Spring 1980

Thixotropic properties of whole human blood

Jen An Su

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THIXOTROPIC PROPERTIES OF WHOLE HUMAN BLOOD

BY

JEN AN SU

A DISSERTATION

PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE

OF

DOCTOR OF ENGINEERING SCIENCE IN CHEMICAL ENGINEERING

AT

NEW JERSEY INSTITUTE OF TECHNOLOGY

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THIXOTROPIC PROPERTIES OF WHOLE HUMAN BLOOD

BY

JEN AN SU

FOR

DEPARTMENT OF CHEMICAL ENGINEERING
AND
CHEMISTRY

NEW JERSEY INSTITUTE OF TECHNOLOGY

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ABSTRACT

The rheological property of whole blood from various human subjects was studied with a Weissenberg Rheogoniometer, modified with a continuously variable speed drive. Experimental data showed a hysteresis loop in the shear stress versus the shear rate plot and a torque-decay in the shear stress versus the shearing time plot which is under a constant shear rate. The rheological equation previously developed by Huang was employed to define the thixotropic parameters of each whole blood sample based upon the recorded rheograms.

The altered thixotropic parameters for the blood from patients with open heart surgery at different clinical stages were quantitatively determined. The viscosity by non-Newtonian contribution during the stage of cardiopulmonary bypass showed tremendously high values for the expired patients. Effect of temperature on the blood from normal healthy adults may imply a particular thixotropic temperature existing in a thixotropic system, at which the thixotropic properties reach minimum. It also reveals that 37°C is the optimal temperature for human subjects at normal physiological conditions. The rheological behaviors of blood affected by normal linear alkanols were mainly determined
by the solubilities of alkanols in water and chemical speciality of the red blood cell. Both hydrophilic and hydrophobic alkanols tended to increase blood thixotropic properties. Amphiphilic alkanols increased blood thixotropy at low concentration and, hemolysed blood to a Newtonian fluid at high concentration.

A theoretical analysis of the artifacts of the torsion head to the experimentally obtained rheograms of torque-decay curve and hysteresis loop demonstrated the dynamic behaviors of the torsion head as well predicted the real rheograms of the tested fluid. The experimental data which have been proved from the study are true hemorheological properties and involve no artifacts.

This investigation has shown the significance of the rheological test of whole human blood. It can be developed as a clinical test, which will supply diagnostic information beyond the standard clinical tests available at this time.
DEDICATION

To my wife, Shuh, whose inspiration, encouragement and understanding made it possible; and to my son, Hansen, who has made it worthwhile; and to my parents who taught me the value of education.
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CHAPTER I

INTRODUCTION

To induce flow of a fluid, a force must be exerted on the fluid so that the viscous forces of mutual attraction between molecules are overcome and the molecules are displaced relative to each other. Rheology is the study of deformation and flow of matter. The physical property that characterizes the flow of simple fluids is the viscosity. The equation that describes the relationship between shear stress and shear rate is called the rheological equation of the fluid at the particular state.

Numerous empirical equations, or models have been proposed to express the steady-state relation between shear stress and shear rate depending on the rheological properties of the fluid at the state. The simplest one which describes the rheological properties of fluids is the Newtonian model.

\[ \tau = \eta \dot{\gamma} \]  

(I.1)

where \( \tau \) is the shear stress, \( \dot{\gamma} \) is the shear rate and, \( \eta \) the viscosity, a constant.

However, there are many materials that flow but for which the viscosity is not a constant and these are called non-Newtonian fluids. They need two or more rheological
parameters to describe their rheological behaviors such as the Bingham model, the Ostwald-de Waele model, the Eyring model (all being two parameter models) and the Ellis model, the Reiner-Philipoff model (all being three parameter models) (1), of which the apparent viscosities are not constants as those of Newtonian fluids but a function of shear rate or shear stress. All these models are mainly these dealing with fluids with a monotonic rheological properties, for which there is one definite shear stress associated with each value of the shear rate.

Among the non-Newtonian fluids, there are certain materials which have more complicated rheological behaviors. Their viscosities are not just a function of shear rate but also a function of time. This usually indicates that the fluid processes a structure transformation while a mechanical disturbance is induced to the system. The amount of structure change is dependent on the energy (shear rate) that is forced into the system and how long a time the mechanical disturbance acts on the system. The thixotropic material is characterized by an isothermal, reversible structural breakdown due to the action of a mechanical disturbance on the material. The thixotropic system exhibits the following rheological properties (2):

1. A torque-decay curve (Fig.1.1) will be generated if a suitable single step change shear rate is induced to the system.
Shear stress

Fig. I.1 Torque-decay curve

Shear stress

Shear rate

Fig. I.2 Hysteresis loop
2. A hysteresis loop will happen (Fig.12.) if a triangular step change shear rate is induced to the system.

3. A shear-thinning phenomenon will be brought up if the mechanical disturbance continues as the 2 above. That means the hysteresis loop will become smaller and smaller and, finally turn to pseudoplastic behaviors.

4. Once the mechanical disturbance is removed, the system will recover to its original structure after certain time. This means that the thixotropic material has memory.

5. The system may have or may not have yield stress.

Since Freundlich introduced thixotropy in 1928, many investigators (47 to 53) have been attracted to study it both empirically and theoretically. Most of equations available in the literature are unable to explain the various thixotropic phenomena. Based on irreversible thermodynamic principles, using a molecular arrangement parameter to describe the structure breakdown of thixotropic materials during shearing Huang (2) derived an equation containing five parameters which is suitable to describe the rheological behaviors of thixotropic materials. The five parameters can be used to characterize the flow properties of the whole thixotropic system and, simultaneously to avoid the variations in results due to the varying conditions of tests at different shear rates.
From a macroscopic point of view, human blood is a concentrated suspension of formed elements (primarily red cells, white cells, and platelets) in plasma (3). The plasma in turn is a colloidal suspension of the plasma proteins (mainly serum albumin, serum globulins, and fibrinogen) in a weak electrolyte of composition. The predominant formed elements are the red cells, which are typically in the form of biocave disc about $8\mu$ in (42) diameter when relaxed, but which can undergo very severe deformations. They typically make up about 93% by number of the formed elements or about 40 to 45% of the blood volume, and they have very pronounced effect on blood rheology. The platelets are considerably smaller and are present to the extent of only about 5% of the red-cell volume. They have little direct effect on rheology, but play an important role in clotting. The white cells or leucocytes occur in a relatively small numbers, and are of little direct importance in rheology. The major plasma protein, fibrinogen that make red cells tend to aggregate, also play an important effect on the rheological properties of blood.

