2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

Development of a model for an air brake system with leaks

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Abstract— **Brake systems in trucks are crucial for ensuring the safety of vehicles and passengers on the roadways. Most trucks in the US are equipped with S-cam drum brake systems and they are sensitive to maintenance. Brake defects such as leaks are a major cause of accidents involving trucks. Leaks in the air brake systems affect braking performance drastically by decreasing the maximum braking pressure and also increasing the time required to attain the same, thereby resulting in longer stopping distances. In this paper, we present a mathematical model for an air brake system in the presence of leaks with a view towards developing a diagnostic system based on this model in the near future. The model that has been developed builds on earlier research at Texas A&M University in which the pressure evolution in the brake chamber was determined as a function of the brake pedal input in the absence of any leaks in the air brake system. A leak may be characterized by its location and size. Since the connecting pipes are short, the location of the leak does not significantly affect the evolution in the brake pressure as much as its size. We provide a constitutive relationship for the leak and we estimated the associated parameter, namely, the "effective area" of the leak from the experimental data. The supply pressure and effective area of leak comprised the inputs to the model along with the displacement of the brake pedal (treadle valve plunger). We also provide a simple leak detection scheme and estimates of the severity of the leak in terms of the mass flow rate of leaking air based on the input measurements of brake pressure for a full application of the brake pedal and the supply pressure. This scheme can be implemented using a simple look-up table.**

I. INTRODUCTION

Air brake systems are commonly used in commercial vehicles like buses, trucks and tractor-trailers[1]. More than 85% of the commercial vehicles in the US are equipped with S-cam drum brakes[2]. Proper functioning of the brake system of a commercial vehicle is critical not only from the viewpoint of the safety of the vehicle itself, but also for other vehicles and passengers in traffic. An accident involving a commercial vehicle could result not only in economic loss of the goods transported but could also result in loss of life.

As air brake systems are sensitive to maintenance, periodic maintenance and inspection procedures must be frequently conducted[3]. Accidents involving commercial vehicles rarely occur due to brake failures but occur frequently due to brake defects. Typical brake related defects include oversize drums, worn out brake linings, out-of-adjustment pushrod strokes and leaks in the system. Statistics indicate[4] that truck tractors pulling semi-trailers accounted for 63% of the trucks involved in fatal crashes and about 37% of the trucks involved in non-fatal crashes. About 25% of the crashes involving trucks were due to brake deficiency and brake deficiency accounted for 39% of the total one-vehicle crashes.

Out-of-adjustment pushrod strokes drastically decrease the maximum braking force that can be attained and increase the time delay in the response of the brake pressure. This results in increased stopping distances, causing a safety hazard[5]. Leaks affect the brake system by reducing the maximum achievable braking pressure in the brake chamber and by increasing the time for the pressure to build in the brake chambers. Hence, there is a need for a diagnostic scheme to detect leaks and estimate the pushrod stroke in an air brake system. A fast, reliable and accurate diagnostic scheme will reduce inspection times, manpower and costs involved.

Most of the performance tests and visual based inspection tests of the air brake system indirectly correlate pressure in the brake chamber with the torque output, brake pad temperature, pushrod stroke etc[6], [7]. However, none of these tests can provide information concerning the speed of the brake response which is directly affected by leaks and out-of-adjustment of the pushrod. In order to address this problem and to develop an on-board diagnostic system that is convenient for fleet operators and inspectors to conduct maintenance and enforcement inspection, Subramanian et al. [8] proposed a model for predicting the pressure transients in the brake chamber (in the absence of any defects) of a brake system. The idea is to use the model to estimate the pushrod stroke and the severity of leaks in the brake system from the measurements of the displacement of the brake pedal and the pressure in the brake chambers. In the development of a model, Subramanian et al. [8] treated the treadle valve as a nozzle; the input to the model proposed in [8] is the treadle valve plunger displacement (brake pedal displacement). This paper extends the model of Subramanian et al. and deals with the development of a mathematical model for predicting pressure transients in the brake chamber in the presence of leaks and the experimental corroboration of the same.

