_2^c \qquad (2.3)$$

where a, b_o and c are constants that can be derived from these experimental results $p(M_2)$ by using a slight variation of the minimum mean square error method /5/.

Model for the Heated Part of Sensor Pipe

The most difficult part of the whole system for modelling is the heated length of the sensor pipe (see Fig. 1). This part is the source for all dynamic changes in the system. In order to produce a fairly well solvable differential equation (see eq. 3.7) the calculation model is based on the idea to replace the heated air volume by a volume of the same size V_q at constant temperature T_o and an additional time varying air flow $M_o(t)$ as indicated in Fig. 3. The left hand part of Fig. 3 a) and b) models the source while the right hand part (volume V) is a general pneumatic load that represents the remaining pneumatic system. This procedure follows the idea of equivalent-source-technique which is very common in electrical network theory. It is not quite correct to model the remaining pneumatic system simply by a volume V because V represents a purely "capacitive" load while the system contains a resistive element as well. Numerical calculations show that this error has an acceptable small influence on the final result at least for the system under consideration.

Assume that the temperature in the heated volume is rising according to

$$T(t) = T_o\, f(t) \quad \text{and} \quad f(t) = \begin{cases} 1 & \text{for } t < 0 \\ f(t) & \text{for } t \geq 0 \end{cases} \tag{2.4}$$

where f(t) is some suitable function of time.

The system in Fig. 3 a) is obviously described by

$$p_q = p \qquad \Rightarrow \mathring{p}_q = \mathring{p} \tag{2.5}$$

$$M_q + M = \text{const.} \qquad \Rightarrow -\mathring{M}_q = \mathring{M} \tag{2.6}$$

$$p_q\, V_q = \beta\, T\, M_q = \beta \int \frac{\partial}{\partial t} \quad (T\, M_q)\, dt \tag{2.7}$$

$$p\, V = \beta\, T_o\, M = \beta\, T_o \int \frac{\partial}{\partial t} \quad M\, dt \tag{2.8}$$

Rewriting (2.7) and (2.8) and using (2.4) we get

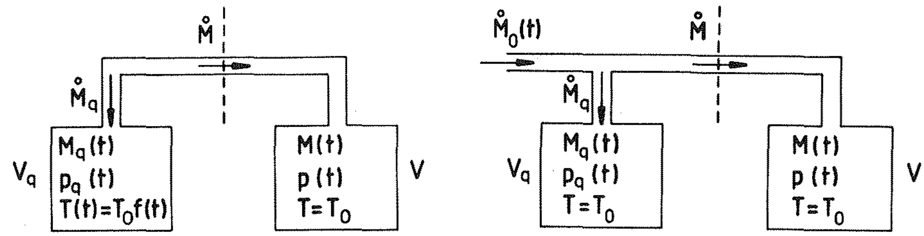
$$\mathring{p}_q = \frac{\beta\, T_o}{V_q} \, (\mathring{f}\, M_q + f\, \mathring{M}_q) \quad \text{and} \tag{2.9}$$

$$\mathring{p} = \frac{\beta\, T_o}{V} \, \mathring{M}. \tag{2.10}$$

Using (2.5) and (2.6) the result after some minor calculations is

$$\mathring{M}(t) = M_{qo}\, (1 + \frac{V}{V_q}) \, \frac{\frac{V}{V_q}\, \mathring{f}(t)}{(1 + \frac{V}{V_q}\, f(t))^2} \tag{2.11}$$

where



a.) Physical source model

b.) Source model using equivalent source technique

Fig. 3 Approximative models of pneumatic source

$$M_{qo} = M_q(t)\Big|_{t=0} = \rho\, V_q \tag{2.12}$$

In order to be equivalent the model according to Fig. 3 b) has to deliver the same flow $\dot{M}$ to the load V.

From Fig. 3 b) we get

$$p_q = p \qquad \Longrightarrow \dot{p}_q = \dot{p} \tag{2.13}$$

$$\dot{M}_o = \dot{M}_q + \dot{M} \tag{2.14}$$

$$p_q\, V_q = \beta\, T_o\, M_q \qquad \Longrightarrow \dot{p}_q = \frac{\beta\, T_o}{V_q}\, \dot{M}_q \tag{2.15}$$

$$p\, V = \beta\, T_o\, M \qquad \Longrightarrow \dot{p} = \frac{\beta\, T_o}{V}\, \dot{M} \tag{2.16}$$

Following the same line as above the introduced mass flow $\dot{M}_o$ can be written as

$$\dot{M}_o = \frac{V_q}{V}\,\dot{M} + \dot{M} = \frac{V + V_q}{V}\,\dot{M}$$

or using the result from (2.11)

$$\dot{M}_o(t) = \rho\, \frac{(V + V_q)^2}{V_q}\; \frac{\dot{f}(t)}{\left(1 + \frac{V}{V_q}\, f(t)\right)^2} \tag{2.17}$$

Having obtained this result it is necessary to consider the following items:

- The introduced source mass flow $\dot{M}_o$ depends on the load V. In other words it models the system including this particular capacitive load.