Recently it was confirmed that blood is a nearly Newtonian fluid at sufficiently high shear rates which can usually be considered so in arterial flow. However at low shear rates which are of most clinical importance in the
microcirculation where shear rates tend to low, blood is a complex thixotropic system (37).

Basically, the bulk of thixotropic properties of the blood appear to be due to the reversible aggregation of the red cells. The degree of aggregation of the red cells may be affected due to a number of causes such as physical (shear rate, time, force fields, etc.), chemical (hematocrit, fibrinogen, chemicals, etc.), and pathological (heart diseases, diabetes, etc.) reasons. One of these investigations which has been done in this study is relative to open heart surgery. An extensive research on its pathogenesis attracted many able investigators, and the biochemistry and histology have been studied. Yet at the same time, little attention has been paid to the role of the fluid which has been driven through the heart, and particularly the studies of the altered rheological properties of the blood from patients at various clinical stages were also neglected. Effects of temperature and chemicals on blood rheology are also very significant. Based on the Huang model, the rheological parameters generated from these investigations on the blood under different pathological, chemical, and physical conditions appear to be truly meaningful and valuable.

Theoretical study showed (9) that a Newtonian fluid would generate a hysteresis loop provided that a triangular step shear rate change was induced to the system. The artifact
of rheograms due to the influence of torsion head should be eliminated, or at least minimized in order to obtain most accurate experimental results from the system. Thus, to understand the dynamic behaviors of torsion head, a theoretical analysis of the system is necessary, which will provide some critical information in the arrangement of torsion head, and in determining the accuracy of experiments.

The significance of this theoretical analysis is its ability to predict the real rheograms of the tested fluid. The experimentally rheological data for whole blood from this investigation, which have been proved by this theoretical analysis are true hemorheological properties without any artifacts.
CHAPTER II

THEORY

1. The Huang Model - Thixotropic Fluids

Since Freundlich first introduced the term thixotropy in 1928, various attempts have been made, over the years, to define "thixotropy". Most of the model available in the literature (47, 48, 49, 50, 51) are only specific with respect to a particular thixotropic property. Others (52, 53) which are more general require too many constants to be evaluated, are not quantitative, or have not been rigorously tested.

Recently it has been confirmed that blood, mainly due to the rouleaux formation of red cells, is a thixotropic fluid. Much of the work on blood and its components involves quite advanced mathematics as well a considerable knowledge of haematological terms (3). Casson's equation could be only applied at low shear-rates, and especially for bovine blood which will not form rouleaux. Based on an unsuitable assumption that the red cell was a rigid spherical particle and the rouleaux were broken into two equal parts by shearing, Murata (4) theoretically studied the effect of rouleaux on the non-Newtonian viscosity of blood at low shear rates. His derivation finally resulted in an equation much the same as Casson's equation.

More recently, Thurston (5) used a generalized Maxwell
model containing N relaxing spring-dashpot combinations to describe the viscoelastic behaviors of blood. This model would induce uncertain rheological parameters for different blood under same experimental conditions, and brought difficulties to explain the physical meaning of blood thixotropy. Bureau et al. (6) only chose the acceleration constant and the time at the maximum shear rate as parameters from a triangular step change shear rate to correlate the hysteresis shape of blood. Again, these two experimental parameters do not reveal any thixotropic meaning of blood.

Based on irreversible thermodynamic principle as mentioned red cell rouleaux dissociation which is the basis of the model Huang (2), who introduced a molecular arrangement parameter, generalized a rheological equation for time-dependent and time-independent non-Newtonian fluids. This equation containing five parameters with their suitable physical meanings is adapted to be used in quantitative analysis of the hysteresis (including single and multiple) and torque-decay phenomena of thixotropic materials.

The Huang equation (Appendix I.2) is:

\[ \gamma_{re} = \gamma_0 + \mu \int_0^t \gamma_{\dot{r}} \gamma_{\dot{r}}^n dt + c A \gamma_{r_0}^n e^{-t/t_1} \]  

(II.1-1)

For a single hysteresis loop, the shear rate linearly increases from zero to a maximum value (at time \( t_1 \)) and then decreases again toward zero (at time \( 2t_1 \)).
when \( 0 \leq t \leq t_1 \)

\[
\tau_{\theta} = \tau_0 + \mu \dot{\gamma}_\theta + CA \dot{\gamma}_\theta^n \exp \left( - \frac{C \dot{\gamma}_\theta^n}{\alpha (\eta + 1)} \right)
\]

when \( t_1 \leq t \leq 2t_1 \)

\[
\tau_{\theta} = \tau_0 + \mu \dot{\gamma}_\theta + CA \dot{\gamma}_\theta^n \exp \left( - \frac{C}{\alpha (\eta + 1)} \left[ 2 \dot{\gamma}_\theta^n (t_1) - \dot{\gamma}_\theta^n (t) \right] \right)
\]

For a torque-decay curve: a single step change shear rate.

\[
\tau_{\gamma\theta} = \tau_0 + \mu \dot{\gamma}_\theta + CA \dot{\gamma}_\theta^n \exp \left( - C \dot{\gamma}_\theta^n t \right)
\]

Where

\( \tau_{\theta} \) = \( r_\theta \)-component of shear stress, \( \text{dyne-cm}^{-2} \)

\( \dot{\gamma}_\theta \) = \( r_\theta \)-component of shear rate, \( \text{sec}^{-1} \)

\( t \) = time of shear, sec

\( \tau_0 \) = yield stress, \( \text{dyne-cm}^{-2} \)

\( \mu \) = Newtonian contribution of blood viscosity, \( \text{dyne-sec-cm}^{-2} \)

\( C \) = kinetic rate constant of structural breakdown of rouleaux to individual erythrocytes, \( \text{sec}^{\eta-1} \)

\( A \) = equilibrium value of structural arrangement parameter, \( \text{dyne-sec-cm}^{-2} \)

\( \eta \) = reaction order of structural breakdown of rouleaux to individual erythrocytes
Theoretically this model can be applied to any ranges of shear rates and time. As to the steady state viscosity at a constant shear rate, which most investigators used to test the rheological properties of blood, this too can be obtained from the above model as time goes to infinity. The non-Newtonian contribution of viscosity at a constant shear rate is determined by \( \eta_s - \mu \) where \( \eta_s \) is the steady state viscosity at a constant shear rate.

