Proceedings of the 11th
KACC, October 1996

CONTROLLER DESIGN FOR A HYDROCONE CRUSHER
Part 1: Modeling and Simulation of the Hydroset Circuit.

"Raphael Mwangobola, Minoru Sasaki, Fumio Fujisawa, and Hiroshi Yamamoto

Dept. of Mechanical Engineering, Gifu University, Yanagido 1-1, Gifu 501-11 Japan
Tel: +81-58-230-1111; Fax:+81-58-230-1892; E-mail:ralph@cc.gifu-u.ac.jp

Abstracts This paper proposes an approach in modeling a 4x60inch Allis Chalmers® Hydrocone Crusher [1] hydroset and presents some numerical simulation results. The mining and quarry industry is one of the industries which extensively use hydrocone crushers, which are a family of cone crushers, for rock size reduction. Field studies have proved that if proper control and management of these machines is undertaken, they can yield an increased production output of more than 30%, in addition substantial savings in both energy consumption per unit ton produced and manpower can be easily realized. In order to achieve these economic benefits, high performance from these machines is expected. Implementing automatic control for such machines would be a great leap towards achieving both economic benefits and more effective fool-proof predictive maintenance. But, unfortunately, for such a control system to be designed, it necessary to make a mechatronical model of this plant. The plant model is able to give us an insight into variations of both the plant gap setting (displacement) and system pressure due to variable loading arising from the crushing process.

Keywords Hydrocone Crusher, Hydroset Circuit Modeling, Numerical Simulation

1. INTRODUCTION

Aggregate produced by a crushing plant of a mine or quarry is judged by its quality and size distribution, depending on its final usage (metal extraction, road surfacing, etc.). Adhering to product quality (i.e. shape, and consistency) requires that the aggregate producing machine be able to control the size accurately to the required quality control standards (e.g. BS 812:Part 102:1989). In the case of the mining industry, very fine ore is required in order to facilitate easier grinding which leads to higher mill throughput, hence high productivity. Traditional control systems for cone crushers rely on personnel observation and manual machine control. Thus, it is not an easy task to produce such homogenous material due to both objective (machine control) and subjective (human) factors inherent in the production process. Our major aim is to control the aggregate size to conform to required standards. In the case of the 4x60inch Allis Chalmers® hydrocone crusher, which forms the secondary or tertiary crushing unit of crushing plant, the aggregate size can be controlled using the in-built hydraulic system[1]. Size control is accomplished by keeping constant the gap between the mantle liner and the concave ring, i.e. crushing members. This is termed the crusher closed side setting or gap setting. Unfortunately, this is accompanied by complexities due to non-linearity in the machine arising from non-linear wear patterns of the crushing members, oil compressibility, variable friction etc. To realize precise gap setting, it is necessary that the dynamics of the hydroset be modeled as accurately as possible.

2. HYDROSET MATHEMATICAL MODEL

The crusher in-built hydraulic set or hydroset (figure 1) of the hydrocone crusher [1], consists of a simple arrangement of standard hydraulic equipment

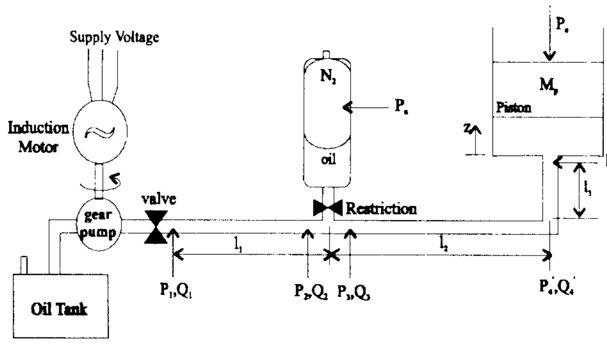

Figure 1. Hydroset model schematic diagram.

components including a hydraulic jack (piston-cylinder), oil reservoir, high pressure gear-type pump, nitrogen gas filled accumulator and pipelines. The equivalent models of these components, roughly scaled down models using geometric and kinetic similarities, are dealt with individually in this paper. The only model available for a cone crusher is that proposed by W. J. Whiten, this model is useful for dealing with crushing plant material balance. We are interested in a mechatronic model of the crusher which influences the gap setting directly. A schematic diagram of the hydroset which will be used to create a model is shown in figure 1.