- Thus this way to proceed seems to be somewhat artificial and yields only approximative results if one predetermined source is applied to several pneumatic networks different from that used to determine it. On the other hand it can be easily shown that the resulting differential equation (3.7) becomes unsuitably sophisticated for practical use if the system in Fig. 4

would be calculated using the original source model according to Fig. 3a). The results in section 3 indicate that (2.17) can be applied for practical purposes to obtain a fairly suitable accuracy.

It should be mentioned that (2.17) contains both pneumatic open circuit

$$V = 0 \quad \Rightarrow \mathring{M}_o(t) = \rho\ V_q\ \mathring{f}(t)$$

and pneumatic short circuit

$$V \to \infty \Rightarrow \mathring{M}_o(t) = \rho\ V_q\ \frac{\mathring{f}(t)}{f^2(t)}$$

as well. So it covers the whole possible load range.

3. A CALCULATION MODEL FOR TUBE TYPE FIRE DETECTION SYSTEMS

Using the element models discussed in section 2 the tube type fire detection system according to Fig. 1 can be represented by an approximative model as shown in Fig. 4. V_q represents the heated part of the sensor pipe, V_2 is the compensation volume, $V_q + V_1 = V_o$ stands for the sensor pipe volume and $V_q + V_1 + V_2 = V_{ges}$ represents the whole volume of the pneumatic system.

The following equations can easily be derived from Fig. 4:

$$p_q = p_1 \qquad \Rightarrow \quad \mathring{p}_q = \mathring{p}_1 \tag{3.1}$$

$$p_1 = \Delta p + p_2 \qquad \Rightarrow \quad \mathring{p}_1 = \mathring{\Delta p} + \mathring{p}_2 \tag{3.2}$$

$$\mathring{M}_o = \mathring{M}_q + \mathring{M} \tag{3.3}$$

$$\mathring{M} = \mathring{M}_1 + \mathring{M}_2 \tag{3.4}$$

The expression (2.3) in sec. 2 can be written in a more general form

$$\Delta p = F(\mathring{M}_2) \tag{2.3}$$

and yields

$$\mathring{\Delta p} = \frac{d}{dt}\ F(\mathring{M}_2) = \frac{\partial F}{\partial M_2}\ \overset{\circ\circ}{M}_2 \tag{3.5}$$

and using (2.2) we have

$$\mathring{p}_q = \frac{\beta T_o}{V_q}\ \mathring{M}_q; \qquad \mathring{p}_1 = \frac{\beta T_o}{V_1}\ \mathring{M}_1; \qquad \mathring{p}_2 = \frac{\beta T_o}{V_2}\ \mathring{M}_2 \tag{3.6}$$

Combining (3.1) through (3.6) we arrive, after some simple calculations, at a differential equation for $\mathring{M}_2$:

$$\frac{\partial F}{\partial M_2}\ \overset{\circ\circ}{M}_2 + \frac{\beta\ T_o V_{ges}}{V_o V_2}\ \mathring{M}_2 = \rho\ \beta\ T_o\ \frac{V_q}{V_o}\ (\frac{V}{V_q} + 1)^2\ \frac{\mathring{f}(t)}{(1 + \frac{V}{V_q}\ f(t))^2} \tag{3.7}$$

with the initial condition $\mathring{M}_2(0) = 0$.

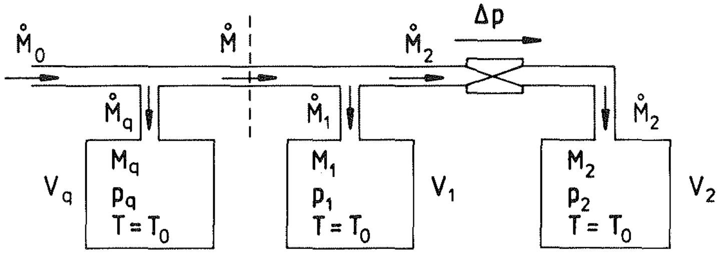


Fig. 4 Approximative model of a tube type fire detection system (SECURITON AG, Zollikofen, Switzerland)

After solving this for $\mathring{M}_2$ (2.3) can be used to calculate Δp as a function of time. In general (3.7) cannot be solved analytically and some numerical methods have to be applied. There are only very special parameter sets that result in an easy analytical solution, e.g. F being a quadratic function of $\mathring{M}_2$, f a linear function of t and $V \to 0$ (see /5/).

So a computer program based on a suitable Runge-Kutta method has been developed and carefully tested that is based on

$$\Delta p = F(\mathring{M}_2) = a\mathring{M}_2 + b\mathring{M}_2^c \qquad (2.3)$$

with a wide range for the parameters a, b and c and on four different functions f(t) for the temperature rise in the heated part of the sensor vessel.

$$f_1(t) = 1 + \alpha_1 t \qquad (3.8)$$

a linear temperature rise

$$f_2(t) = e^{\alpha_4 t} \qquad (3.9)$$

an exponential temperature rise

$$f_3(t) = f_{max} - (f_{max} - 1)\, e^{-\alpha_3 t} \qquad (3.10)$$

an exponential temperature rise with a predetermined limit f_{max}

$$f_4(t) = \frac{f_{max}\, e^{\alpha_4 t}}{(f_{max} - 1) + e^{\alpha_4 t}} \qquad (3.11)$$

a mixture of (3.9) and (3.10) that is likely to model practical cases quite well.