Most investigators in rheology have only considered that the apparent viscosities of thixotropic materials (blood) are a function of shear-stress or, shear-rate, and have ignored the importance of time factor. To emphasize the time dependency, which will affect the rheological properties of thixotropic materials under a certain shear rate is one of the particular points in the Huang model. The separation of mechanical disturbance (shear-rate), time, and other factors which will influence the thixotropic behaviors of blood is another speciality of the model. So to characterize the thixotropic properties of blood quantitatively and qualitatively, the Huang model is able to provide some simple and meaningful index through its rheological parameters which actually are the functions of blood under various physical, chemical, and pathological
conditions. It is possible that the rheological parameters introduced through the Huang equation could be applied in the various branches of science related to technologies of thixotropic materials.
2. **Dynamic Behaviors of the Torsion Head**

In most conventional viscometers, such as two parallel plates, two coaxial cylinders, cone and plate system, etc., the torque is transmitted by the measured fluid to the torsion bar due to the angular movement of the rotating part of the viscometer. Calibration of the torsion bar constant is usually done experimentally, and it is assumed that the angular deflection of the torsion bar is proportional to the supplied torque. Van de Ven (8) analyzed the dynamic behavior of viscometer by assuming the hollow cylinder or bob is suspended by a torsion wire which was given a forced oscillation at the top. He made a flat plate approximation in which he failed to consider the curvature of the bob. Also a little attention has been paid to the artefact of rheograms due to the influence of the mechanical properties of the torsion head. In this analysis, the angular displacement, angular velocity, and the angular acceleration of the whole torsion head induced by the rotating cup all are considered. In the following derivation, both a single step rotation and a triangular step rotation have been forced on the system.
Fig. II.1-1 Single couette cell

\( \alpha \) = Angular deflection of torsion bar
\( G \) = Torsion bar constant
\( \eta \) = Torsion head damping coefficient
\( I \) = Moment of Inertia of torsion head
\( \mu \) = Viscosity of tested fluid
\( R \) = Radius of rotating cylinder
\( L \) = Length of inner cylinder
\( \Omega \) = RPM of rotating cylinder
\( a \) = Acceleration (deceleration) constant for a triangular step change
\( t \) = Time
\( \dot{\gamma}_r \) = Shear rate
(1) = Single step change
(2) = Triangular step change
Equation of motion of the torsion head

\[ I \frac{d^2 \alpha}{dt^2} + \eta \frac{d \alpha}{dt} + G \alpha = T(t) \]  \hspace{1cm} (11.2-1)

B.C. \hspace{1cm} \alpha(0) = 0 \hspace{1cm} ; \hspace{1cm} \alpha'(0) = 0

Assume an incompressible Newtonian fluid in the viscometer.

Equation of motion of the fluid

\[ \rho \frac{\partial \mathbf{v}_0}{\partial t} = \mu \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial (r \mathbf{v}_0)}{\partial r} \right] \]  \hspace{1cm} (11.2-2)

For a step change

\[ \mathbf{v}_0(r, 0) = 0 \hspace{1cm} t = 0 \]

\[ \mathbf{v}_0(kR, t) = 0 \hspace{1cm} t > 0 \]  \hspace{1cm} (11.2-3)

\[ \mathbf{v}_0(R, t) = R \Omega \hspace{1cm} t > 0 \]

Fabisiak and Huang (9) have found that the transient terms are very small, and can be neglected. The torque applied to the inner cylinder is:

\[ T(t) = 2\pi k^2 R^2 \mu \frac{2\Omega}{1 - k^2} = A_0 = \text{Constant} \]  \hspace{1cm} (11.2-4)

Similarly for a triangular step change (hysteresis loop),
the boundary conditions for the fluid will be:

\[ V_\theta(r, 0) = 0 \]
\[ V_\theta(kr, t) = 0 \]
\[ V_\theta(R, t) = \mathcal{F}(t) = \begin{cases} \arctan t & ; 0 \leq t \leq t_1 \\ 2\arctan t - \arctan t & ; t_1 \leq t \leq 2t_1 \end{cases} \] (II.2-5)

where \( a \) = angular acceleration constant of outer cylinder.

It was shown (9) that the dimensionless group, \( \mathbf{N}_{HF} \), may be defined:

\[ \mathbf{N}_{HF} = \frac{(1-K^2)R}{2t_1} \sqrt{\frac{\rho}{\mu}} \frac{E_1}{\beta_1} Z_0 \left( \sqrt{\frac{\rho}{\mu}} \beta_1 kr \right) \ll 1 \] (II.2-6)

The torque applied to the inner cylinder by an incompressible Newtonian fluid can be simplified as follow:

\[ T(t) = \frac{4\pi aLk^2r^2\mu t}{1-K^2} = \beta t \]
\[ = \beta (2t_1 - t) \]
\[ ; t_1 \leq t \leq 2t_1 \] (II.2-7)

Equation (II.2-1) can be rewritten as follow:
\[
\ddot{\chi} + 2\zeta \dot{\chi} + \chi = \frac{1}{G} T(t) \tag{II.2-8}
\]

Boundary conditions:
\[\chi(0) = 0\]
\[\chi'(0) = 0\]

Where
\[\tau = (\frac{1}{G})^{\frac{1}{2}}\]  
Time constant
\[\zeta = \frac{\tau}{2(I G)^{\frac{1}{2}}}\]  
Damping factor

Substitute Eq. II.2-4 for a single step change, (40) and Eq. II.2-7 for a triangular step change (hysteresis loop) into Eq. II.2-8. Then, apply the method of Laplace transformation to solve Eq. II.2-8. The following solutions were obtained:

Case 1: For small \(\tau\) and \(\zeta\), or \(\tau \to 0\), \(\zeta \to 0\)

Step change
\[
\chi = \frac{4\pi K^2 L \mu \Omega}{(1-K^2) G} = \frac{A_0}{G} \tag{II.2-9}
\]

Triangular step change
\[
\chi(t) = \begin{cases} 
\frac{B}{G} t & ; & 0 \leq t \leq t, \\
\frac{B}{G} (2t - t) & ; & t \leq t \leq 2t
\end{cases} \tag{II.2-10}
\]