2.1 Transmission line model

The hydroset has a short transmission line and another relatively long one. The distributed parameter approach is used to create a model of the transmission line because this gives a good insight of the complex dynamics of the machine to a certain degree. The transfer function of the transmission line is found by solving the Navier-Stokes equations assuming constant temperature (45℃), rotational symmetry, and ignoring axial heat transfer[1]. The flow is also assumed to be laminar, hence a low Reynolds number. All these approximations lead to a one dimensional Navier-Stokes equation whose solution involves Bessel functions of the zero order, $\mathbf{J}_0$, and the first order, $\mathbf{J}_1$. The exact model of a transmission line[1] is given by equation (1).

$$\begin{bmatrix} P_1 \\ Q_1 \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_c \sinh \gamma l \\ \frac{1}{Z_c} \sinh \gamma l & \cosh \gamma l \end{bmatrix} \begin{bmatrix} P_2 \\ Q_2 \end{bmatrix} \tag{1}$$

Here, P_1 and P_2, are the input and output pressure, Q_1 and Q_2 are the respective input and output flow rates, l is the length of the transmission line, and the propagation coefficient is

$$\gamma_l = \frac{s}{c}\left\{1 - \frac{2}{j\sqrt{\bar{s}}} \frac{\mathbf{J}_1\left[j\sqrt{\bar{s}}\right]}{\mathbf{J}_0\left[j\sqrt{\bar{s}}\right]}\right\}^{1/2} \tag{2}$$

while the characteristic impedance is expressed as

$$\mathbf{Z}_c = Z_0\left\{1 - \frac{2}{j\sqrt{\bar{s}}} \frac{\mathbf{J}_1\left[j\sqrt{\bar{s}}\right]}{\mathbf{J}_0\left[j\sqrt{\bar{s}}\right]}\right\}^{-1/2} \tag{3}$$

Here, we use the normalized Laplace transform function $\bar{s} = s\upsilon/r^2$, r is the radius of the pipe, and υ is the dynamic viscosity and the impedance constant is $Z_0 = \rho c/\pi r^2$. Depending on the causality, 4 different cases can be distinguished and these are given in TABLE 1[4]. For our particular study purposes, we adopt configuration C and the equation of the transmission line can be written as

$$\begin{bmatrix} P_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} \frac{\sinh \gamma l}{Z_c \cosh \gamma l} & \frac{1}{\cosh \gamma l} \\ \frac{1}{\cosh \gamma l} & -\frac{Z_c \sinh \gamma l}{\cosh \gamma l} \end{bmatrix} \begin{bmatrix} Q_1 \\ P_2 \end{bmatrix} \tag{4}$$

The hyperbolic functions of are complex functions and they are non-linear containing many vibration modes. We use the modal approximation analysis method, suggested by Hsue et. al[3], which is a good approach for analyzing such systems.

TABLE 1. Possible configurations of a transmission line

Model	$P_1 \rightarrow$ A $\rightarrow Q_2$; $Q_1 \leftarrow$ A $\leftarrow P_2$	$P_1 \rightarrow$ B $\rightarrow P_2$; $Q_1 \leftarrow$ B $\leftarrow Q_2$	$Q_1 \rightarrow$ C $\rightarrow Q_2$; $P_1 \leftarrow$ C $\leftarrow P_2$	$Q_1 \rightarrow$ D $\rightarrow P_2$; $P_1 \leftarrow$ D $\leftarrow Q_2$
G_{11}	$\frac{\sinh \gamma_l}{Z_c \cosh \gamma_l}$	$\frac{\cosh \gamma_l}{Z_c \sinh \gamma_l}$	$\frac{Z_c \sinh \gamma_l}{\cosh \gamma_l}$	$\frac{Z_c \cosh \gamma_l}{\sinh \gamma_l}$
G_{12}	$\frac{1}{\cosh \gamma_l}$	$\frac{1}{Z_c \sinh \gamma_l}$	$\frac{1}{\cosh \gamma_l}$	$\frac{Z_c}{\sinh \gamma_l}$
G_{21}	$\frac{1}{\cosh \gamma_l}$	$-\frac{1}{Z_c \sinh \gamma_l}$	$\frac{1}{\cosh \gamma_l}$	$-\frac{Z_c}{\sinh \gamma_l}$
G_{22}	$-\frac{Z_c \sinh \gamma_l}{\cosh \gamma_l}$	$-\frac{\cosh \gamma_l}{Z_c \sinh \gamma_l}$	$-\frac{\sinh \gamma_l}{Z_c \cosh \gamma}$	$\frac{Z_c \cosh \gamma_l}{\sinh \gamma_l}$