A. Air Brakes System

A typical brake system layout for a tractor trailer is presented in Fig.1[9]. The air brake system layout is also called as a dual brake circuit. The braking circuit is designed in such a way that, in case of a failure of one of the circuits, partial braking is possible with the help of the other. The two circuits are highlighted in green and orange colors in Fig.1. Some of the major components of an air brake system are the compressor and reservoirs, brake valve (treadle valve), quick release and relay valves, foundation brake assembly, brake chambers and slack adjusters. For a

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978-1-4244-4524-0/09/$25.00 ©2009 AACC

complete and detailed description of all the components, their specifications, working principles, maintenance and testing details of the air brake system, the reader is referred to [9], [5] and [10].

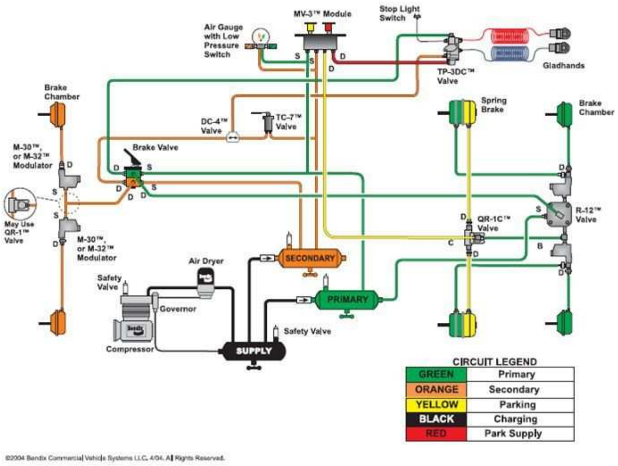

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Fig. 1. Layout of an air brake system.

II. EXPERIMENTAL SETUP

An experimental setup that closely resembles the actual air brake system in a commercial vehicle was built at Texas A&M University. A representative sketch of the experimental setup is shown in Fig.2 [11].

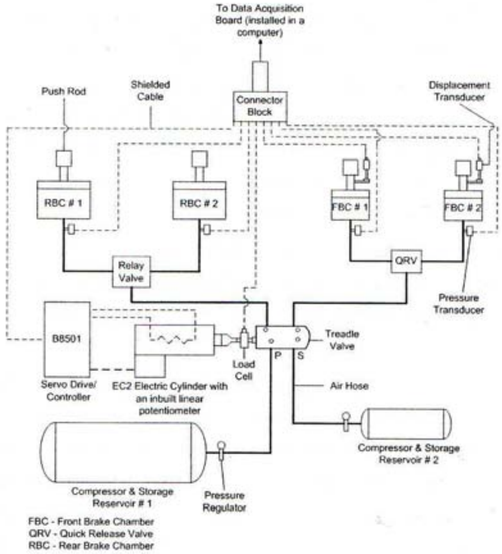

Fig. 2. Schematic of the experimental setup.

A. Details of the setup

The setup has two "Type-20" brake chambers on the front axle brakes and two "Type-30" brake chambers mounted on a fixture designed to simulate a rear axle. Air is supplied by a 5HP air compressor and a 15 gallon storage reservoir. Pressure regulators are installed at the delivery side of the reservoir to control the air pressure supplied to the system. A dual brake valve (treadle valve) serves as the input to the braking system.

The treadle valve is actuated using an electromechanical actuator with position feedback. The actuator is controlled by a servo drive/controller. Pressure transducers are mounted at the entrance of all brake chambers to record the pressure transients. A displacement transducer is mounted on each of the front brake chamber pushrods to record the pushrod stroke. All the sensors were interfaced using a Data Acquisition (DAQ) card mounted on a PC for data collection during the test runs. The desired treadle valve plunger motion is the input from the computer to the servo drive through the DAQ card. A MATLAB/Simulink application records and analyze the data. A complete description of all the foundation brake, actuation and data acquisition components of the setup can be found in [11].

For the purpose of measuring the mass flow rate of leaking air, a graduated Flow Control Valve (FCV) manufactured by Mead Fluid Dynamics[12], was installed to obtain a greater control over the degree of leak introduced in the system. Four turns on the dial of the FCV completely opens the valve. The primary delivery of the treadle valve was directly connected to one of the front brake chambers for all test runs. The FCV was installed between the primary delivery and the brake chamber as shown in Fig.II-A. Leaks of varying degrees were introduced by turning the dial of the FCV by half-a-turn, one full turn, two full turns etc.