Case 2: For small \(\zeta\), or \(\zeta \to 0\)
Step change

\[ \alpha(t) = \frac{A_0}{G} \left( 1 - \cos \frac{t}{\tau} \right) \]  \hspace{2cm} (II.2-11)

Triangular step change

\[ \alpha(t) = \begin{cases} \frac{B}{G} \left( t - \tau \sin \frac{t}{\tau} \right) & ; \quad 0 \leq t \leq t_1 \\ \frac{B}{G} \left[ t_1 \left( 1 - \cos \frac{t}{\tau} \right) - \left( t - \tau \sin \frac{t}{\tau} \right) \right] & ; \quad t_1 \leq t \leq 2t_1 \end{cases} \]  \hspace{2cm} (II.2-12)

Case 3. Overdamped, \( \xi > 1 \)

Step change

\[ \alpha(t) = \frac{A_0}{G} \left[ 1 - \frac{1}{2 \sqrt{\xi^2 - 1}} \left\{ (\xi + \sqrt{\xi^2 - 1}) e^{-\left(\xi - \sqrt{\xi^2 - 1}\right) \frac{t}{\tau}} ight. \right. \]
\[ \left. \left. - (\xi - \sqrt{\xi^2 - 1}) e^{-\left(\xi + \sqrt{\xi^2 - 1}\right) \frac{t}{\tau}} \right\} \right] \]  \hspace{2cm} (II.2-13)

Triangular step change

\[ \alpha(t) = \frac{B}{G} \left[ t - 2 \xi \tau + \tau \frac{\xi}{\sqrt{\xi^2 - 1}} \left\{ (2 \xi^2 - 1) + 2 \xi \sqrt{\xi^2 - 1} \right\} \right. \]
\[ \left. - \left( \xi + \sqrt{\xi^2 - 1} \right) \frac{t}{\tau} \right] - \left( 2 \xi^2 - 1 - 2 \xi \sqrt{\xi^2 - 1} \right) e^{-\left( \xi - \sqrt{\xi^2 - 1} \right) \frac{t}{\tau}} \right] \]  \hspace{2cm} (II.2-14)
\[
\alpha(t) = \frac{2tB}{G} \left[1 + \frac{1}{2\sqrt{\xi^2-1}} \left\{ (\xi - \sqrt{\xi^2-1}) e^{-\left(\xi + \sqrt{\xi^2-1}\right) \frac{t}{\tau}} - \right.\right.
\]
\[
\left.\left.\left(\xi + \sqrt{\xi^2-1}\right) e^{-\left(\xi - \sqrt{\xi^2-1}\right) \frac{t}{\tau}}\right\} \right] - \frac{B}{G} \left[ t - 2\xi \tau \right.
\]
\[
+ \frac{\tau}{2\sqrt{\xi^2-1}} \left\{ (2\xi^2-1 + 2\xi \sqrt{\xi^2-1}) e^{-\left(\xi + \sqrt{\xi^2-1}\right) \frac{t}{\tau}} - \right.\right.
\]
\[
\left.\left.\left(2\xi^2-1 - 2\xi \sqrt{\xi^2-1}\right) e^{-\left(\xi - \sqrt{\xi^2-1}\right) \frac{t}{\tau}}\right\} \right], \quad t_1 \leq t \leq 2t_1
\]

Case 4. Underdamping, \( \xi < 1 \)

Step change

\[
\alpha(t) = \frac{A_0}{G} \left[1 - \frac{e^{-\xi \frac{t}{\tau}} \sin \left(\sqrt{1-\xi^2} \frac{t}{\tau} - \phi\right)}{\sqrt{1-\xi^2}}\right]
\]

where \( \phi = +\tan^{-1} \frac{\sqrt{1-\xi^2}}{-\xi} \)

Triangular step change

\[
\alpha(t) = \frac{B}{G} \left[t - 2\xi \tau + \frac{\tau e^{-\xi \frac{t}{\tau}}}{\sqrt{1-\xi^2}} \sin \left\{\sqrt{1-\xi^2} \frac{t}{\tau} - \right.\right.
\]
\[
\left.\left.\left[2 + \tan^{-1} \left(\frac{\sqrt{1-\xi^2}}{-\xi}\right)\right]\right\} \right], \quad 0 \leq t \leq t_1
\]

(II.2-16)
\[
d\alpha(t) = \frac{2tB}{G} \left[ 1 + e^{-\frac{t}{\tau}} \sin \left\{ \sqrt{1-\frac{\tau^2}{\tau^2}} \cdot \frac{t}{\tau} - \tan^{-1} \left( \frac{\sqrt{1-\frac{\tau^2}{\tau^2}}}{\frac{\tau}{\tau}} \right) \right\} \right] \\
- \frac{B}{G} \left[ t - 2\tau \right] + \frac{\tau}{\sqrt{1-\frac{\tau^2}{\tau^2}}} \sin \left\{ \sqrt{1-\frac{\tau^2}{\tau^2}} \cdot \frac{t}{\tau} - 2\tan^{-1} \left( \frac{\sqrt{1-\frac{\tau^2}{\tau^2}}}{\frac{\tau}{\tau}} \right) \right\} \right] \right] \quad ; \quad t_1 \leq t \leq 2t_1
\]

**Case 5. Critical damping, \( \zeta = 1 \)**

**Step change**

\[
\alpha(t) = \frac{\alpha_0}{G} \left[ 1 - \left( 1 + \frac{t}{\tau} \right) e^{-t/\tau} \right] \quad \text{(II.2-17)}
\]

**Triangular step change**

\[
\alpha(t) = \frac{B}{G} \left( t e^{-t/\tau} + \frac{2}{\tau} e^{-t/\tau} + t - \frac{2}{\tau} \right) \\
= \frac{B}{G} F_i(t) \quad ; \quad 0 \leq t \leq t_1
\]

\[
\alpha(t) = \frac{B}{G} \left[ 2t_1 \left\{ 1 - \left( 1 + \frac{t}{\tau} \right) e^{-t/\tau} \right\} - F_i(t) \right] \quad ; \quad t_1 \leq t \leq 2t_1 \quad \text{(II.2-18)}
\]
Comparison of the theoretical shear stress and the artificial shear stress

The theoretical shear stress is directly from the solution of Eq.II.2-2. with some suitable boundary conditions (Appendix I.1).