The only parameter in (3.7) which is not directly derived from the detection system under consideration is the volume V. V had been used to derive the model for the driving source and models the not heated part of the pneumatic system (see Fig. 3). Therefore it is a free parameter which may have an unsuitable influence on the result. In order to check this influence, some calculations have been made using the actual parameters of the above mentioned system (TRANSAFE, Securiton AG, Zollikofen, Switzerland) with four different choices for the volume V:

$V = 0$	pneumatic open circuit
$V \to \infty$	pneumatic short circuit
$V = V_1$	not heated part of the sensor vessel
$V = V_1 + V_2$	not heated part of the whole system volume

and a linear temperature rising according to (3.8).

The result is shown in Fig. 5. Very similar results can be obtained with other types of temperature rises. They indicate considerable differences which disqualify the outlined calculation method for general application. On the other hand it has to be taken into account that the alarm pressure threshold Δp_a for the pneumatic switch normally is in the range of 150 Pa to 400 Pa. In this range no significant differences are produced in the whole range possible for V by the calculation method discussed above. This is shown in Fig. 6 in some more detail. It justifies the conclusion that the above mentioned method may be applied successfully to calculate the response time of tube type heat sensitive fire detection systems in practice. In addition it can very well be applied to calculate the minimum rate of rise of temperature in the heated part of the sensor that is necessary to trigger an alarm signal at all if the response pressure threshold is fixed. Or it can be used to calculate the minimum length of the sensor vessel to be heated that is necessary to produce an alarm. Or it can be used to calculate the temperature variations within the protected premises which are tolerated by the system without a false alarm.

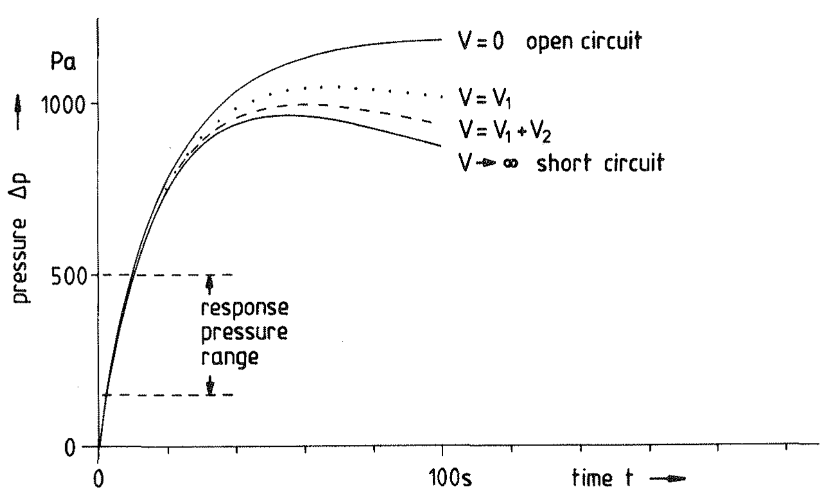


Fig. 5 Pressure Δp at the pneumatic switch as a function of time

4. SUMMARY

An approximative method has been presented for the calculation of the dynamic performance of tube type heat sensitive fire detection systems. It is based on some basic assumptions which simplifiy the calculation procedure to make it

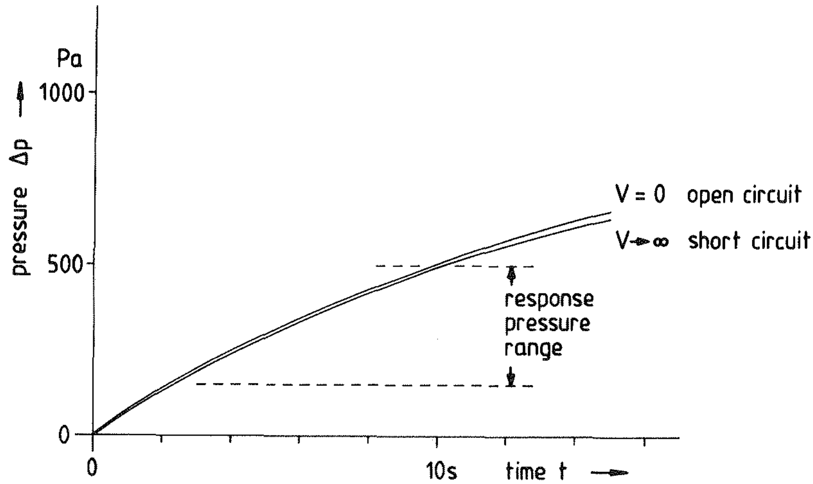


Fig. 6 Pressure Δp at the pneumatic switch

applicable in practical cases. On the other hand it is limited to a time range of approximately 50 s and a response pressure threshold up to 400 Pa for the pneumatic switch. Within this range the method can be used to calculate e.g. response times or suitable response pressure thresholds under different system parameters.

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