2.2 Modal analysis approach

The modal analysis approach is based on a technique for formulating rational polynomial approximations using product series for both Bessel functions and hyperbolic functions. This approach accounts for real poles of these functions as well as second order zeros. There are 7 basic polynomials used for analyzing transmission lines and these are:

$$\begin{aligned}
\frac{\cosh \gamma}{Z_c \sinh \gamma} &= \sum_{i=1}^{m} \frac{k_i'}{\bar{s} + u_i} + \sum_{i=1}^{n} \frac{a_{1i}'\bar{s} + b_{1i}'}{\bar{s}^2 + 2\bar{s}\zeta_{1i}\omega_{n1i} + \omega_{n1i}^2} \\
\frac{1}{Z_c \sinh \gamma} &= \sum_{i=1}^{m} \frac{k_i'}{\bar{s} + u_i} + \sum_{i=1}^{n} \frac{a_{2i}'\bar{s} + b_{2i}'}{\bar{s}^2 + 2\bar{s}\zeta_{1i}\omega_{n1i} + \omega_{n1i}^2} \\
\frac{Z_c \cosh \gamma}{\sinh \gamma} &= \frac{Z_0}{D_n \bar{s}} + \sum_{i=1}^{n} \frac{a_{3i}'\bar{s} + b_{3i}'}{\bar{s}^2 + 2\bar{s}\zeta_{1i}\omega_{n1i} + \omega_{n1i}^2} \\
\frac{Z_c}{\sinh \gamma} &= \frac{Z_0}{D_n \bar{s}} + \sum_{i=1}^{n} \frac{a_{4i}'\bar{s} + b_{4i}'}{\bar{s}^2 + 2\bar{s}\zeta_{1i}\omega_{n1i} + \omega_{n1i}^2} \\
\frac{1}{\cosh \gamma} &= \sum_{i=1}^{n} \frac{a_{5i}'\bar{s} + b_{5i}'}{\bar{s}^2 + 2\bar{s}\zeta_{1i}\omega_{n1i} + \omega_{n1i}^2} \\
\frac{Z_c \sinh \gamma}{\cosh \gamma} &= 8D_n Z_0 - \sum_{i=1}^{n} \frac{b_{6i}}{\omega_{n2i}^2} + \sum_{i=1}^{n} \frac{a_{6i}'\bar{s} + b_{6i}'}{\bar{s}^2 + 2\bar{s}\zeta_{2i}\omega_{n2i} + \omega_{n2i}^2} \\
\frac{\sinh \gamma}{Z_c \cosh \gamma} &= -\sum_{i=1}^{n} \frac{b_{7i}}{\omega_{n2i}^2} + \sum_{i=1}^{n} \frac{a_{7i}'\bar{s} + b_{7i}'}{\bar{s}^2 + 2\bar{s}\zeta_{2i}\omega_{n2i} + \omega_{n2i}^2}
\end{aligned} \tag{5}$$

$D_n = \upsilon c/lr^2$ is the dissipation number. The coefficients a, b, ω_n, ζ are obtained by fitting the transfer function to the distributed parameter theory in the frequency domain via pole/zero mapping. The above coefficients are extracted from tables supplied by Hsue et. al[3], and their values depend on the values of the dimension-less root index which must be computed using the equation

$$\lambda_i = (i - \tfrac{1}{2})/D_n, \quad i = 1, \ldots, n \tag{6}$$

n is the number of modes which we select to use depending on the accuracy needed to be achieved. In our case, we use a 2-mode approximation assuming a two-degree expansion of the Bessel functions i.e. $n = 2$ and $m = 2$.