**Single step change**

\[
(\gamma_{re})_{T.s} = -\mu r \frac{\partial}{\partial r} \frac{V_\theta}{r} \bigg|_{r=KR} = -\mu \frac{2\Omega}{1-K^2} \quad (II.2-19)
\]

**Triangular step change**

The transient terms have been found very small (9), so

\[
(\gamma_{re})_{T.t} = -\mu r \frac{\partial}{\partial r} \frac{V_\theta}{r} \bigg|_{r=KR} = \begin{cases} 
-\mu \frac{2at}{1-K^2}; & 0 \leq t \leq t_i \\
-\mu \frac{2a(2t_i-t)}{1-K^2}; & t_i \leq t \leq 2t_i 
\end{cases} \quad (II.2-20)
\]

At the same single step change and the same triangular step change, the real shear stress due to the effect of the torsion head will be:

\[
(\gamma_{re})_{j,i} = -\frac{T}{2\pi L (KR)^2} = -\frac{K_f \cdot \alpha_{j,i}(\tau, \xi)}{2\pi L (KR)^2} \quad (II.2-21)
\]

Where \(i\) is \(s\) (single step change) or \(t\) (triangular step change), \(j\) is the real Case No., \(f\) is a scale
adjusting factor of instrument for clear readings on recorder. The artifact will be:

\[
(A \varepsilon_{re})_{j,i} = (\varepsilon_{re})_{j,i} - (\varepsilon_{re})_{T,i}
\]  \hspace{1cm} (II.2-22)

It is obviously that Case 1., in which the influence of the torsion head \((\varepsilon, \xi)\) is almost zero is an ideal case. The shear stress derived from Case 2. with very small damping factor \((\xi \Rightarrow 0)\) is in a continuous oscillation with respect to time. This can be corrected by adjusting the factor.

The following typical figures coming from a computer program (Appendix I.2) exhibit how the damping factor combined with a time constant influences the rheogram. This involves three cases: underdamping \((\xi < 1)\), critical damping \((\xi = 1)\), and overdamping \((\xi > 1)\).
In case \( \zeta \) is very small, the system even with a large overdamped coefficient \( \xi \) (but never for critical damping) can provide very well responses closing to the ones in ideal case for both a single step change and a triangular step change (see Fig.III.1-2 at \( \zeta = 0.01 \text{ sec}^{-1} \)).

Explanation of Fig.III.1-2:

1. Upper figure : System responses due to a single step change.
2. Lower figure : System responses due to a triangular step change.
3. Solid lines : Not ideal cases.
4. Dashed lines : Ideal cases.
Fig. III.1-2 Dynamic behaviors of torsion head at $\tau = 0.01\,\text{sec}$. (A. System response to a single step change, B. System response to a triangular step change; dashed lines for ideal cases, solid lines for no ideal cases due to the artifacts of torsion head; $(\tau_{re})_{o,m}$ and $(\gamma)_{o,m}$ theoretical maximum shear stress and shear rate for ideal cases during a triangular step change; $(\tau_{re})_{o}$ theoretical shear stress at a single step change). $\tau$ is time constant of torsion head.
Fig. III.1-3 Dynamic behaviors of torsion head at time constant $\zeta = 0.1$ sec. ($\xi$, damping coefficients of torsion head; $\epsilon$, maximum deviation from theoretical line; the other descriptions for this figure are same as Fig. III.1-2).
Fig. III.1-4 Dynamic behaviors of torsion head at time constant $\tau = 0.2$ sec. ($\xi$, damping coefficients of torsion head; the other descriptions for this figure are same as Fig. III.1-2).
Fig. III.1-5 Dynamic behaviors of torsion head at time constant $\gamma = 1.0$ sec. (for details, see Fig. III.1-4).
Discussion

Case 1 is an ideal case for both a single step change and a triangular step change.

Case 2. Sine waves are generated for both cases, they can be corrected by the installation of a damping plate placed in a viscous fluid in order to adjust the damping factor.

Case 3. The response due to a single step change will be slow. For the triangular step change, artificial hysteresis loops will happen, their sizes and shapes are dependent on the combination of time constant and damping factor.

Case 4. If a suitable combination of time constant and damping factor are selected, the artifacts for both a single step change and a triangular step change would be very small and can be neglected.

Case 5. The artifact may be very small for a step change, but always generate tremendous artifact for a triangular step change.

So, to minimize the artifacts for both cases, the torsion head must be at underdamping. And, a particular set of time constant and damping factor of the system is only suitable for a specific range of shear rates without obvious errors happened in the rheograms generated by the viscometer with a specific damping fluid.
And, from (40), page 88, system parameters $\tau$ and $\zeta$ for the underdamping case can be calculated from experimental response of $\phi(t)$ in a single step change.

Angle deflection of torsion bar

$A/B = \text{overshot} = \exp (-\pi \sqrt{1 - \zeta^2})$

$C/A = \text{decay ratio} = \exp (-2\pi \sqrt{1 - \zeta^2}) = (A/B)^2$

$f = \text{frequency} = 1/T$

These relationships can be further applied to modify the torsion head system.
CHAPTER III

APPARATUS AND EXPERIMENTAL PROCEDURES

1. Apparatus

A modified Weissenberg Rheogoniometer Model R-18 was used in the generation of rheograms including a hysteresis loop and a torque-decay curve. The whole experimental system is shown in a schematic diagram as Fig.III.1-1. The main functions of each part are described as follow:

(a). The double couette cell

In order to minimize the unnecessary chemical reactions between blood and the cell, a gold plated double couvette cell was designed as shown in Fig.III.1-2. All the rings have the same working height as \( L \) 2.003 inches, but their inner and outer radii differ. The inner and outer radii of the suspended hollow (bob) were 1.137 inches and 1.218 inches, and those of the annulus (rotating ring or cup) were 1.104 inches and 1.252 inches. The dimensions were selected in such manner that the shear rate developed at the inner and outer surface of the suspended hollow is always the same (Appendix III). The actual gap between the surfaces of bob and of cup is 0.017 inches. The gap between the bottoms of the two rings is 500 micrometer. Thus the errors induced by the end effect can be neglected due to the
Fig. III.1-1 Block diagram of the modified Weissenberg Rheogoniometer
Fig. III.1-2 The double couette cell
large ratios of the ring height to the gaps between bob and cup, and of the shearing area of the vertical surfaces to the shearing surfaces of the cell ends.