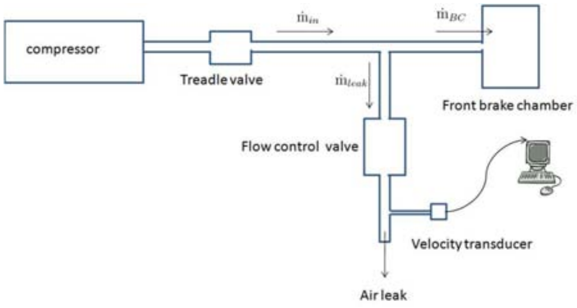

Fig. 3. Schematic of the leak measurement setup.

To measure the mass flow rate of leaking air, a velocity transducer was installed. The sensor was interfaced using the DAQ card and the voltage outputs were recorded during the test runs. The voltage outputs from the sensor were then converted to dynamic pressure using the calibration curve of the sensor. This pressure data was converted to mass flow rate using suitable multiplication factors. A photograph of the experimental setup in Fig.4[11].

III. A MATHEMATICAL MODEL FOR THE AIR BRAKE SYSTEM IN THE PRESENCE OF LEAKS

Before we consider a mathematical model for the air brake system in the presence of leaks, we will present a brief description of the "fault-free" model developed in [11] as it forms the basis for the mathematical model that is desired.

Fig. 4. Air brakes system laboratory.

A. "Fault-free" model

As the name implies, the "fault-free" model predicts the pressure response of the brake system in the absence of any faults such as leaks etc. This model describes the evolution of pressure in the brake chamber in response to the treadle valve plunger displacement and the supply pressure to the system. The model was developed for a brake system configuration where one of the front brake chambers was directly connected to the primary delivery port of the treadle valve. A lumped parameter approach was employed to develop the model.

1) Assumptions: The governing equations of the "fault-free" model were developed using the following assumptions:

1) Friction at all sliding surfaces of the valves may be assumed to be negligible since all components were well lubricated.
2) Inertial forces were assumed to be small compared to the pressure forces and spring forces.
3) The primary inlet valve opening of the treadle valve may be assumed to behave like a nozzle.
4) Thermal properties in the supply chamber of the treadle valve were assumed to be the stagnation properties for the inlet of the nozzle.
5) Flow through the treadle valve opening was assumed to be one-dimensional and isentropic.
6) Air was assumed to behave like an ideal gas with constant specific heats.
7) Uniform fluid properties were assumed at all sections in the nozzle. Also, the peak Mach number of the compressed air flow in the system was measured and found to be less than 0.2.

For a complete list of assumptions involved in the development of the governing equations, the reader may refer to [11]. The nomenclature for the variables used in the model is given in Table I. The governing equations for determining the pressure response of the brake system is based on an application of balance of mass and energy for the pneumatic subsystem as shown in Fig.5[11]. For a detailed derivation, the reader is referred to [8]. The governing equations are:

$$(\frac{2\gamma}{(\gamma-1)RT_0}[(\frac{P_b}{P_0})^{\frac{2}{\gamma}} - (\frac{P_b}{P_0})^{\frac{\gamma+1}{\gamma}}])^{\frac{1}{2}} A_p C_D P_o sgn(P_o - P_b) =$$

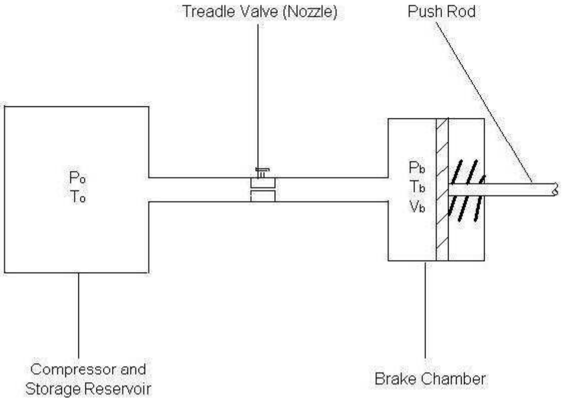

Fig. 5. Schematic of the pneumatic subsystem.