The parameters used for the transmission lines are given in TABLE 2. The second and third sections of the long transmission line are considered as a single line of length l_2. All effects due to bends and changes in cross-sectional area are ignored. The frequency response

TABLE. 2 Modeling parameters

Transmission lines and oil	$l_1 = 1.3m$, $l_1 = 5.7m$, $r = 0.0125m$, $\rho = 891kg/m^3$, $c = 1245m/s^2$ $\upsilon = 7.27 \times 10^{-5} m^2/s$
Hydraulic jack	$m = 1kg$, $c_f = 100Ns/m$, $V = 5 \times 10^{-4} m^3$, $k = 5.47 \times 10^4 N/m$
Accumulator	$V_a = 200cm^3$, $l_a = 0.045m$, $d_a = 0.018m$, $P_a = 6MPa$

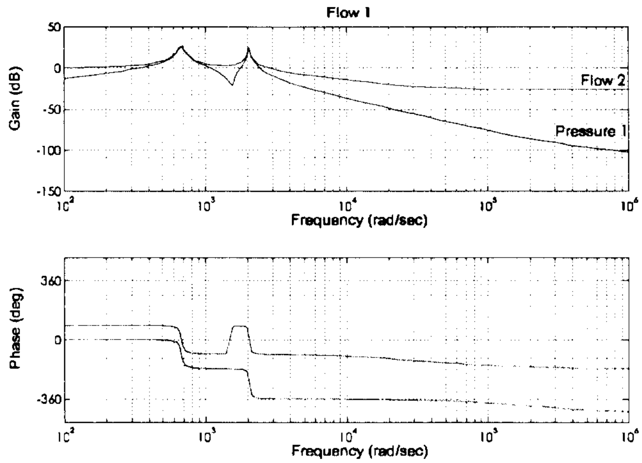

Figure 2. Bode plot for a transmission line (1).

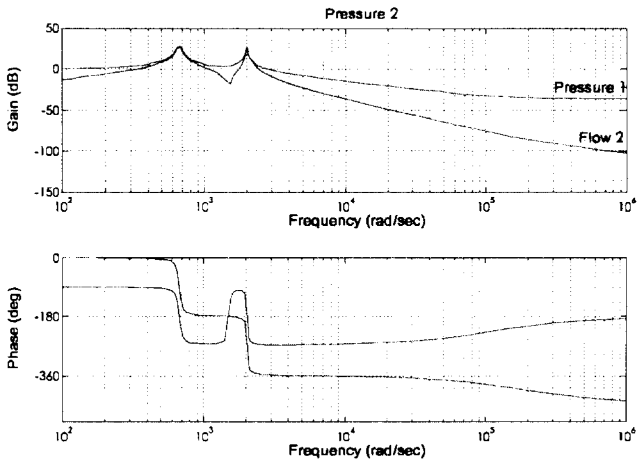

Figure 2. Bode plot for a transmission line (2).

curves for the long transmission line are shown in figures 2 and 3 for the both the two inputs and outputs, since a transmission line is a four terminal network.

2.3 Hydraulic jack model

The hydraulic jack is modeled as a simple piston-cylinder mechanism. Oil compressibility and friction coefficient approximations are used based on existing experimental models[4]. The mass of the mantle shaft, wearing plates, and jack are lumped into an equivalent mass.

Using data given in TABLE 2, the transfer functions of the hydraulic jack is written in the following two forms

$$G_p(s) = \frac{Q_4}{P_4} = \frac{a_p s + b_p}{s^2 + 2\zeta_p \omega_p s + \omega_p^2} \quad (7)$$

$$G_z(s) = \frac{Z}{P_4} = \frac{1}{s(a_p s + b_p)} \quad (8)$$

where: $a_p = k/V$, $b_p = \frac{ck}{VM}$, $\omega_p = A/\sqrt{k_o/VM_p}$ and $\zeta_p = c/2A\omega_p$, k_o is the bulk modulus of oil, M_p is the mass of the piston, V is the volume and c is a frictional constant. Equation (7) is used for analyzing the developed pressure while equation (8) analyzes the piston movement.