A guard ring was also extended from the top of the hollow to reduce the reaction between blood and air. The hollow is attached through a universal joint to the torsion bar, and is floated by a 20 psi. dry compressed air in order to eliminate any mechanical friction. The volume of sample needed is at least 4.20 ml. It must be stressed that the shear rates given by this rotational viscometer are homogenous ones. The equations used to calculate the shear rate and the shear stress are adhered in Appendix III.

(b). Direct reading transducer meter

A type EP597A Sangamo Controls Limited (England) transducer was used. Amplifying ranges contain 5, 20, 50, 200, 500, and 2000 times. Output of the torque from cell can directly be read out in this meter, and can also be transferred to the X-Y recorder.

(c). X-Y recorder

Hewlett Packard 7045A X-Y recorder was connected to the system as shown in Fig.III.1-1. The surface area which can be utilized is 15 inches by 10 inches (X by Y).

(d). Temperature control chamber

The whole rheogoniometer was enveloped by a highly heat-resistant plastic chamber. Eight 60 watt electric
bulbs as heat source were installed around the bottom inside the chamber. Temperature controller can control the viscometer temperature from room temperature up to 45°C with an accuracy of ±0.1°C.

(e). Original motor, gear box, and drive unit

A SLO-SYN Synchronous motor with 1500 rpm was installed, and controlled by a home-made control panel. Gear box has 60 step settings. Drive unit is controlled by a clutch including "Drive", "Brake", and "Off".

(f). Control panel

A home-made electronic device combining with (e) can control the rotating speed of cup from 0 to 146.5 rpm differentially. It also included a time setting. By adjusting the setting in the panel and using the clutch, the following functions for the rotating part of viscometer can be generated:

<table>
<thead>
<tr>
<th>RPM</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular</td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td></td>
</tr>
<tr>
<td>Ramp &amp;</td>
<td></td>
</tr>
<tr>
<td>Rectangular</td>
<td>Step Change</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step Change</th>
<th>Step Change</th>
<th>Step Change</th>
<th>Step Change</th>
</tr>
</thead>
</table>
(g). Refrigerator was kept at 4°C for the storage of blood samples. Water bath was used to warm the blood sample at the designed degree and time.

(h). Syringe: 5 c.c. sterile single-use Plastipak B-D syringe was utilized to inject the blood sample into the double couette.

2. Experimental procedures

(a). Set the desired experimental temperature, let the rheogoniometer (vicometer) warm overnight in order that its temperature reaches a steady state.

(b). Choose a suitable setting at gear box. For blood, the setting at 2.3218 rpm for the stepping motor is desired, since it will give the maximum shear rate at 8.0361 sec⁻¹ for the double couvette (Appendix IV). This low shear rate would not cause any damage to the blood subphases, and would generate a clear hysteresis loop for whole blood.

(c). Adjust transducer meter and X-Y recorder to a suitable scale.

(d). Gently shake and heat the blood sample in water bath at the desired temperature and time, then gently inject it into the viscometer.

(e). For hysteresis loop, use control panel to make a triangular step change at cup (shear rate linearly accelerates from 0 to 8.0361 sec⁻¹, then linearly decelerates to 0).

(f). For torque-decay curve, use control panel
to set the shear rate at 3.2144 sec\(^{-1}\), which will
generally make clear torque-decay curve for whole blood,
then suddenly switch the clutch which originally set at
"Brake" to "Drive". A shear stress at constant shear rate
3.2144 sec\(^{-1}\) can also be obtained.

To check if the rheograms can be reproduced, several
runs for (e) and (f) should be carried out.

(g). The experimental data from both rheograms have been
transferred to the modified Marquardt computer program.
Eventually, the five thixotropic parameters in the Huang
model have been evaluated. Because of its importance for
the main topic of the thesis and its complexity, the actual
computer program has been included into the thesis as an
Appendix I.3.
CHAPTER IV

EXPERIMENTAL RESULTS

1. Altered thixotropic properties of blood during cardiopulmonary bypass

Variations of blood rheological properties are always accompanied by changes in physiological, psychological, and pathological factors. Ehrly (10) exhibited circadian rhythm of young female blood viscosity. Dintenfass (11,12) correlated between biochemical and rheological parameters in patients with myocardial infarction, haemophilia and thyroid diseases; also described the influences of ABO blood groups and fibrinogen on thrombus formation and aggregation of red cells in cardiovascular and malignant diseases (13). Schönbein, et al. had found that pathological red cell aggregation in myeloma patients presented higher abnormal shear resistance. Again Dintenfass (14,15) introduced the psychological score index related to the elevation of blood viscosity, and assumed a hypothetical viscoreceptor mechanism. Elevation of any of the blood viscosity factors is a risk factor and a warning sign, especially in the cardiovascular disorder.

The orthodox studies on open heart surgery were
mainly with the pathogenetic pathways via abnormalities of blood pressure, metabolism, dietary regime, formation of atherosclerotic plaques, cholesterol level, and so on; but the intrinsic role of blood rheology was paid little attention, or just was partially investigated only at steady state shear rates. Its thixotropic properties including hysteresis loop and torque-decay curve were rather neglected.

This investigation was concerned with the thixotropic properties of blood during cardiopulmonary bypass. The blood was collected at different clinical stages from patients from the time of entering hospital to the time of leaving hospital (Dr. J. Cohn, St. Barnabas Medical Center, Livingston, New Jersey, 1977-79). For each stage, haemoanalysis was done by routine hospital work. For rheological analysis, each sample was collected as 7 ml. aliquots and anticoagulated with 10.5 mg. EDTA (ethylene diaminetetraacetic acid). Then rheograms of hysteresis loop and torque-decay curve were obtained through the modified Weissenberg rheogoniometer at room temperature. The thixotropic parameters were evaluated by a method of non-linear least square parameter estimation based upon a modified Marquardt program on a Univac Spectra 70 digital computer (Appendix 1.3).
The data of hematological evaluation have proved that there are no constituents in blood from all stages from all blood samples that present any abnormality (Appendix II.1-A).

However, the rheological evaluation indicates that the rheological results have shown a significant difference between patients and normal healthy people, and the results at each clinical stage on patients are also different. Fig.IV.1-1 summarizes their rheological data (Appendix II.1-B).

The parameter A, the equilibrium value of structural arrangement is proportional to the number of erythrocytes in the form of ordered rouleaux formation. The decrease in the value for the structural arrangement parameter A, indicates that more individual erythrocytes or fewer rouleaux formations are present within the whole blood sample at the applied shear rate.