TABLE I

NOMENCLATURE OF PARAMETERS USED IN THE GOVERNING EQUATIONS

Parameter	Description
γ	Ratio of specific heats for air, 1.4
R	Gas constant for air, 287 J/kgK
T_0	Stagnation temperature, K
P_b	Local pressure inside the brake chamber, Pa
P_0	Supply pressure, Pa
A_p	Area of treadle valve opening, m^2
C_D	Coefficient of discharge
V_{01}	Initial volume of air in brake chamber, m^3
P_{th}	Push-out pressure, Pa
V_b	Volume of air inside the brake chamber, m^3
A_b	Area of brake chamber diaphragm, m^2
M_1	Calibration constant, 1.419e-6 m/Pa
M_2	Calibration constant, 2.341e-8 m/Pa
P_{ct}	Brake pad contact pressure, Pa

$$\begin{cases} (\frac{V_{o1}P_0^{\frac{\gamma-1}{\gamma}}}{\gamma RT_0 P_b^{\frac{\gamma-1}{\gamma}}})\dot{P}_b & \text{if } P_b < P_{th}, \\ (\frac{V_b P_0^{\frac{\gamma-1}{\gamma}}}{\gamma RT_0 P_b^{\frac{\gamma-1}{\gamma}}} + \frac{P_b^{\frac{1}{\gamma}} A_b M_1 P_0^{\frac{\gamma-1}{\gamma}}}{RT_0})\dot{P}_b & \text{if } P_{th} \le P_b < P_{ct}, \\ (\frac{V_b P_0^{\frac{\gamma-1}{\gamma}}}{\gamma RT_0 P_b^{\frac{\gamma-1}{\gamma}}} + \frac{P_b^{\frac{1}{\gamma}} A_b M_2 P_0^{\frac{\gamma-1}{\gamma}}}{RT_0})\dot{P}_b & \text{if } P_b \ge P_{ct}. \end{cases} \tag{1}$$

2) Features of the "fault-free" model: The following are the important features of the "fault-free" model:

1) The pressure increases until the preload on the spring in the brake chamber is overcome. Once the preload of the spring is overcome, the system switches from the first mode to the second mode in which the pushrod moves until the gap between the brake pads and the drum is cleared and the brake shoes contact the brake drum. Once the brake shoes contact the drum, the system switches from the second mode to the third mode and the pressure increases in the brake chamber to the steady state value. Only after the brake shoes contact the drum (i.e. the system is in the third mode), braking action occurs.
2) The governing equation in each mode is a nonlinear first order ordinary differential equation.

3) The governing equation for each mode is different.
4) The system shifts from one mode to another based upon the transition conditions, which are linear inequalities.

The above set of equations may be solved using the fourth order Runge-Kutta numerical method to obtain the pressure response in the brake chamber. Treadle valve plunger displacement was the input to the numerical scheme.

B. Modeling the air brake system in the presence of leaks

The "fault-free" model discussed above, predicted the pressure transients reasonably well if there were no leaks in the system as shown in Fig.6[11]. A sample corroborative plot is shown below:

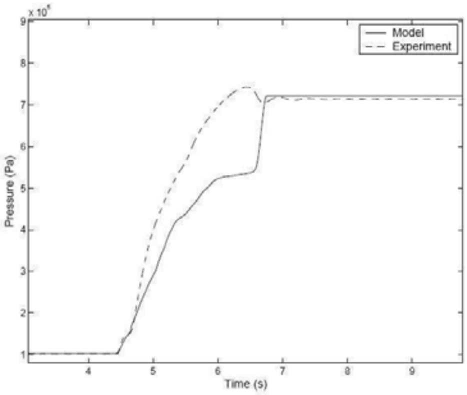

Fig. 6. Pressure transients at 722 kPa (90 psi) supply pressure with no leak.