2.4 The accumulator model

The accumulator's basic functions are store hydraulic energy during emergency operations, $P > 6\,MPa$, and to reduce vibrations which are detrimental to the hydroset and surrounding areas. Under normal conditions its effect is small but it helps absorb shocks due to high pressure impacts developed by variable loads acting on the piston. The accumulator is modeled to include their damping characteristics. The transfer function of the bladder type nitrogen filled accumulator is derived from the basic relationships between the system pressure, oil changes due to its bulk modulus and the oil flow into or out of the accumulator and is given by the equation

$$G_a(s) = \frac{Q_a}{P_a} = \frac{k_a s}{s^2 + 2\zeta_a \omega_a s + \omega_a^2} \quad (9)$$

where $k_a = a/\rho l_R$, $\omega_a = \sqrt{ka/\rho l_R V_a}$ and $\zeta_a = R/2\omega_a$, a is the area of the restriction, l_R is the length of the restriction, V_a is the volume of the nitrogen gas, R is the resistance of the restriction and ρ is the density of nitrogen gas.

The natural frequency and damping factors are calculated using the data in TABLE 1.

2.5 Equivalent system model

The continuity equation is used as well as the developed component transfer functions to find an equivalent system transfer function. This relates the normalized input flow $\overline{Q}_l$ to the normalized output pressure $\overline{P}_l$ sensed on the valve side (figure 1). The order of the polynomial is high (~30th order), but can be

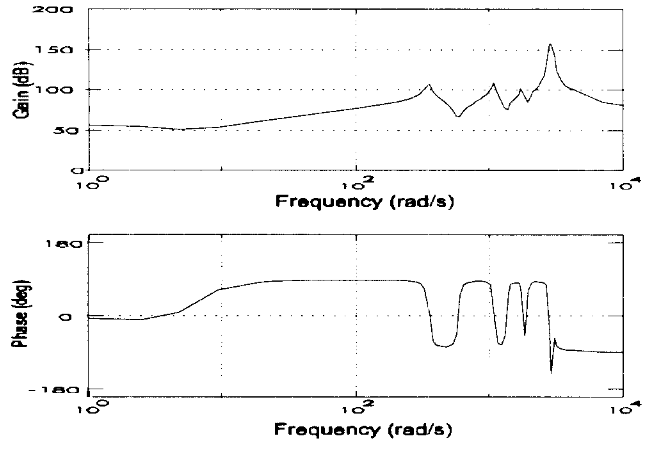

Figure 3. Bode plot for the equivalent system.

reduced depending on the transfer functions of the piston and the accumulator models. A bode diagram of the normalized equivalent plant is shown in figure 4. This plot is calculated by converting the polynomial form into a space state form. The equivalent system is found to have 16 states. A second model which involves only the long transmission line transfer and jack transfer function is used to aide us study the displacement of the jack closely. The displacement of the piston is directly proportional to the gap setting of the crusher, hence it gives an indication of the changes which occur in the gap

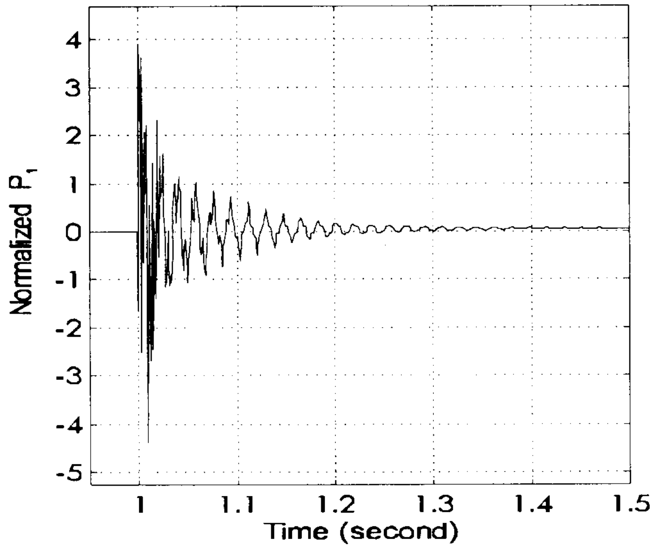

Figure 5. Step response of equivalent system.