The decrease in the value for C implies that the rate constant for obtaining equilibrium between individual erythrocytes and rouleaux arrangement will shift toward the formation of rouleaux forms.

\( \gamma \) is a physical property of blood flow and is directly related or associated with the formation of rouleaux. Variations in this value follow same patterns as A. \( \mu \), \( \gamma' \), and \( \gamma'_s - \mu \) follow same patterns of variation as A. n reflects the order of reaction of rouleaux breakdown, which implies a certain reaction mechanism.

Observations have been made that the high blood viscosity
in non-Newtonian contribution from the expired patients may be due to an excessive aggregation of the red cells. However, the hematological evaluation can not provide any information in this respect. It appear that there could be other causes which easily induce the excessive aggregation of the red cells when some certain shear rates are applied on the blood for specific time intervals.

This investigation implies that the rheological parameters from the Huang model are not only fundamental in indications of pathogenesis and consequences of heart diseases, but that these parameters might supply a solution for prediction and diagnosis. It is also suggested that such rheological tests will allow, in some cases, a more rapid determination of disease when the current laboratory tests are inadequate.
Non-Newtonian viscosity
\[ \eta_s \approx \frac{\mu}{v^2} \)

Steady state viscosity
\[ \eta_s \approx \frac{\mu}{v^2} \)

Reaction order
\[ n \]

Equilibrium constant
\[ A \]

Rate constant
\[ C \]

Yield stress
\[ \gamma_o \]

Fig. IV.1-1 Rheological parameters of patients during cardiopulmonary bypass
2. **Effect of temperature on thixotropic properties of blood**

There are numerous factors that affect the rheological properties of human blood. Temperature changes may be regarded as a thermal disturbance. In 1963, Cokelet (16) found that the apparent viscosities of plasma and water had same temperature dependence i.e. they followed Arrhenius law with the same active energy but with a different rate constant. The relative viscosity of blood (relative to water) was independent of temperature between 10°C and 37°C at shear rates larger than 1 sec⁻¹, but the relative viscosity increased with temperature by about 20% at very low shear rates (less than 1 sec⁻¹). Chien, et al. (17) and Barbee (18) also discovered that the relative viscosity of blood (relative to plasma) was independent of temperature between 20°C and 37°C at high shear rates over 50 sec⁻¹, but had an exponential relationship with hematocrit as follows:

\[ \eta = \eta_0 \exp (bH) \]  

(I.2-1)

Where \( \eta_0 \) is the apparent viscosity of plasma, \( \eta \) is the apparent viscosity of blood, \( H \) is the hematocrit, and \( b \) is a constant which is inversely proportional to the shear rate.
All the previous results were considering only one rheological parameter (apparent viscosity), and which was evaluated at high steady-state shear rate. Due to their ignorance of the historical significance and hysteresis phenomenon in blood, this brings much difficulty to explain its thixotropic properties. Based on the Huang model, an investigation in the effect of temperature on the whole blood from healthy adults was attempted. The statistical results were plotted in Fig.IV.2-1 and Fig.IV.2-2. The detailed data were listed in Appendix II.2.

From the two figures, one may find that \( n \) is constantly independent of temperature, and \( C \) has a slightly exponential relationship with temperature. However, the other parameters vs. temperature almost present same shape with the lowest values at \( 37^\circ C \). Once a slight degree deviation from \( 37^\circ C \) happens in the whole blood, i.e. the blood has absorbed or released a small thermal energy, the yield stress, Newtonian viscosity, equilibrium constant, steady-state viscosity, and non-Newtonian viscosity will increase tremendously. These phenomena may be explained as follow:

Since blood is a solution containing high molecular weight sustances, such as macroglobulins, albumins, cells, and especially fibrinogen, etc., which are sensitive to temperature and are greatly affected by temperature changes, the temperature changes may cause a certain orientation and
Fig. IV.2-1 Rheological parameters vs. temperature.
Fig. IV.2-2 Rheological parameters vs. temperature
morphological changes of the macromolecules, erythrocytes and their rouleaux. At $37^\circ C$, one may say as a transition point, the flexibility and deformability of erythrocytes arrive at their highest points, and the intramolecular forces reach their lowest points. Thus the rheological resistance of blood drops to its minimum. Once a couple of degree offsetting occurred from the turning point ($37^\circ C$), the rheological resistance will increase quickly, and then reach to a constant over certain range of temperature.

If the temperature is beyond $37^\circ C$, the elevation of the thixotropic properties of blood may be due to the orientation changes of high molecules such as fibrinogen, thus changes will make the aggregation of erythrocytes more firmly. In case the temperature of blood drops below $37^\circ C$, the flexibility and deformability of red cells will increase, i.e. RBC will become much stiffer, thus the intercellular friction among red cells in rouleaux will increase. Therefore it needs more mechanical energy to shear the blood and to break its rouleaux. This is probably why the thixotropic properties of blood also increase.

It is worthwhile in a further study to model the temperature dependence of rheological properties of blood mathematically. In general, in gases at low density, the viscosity dependence on temperature follows the following equation:
where \( a \) and \( b \) are empirical constants. For the pure Newtonian fluid, the most commonly used expression relating viscosity to temperature (in normal range) is the Arrhenius equation (19).

\[
\eta = a \sqrt{T} + b \quad \text{(IV.2-2)}
\]

where \( R \) is the gas constant, \( E \) the energy of activation for flow, and \( A_0 \) a coefficient depending upon the nature of the liquid. For non-Newtonian fluids, such as certain polymers, another equation sometimes useful in correlating viscosity-temperature data in the region of Newtonian behavior is suggested (19):

\[
\eta = A_0 \exp(-E/RT) \quad \text{(IV.2-3)}
\]

where \( A_0 \) is a coefficient depending upon the nature of the liquid. For non-Newtonian fluids, such as certain polymers, another equation sometimes useful in correlating viscosity-temperature data in the region of Newtonian behavior is suggested (19):

\[
\eta = a \exp(-bT) \quad \text{(IV.2-4)}
\]

where \( a \) and \( b \) are empirical constants.

However, theoretically it will be very difficult to establish the temperature dependence of the rheological parameters of blood, since blood is a very complex, thixotropic fluid with suspended particles about which there is relatively little knowledge available. While a certain physicochemical disturbance is induced in blood, the suspended
particles may undergo rotation, translation, deformation, aggregation, disaggregation, and other interaction or chemical reaction and so on. But how and why? it will be a worthwhile subject for a further study.