Modeling the pressure transients in the presence of leaks will facilitate the development of a diagnostic system in compliance with the Federal Motor Vehicle Safety Standards (FMVSS) [13]. For the purposes of developing a model, the leak may be assumed to be near the brake chamber and past the treadle valve as shown in Fig.II-A. We assume that the opening through which air leaks behaves like a nozzle. Since air leaks to the atmosphere and the ratio of the supply pressure to the atmospheric pressure is greater than the critical pressure ratio [14], choked flow conditions may be assumed. Therefore, applying the conservation of mass near the leak geometry Fig. II-A, we have

$$\dot{m}_{in} - \dot{m}_{leak} = \dot{m}_{BC} \tag{2}$$

where, the total mass flow rate from the treadle valve is denoted by $\dot{m}_{in}$, the mass flow rate of air leaked to atmosphere is denoted by $\dot{m}_{leak}$ and the mass flow rate of air entering the brake chamber is denoted as $\dot{m}_{BC}$. Since there are no leaks or losses in the system, mass balance for the "fault-free" model is

$$\dot{m}_{in} = \dot{m}_{BC} \tag{3}$$

The expressions for $\dot{m}_{in}$ and $\dot{m}_{BC}$ can be found on the left and right hand side of (1) respectively.

For the model to capture the effects of leak, an expression for $\dot{m}_{leak}$ needs to determined and subtracted from $\dot{m}_{in}$. The resulting expression would then be equated to $\dot{m}_{BC}$ of (1). We derive a constitutive relation for the leak in the next subsection.

C. Derivation of $\dot{m}_{leak}$

In agreement with our intuition, we observed during the experiments that the mass flow rate of the leak increased with the supply pressure and also with the area of leak (determined by the number of turns of the FCV). The influence of location of the leak on the pressure evolution was not as significant as the size of the leak. Hence, we assume $\dot{m}_{leak}$ to be of the form

$$\dot{m}_{leak} = f(P_{sup}, A_l) \tag{4}$$

where, P_{sup} is the supply pressure and A_l is the area of leak. In reality, area of the leak A_l, may not be known a priori and it must be inferred from the pressure response. We further assume that the flow of leaking air is similar to that of a flow through a nozzle and that it is choked and use the following specific functional form for the mass flow rate of leaking air:

$$\dot{m}_{leak} = C_d A_l \frac{P_{sup}}{\sqrt{RT}} \sqrt{(\frac{2}{\gamma+1})^{(\frac{\gamma+1}{\gamma-1})}} \tag{5}$$

where C_d is coefficient of discharge, γ is the ratio of specific heats for air, R is the gas constant for air. Since the variables in the above expression (5) are pressure P_{sup} and temperature T, we define a new parameter K as follows:

$$K = \frac{C_d A_l}{\sqrt{R}} \sqrt{(\frac{2}{\gamma+1})^{(\frac{\gamma+1}{\gamma-1})}} \tag{6}$$

so that

$$\dot{m}_{leak} = \frac{K P_{sup}}{\sqrt{T}}. \tag{7}$$

The term $C_d A_l$ will be referred to as "effective leak area" since the actual leak area is not known. From (6), $C_d A_l$ can be easily obtained.

We will employ a least squares approach to determine the effective area of the leak. One can determine the value of K that minimizes the least squares error ϵ given below:

$$\epsilon = \sum_{i=1}^{N} (\dot{m}_{meas}(i) - K\frac{P_{sup}(i)}{\sqrt{T}})^2 \tag{8}$$

where N is the total number of samples, i is the sample number, $\dot{m}_{meas}$ is the measured leak mass flow rate. The parameter K was found for leak measurements performed at different supply pressures (90 psi, 80 psi etc) and at different FCV settings (half-a-turn, single turn, two turns etc) . The corresponding effective leak area, $C_d A_l$ was obtained from (6).

The least squares approach requires the values of $\dot{m}_{meas}, P_{sup}$ and T, of which the last two variables are measurable with reasonable accuracy using the sensors we have in our laboratory set up. The flow of leaking air in the air brake system is turbulent and to compute the mass flow rate, the following approach was adopted: We had a cylindrical pipe connected to the output port of the FCV so that the leaking air flows through the pipe. We then measure the centerline velocity of the flow through the pipe and use the correction factor for the measured velocity using the "one-seventh" power law approximation of velocity profiles [15], [16]. Using the correction factor, the ratio of average velocity, $\overline{V}$ to the measured centerline velocity, U, is

$$\frac{\overline{V}}{U} = \frac{49}{60} \tag{9}$$

We then computed the mass flow rate of leaking air using the following relation:

$$\dot{m}_{meas} = \rho_{air} A_{pipe} \overline{V} \tag{10}$$

where $\dot{m}_{meas}$ is computed value of mass flow rate of leaking air, ρ_{air} is the density of air at ambient temperature and A_{pipe} is the cross-sectional area of the pipe of diameter 10 mm used in the experiment.