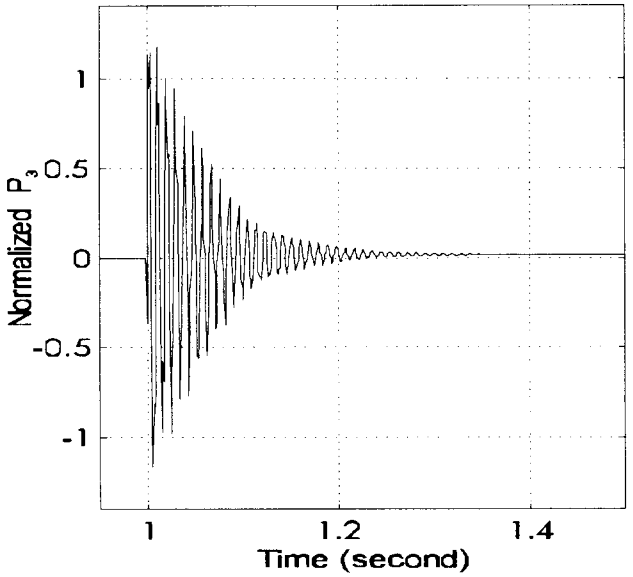

Figure 6. Step response of pipeline and jack.

setting. This is what we would like to monitor in order to produce a homogenous product from our machine.

3. SIMULATION RESULTS AND DISCUSSIONS

The transmission line approximation is bi-modal, and this can be clearly seen on the bode diagram of the equivalent system. The accumulator and piston parameters have great influence on the equivalent system because a slight change in their values causes a remarkable change in the shape of the bode diagram. Figure 5 shows the step response of the equivalent system. High frequency vibrations with a duration of about 0.25 [sec] are observable. The peak value of these vibrations is high and need to be reduced. A simulation of the piston motion, which is our primary concern was also done for the long transmission line-piston configuration and the results are shown in figure 6 and 7. The duration of the response characteristics of the piston displacement is in the order of 0.4 [sec] and have a

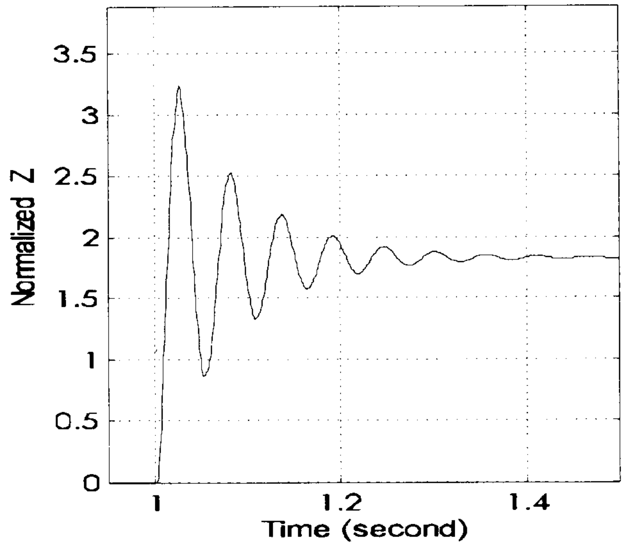

Figure 7. Step response of pipeline and jack.

higher frequency compared to that of the equivalent system. The piston has a gain in its value after the transient vibrations have stabilized. In order to avoid structural failure (bush failure, liners cracking etc.) and maintain a constant gap setting, it is necessary to control the peak values of both the displacement and pressure.

4. CONCLUSION

A dynamic model for studying the pressure and displacement phenomena in a hydroset circuit has been accomplished using the distributed parameter system. The modal approximation method was used to approximate the transfer functions of the transmission line. The bode diagram reveals the natural frequencies of the equivalent system, and their effects on pressure variations are observable in the simulation results. This model is the basis of a mechatronic design of a controller for any hydrocone crusher. In order to avoid mechanical damage to the crusher, it is necessary to control the peak values of the transient pressure developed due to variable loads developed in the crushing chamber. Controlling the displacement variations will enable us to keep and monitor a constant gap setting.

REFERENCES

[1] Allis Chalmers, "Hydrocone Crushers: 22 to 84inch", Publication No. 17B5239, 1975.

[2] Brown T. F. "The Transient Response of Fluids Lines", ASME Journal of Basic Engineering, 84-4, pp. 547-553, 1962.

[3] Hsue C. Y. et. al, "Modal Approximation for the Fluid Dynamics of Hydraulic and Pneumatic Lines", Fluid Transmission Line Dynamics, ASME Winter Annual Meeting special publication, pp. 51-77, 1983.

[4] Muto T., et. al, "Fast and Convenient Method for Simulation of Hydraulic Transmission. lines" Transactions of the JSME (in Japanese), Vol. 49, No. 568, pp. 169-173, 1993.