IV. CORROBORATION OF THE MODEL AND EXPERIMENTAL RESULTS

The following table II documents the mass flow rate of leaking air in relation to the supply pressure and the number of turns of the FCV. It also provides the value of steady state brake pressure and the value of parameter K corresponding to the given supply pressure and the number of turns of FCV. From experiments, we observed that the difference between the supply pressure and the steady state pressure in the brake chamber has a strong correlation to amount by which FCV is turned (which correspondingly changes the effective area for leak). This observation serves two purposes: Firstly, one may be able to build a simple diagnostic system where one compares the steady state pressure in the brake chamber with the supply pressure and infers the mass flow rate of leaking air from the table II. One may alternatively relate from the table II the pressure difference to the equivalent number of turns for the FCV that would result in the given pressure difference. The second purpose is to determine the parameter K for "realistic" leaks. Once we obtained the table II, we use it as a reference for obtaining the parameter K for other leaks. In order to simulate realistic leaks, we obtained various orifices of different diameters and replaced the FCV with the orifices and introduced leaks through the orifices. In reality, one may not know the area of the leak; for this reason, we do not use the area of the orifices (and we may not be able to use it because we may have to calibrate the coefficient of discharge for these orifices as well). Instead, we collect the pressure response data over a period of time and compare the "steady state" value of the pressure to the supply pressure. From this comparison, we obtain the parameter K from table II. The parameter K may then be used in (7). The expression for (7) may then be substituted into (2) and numerically integrated and compared with the measured response of the brake pressure so as to corroborate the developed model.

TABLE II

LEAK MASS FLOW RATES FOR A FULL BRAKE APPLICATION AT DIFFERENT SUPPLY PRESSURES

Supply Pressure (psi)	FCV Turns	$\dot{m}_{leak}$ (g/s)	K	Steady State Pressure(psi)
90	0.5	0.83	1.94×10^{-7}	87.28
90	1	1.18	3.23×10^{-7}	86.76
90	1.5	1.60	4.78×10^{-7}	86.02
90	2	1.82	5.78×10^{-7}	85.78
90	2.5	2.35	7.65×10^{-7}	84.07
80	0.5	0.74	1.79×10^{-7}	77.67
80	1	1.10	3.25×10^{-7}	77.21
80	1.5	1.40	4.75×10^{-7}	77.03
80	2	1.66	5.65×10^{-7}	76.77
80	2.5	2.06	7.58×10^{-7}	76.28
70	0.5	0.61	1.67×10^{-7}	68.33
70	1	0.84	3.12×10^{-7}	68.10
70	1.5	1.17	4.61×10^{-7}	67.76
70	2	1.42	5.84×10^{-7}	67.14
70	2.5	1.62	7.77×10^{-7}	66.87

A representative plot of the pressure response of the brake system in the presence of leaks is given in the following figure:

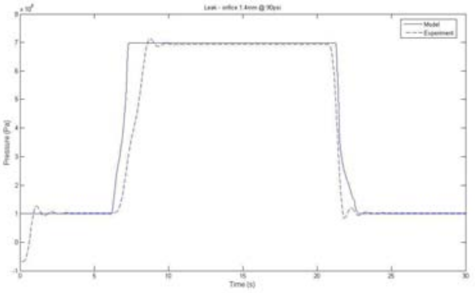

Fig. 7. Pressure transients at 90 psi supply with 1.4mm orifice.

A. Conclusions

In this paper, we have presented a constitutive relationship for the leak in an air brake system and used it in developing a mathematical model for the air brake system in the presence of leaks. Experiments seem to suggest that the difference in the supply pressure and the steady state pressure in the brake chamber is strongly related to the severity of the leak. Based on this observation, we have developed a simple diagnostic scheme for estimating the severity of leak in terms of the "effective area" of the leak that is reflected in the parameter K introduced in this paper. Experiments seem to indicate that the pressure response from the mathematical model seems to agree reasonably well with the experimentally observed pressure response. We believe that this model will be suitable for developing further diagnostic schemes such as the estimation of pushrod stroke in the presence of leaks.

V. ACKNOWLEDGMENTS

The authors greatly acknowledge the support of National Science Foundation under grant CMMI-0556343.

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