The statistical results show that $n$ is always a constant, independent of temperature; the temperature dependence of other parameters $\gamma_0$, $A$, $\mu$, $\gamma_s$, and $\gamma_s$, all present as a valley-shape. It will not be easy to develop an equation to fit the experimental data. It is also a worthwhile subject for a further attack.

The parameter $C$ follows the exponential form as the Arrhenius equation:

$$C = A_0 \exp \left( \frac{-E}{RT} \right)$$

where $E$ the activitis energy, $A_0$ the coefficient depending on the nature of whole blood, $R$ the gas constant. $E$ and $A_0$ can be obtained by plotting $\ln(C)$ versus $1/T$. Their values are $E = 192.2$ cal./mole, and $A_0 = 0.123 \times 0.04 \text{ sec}^{-1}$. 

![Graph showing the relationship between $-\ln(C)$ and $(1/T) \times 10^5$, with $T$ in absolute temperature °K.](image)
All the previous investigations were based upon the normal healthy blood. For the pathological blood, Reis (43) discovered that for rising temperature from 0°C to 50°C, the viscosity of blood serum decreased progressively. There was a temperature existing, above which the viscosity started to increase due to certain physico-chemical, and pathological factors. Stoltz, et al. (44) also showed the abnormal relation between plasma viscosity and temperature for the blood containing extra macromolecules. The temperature dependence of pathological blood may have different profiles of the rheological properties.
3. Correlation of thixotropic properties and chemical tests of whole human blood

There is too much unknown in blood. From the molecular level, the whole structure of blood is still mysterious. The change in part or in whole blood induced by altered physico-chemical environment has attracted many investigators.

Arellie, et al. (20) discovered platelet aggregation in platelet-rich plasma induced by catecholamines (including adrenaline, nonadrenaline, dopamine, and 5-hydroxytryptamine). Newman (21) found that the viscosity of whole blood increased as a result of an increase in cholesterol level, especially more remarkably at the lower shear rates. Also dextran, a plasma expander which influenced the whole blood viscosity was exhibited by Singh (22). Anticoagulant heparin was showed to reduce the storage component of the elastic modulus and to increase the clotting time (24). Using erythrocytes suspended in buffer and morphology altering agents (2,4,6-trinitrobenzene, 2,4-dinitrobenzene, chloropromazine.HCl, and sodium salicylate), Meiselman (25) exhibited that the rheological effects of the discocyte-echinocyte shape transformation existed at the lower shear rates. Houbouyan, et al. (26) indicated that some antibiotics affected the rheological properties of blood and platelet aggregation.
To deal with the field of molecular rheology, subphases of blood, morphological structure of cells, various amphiphilic agents may be employed to transfer the normal biconcave shape (discocyte) into either the crenated (echinocyte) or cupped (stomatocyte) form (25, 26). These agents appear to act as true antagonists, although at high concentrations there is an irreversible process of smooth sphere to haemolysis (27). Sheetz and Singer (28) have proposed a theory for these shape transformations based on an asymmetric bilayer model of the RBC (red cells) membrane; echinocyte agents intercalate preferentially into the exterior half of the bilayer whereas stomatocytic agents are suggested to act mainly on the interior half.

The rheological properties of whole blood are mainly determined by the situation of erythrocytes which present complicated response to various chemicals. Motais (29) found that organic anion (mainly acids) transport in red blood cells was determined by the membrane specificity, Missirlis, et al. (30) used micropipette analysis to estimate the haemolytic stress of hypotonic erythrocytes under the influence of lipid-soluble compounds. Jain, et al. (31) exhibited that the difference of intrinsic perturbing ability of alkanols in lipid bilayers arose from a specificity of interaction between alkanols and lipid bilayer.

Systems are studied generally as a whole. An attempt
to isolate certain rheological processes from individual fragments of more complex blood and then combine them in order to explain the functions of the whole blood can not be expected to supply the whole truth. In this study, first around seventy chemicals which were considered having certain important effect in blood have been selected on a screening test to see if they can cause any influence in the thixotropic properties of blood. Finally a series of normal alkanols including one \( \text{C}_1 \) to eleven \( \text{C}_{11} \) carbons which were found obviously causing the thixotropic changes in blood have been chosen as a typical example in this study. The other reason is that these alkanols have systematically exhibited different molecular sizes and solubilities in water and lipids, which are main compositions in blood and red cells respectively. \(^{32,35,36}\)

To each 5.0 ml. of blood which was obtained from Northen New Jersey Blood Bank, East Orange, New Jersey, a certain amount (not exceeding 0.1 ml.) of alkanol was added; then the blood was gently shaked and warmed at \(37^\circ\text{C}\) for 30 minutes. Then, the sample was ready for rheological tests at \(37^\circ\text{C}\). The results from this investigation were plotted in Fig.IV.3-1 to Fig.IV.3-7. The detailed data have been shown in Appendix II.3.

The \( A, \gamma, C, \) and \( n \) were plotted, on a linear
scale, against the number of carbon molecules (or molecular size). The $\gamma$ and $\mu$ were plotted, on semilog scale, against the number of carbon. One may observe the following phenomena:

(a). Different alkanols have different effects in the rheological properties of the same blood.

(b). Different bloods have different responses to the same alkanol.

(c). In this investigation, all blood, two normal and two abnormal samples follow a similar thixotropic pattern with respect to the eleven alkanols.

(d). Alkanols with $C_5$ to $C_9$ can change the thixotropic blood to a Newtonian blood, in which $C_7$ drops the Newtonian viscosity to the lowest point.

It is also obviously that the results can be grouped according to the solubility of alkanols in water (Fig.IV.3-5). The first group, hydrophilic alkanols, containing methanol ($C_1$), ethyl alcohol ($C_2$), n-propyl alcohol ($C_3$), and n-butanol ($C_4$), shows extreme solubility in water; the second group, amphiphilic alkanols containing normal alkanols with five to nine carbons, shows partial solubility in water and partial solubility in lipids; while the third group, hydrophobic alkanols, composed of 1-decanol and 1-undecanol, exhibits a complete insolubility in water, but is soluble in lipids.
Yield stress
(dyne/cm²)

Alkanol : 0.1 ml.
Blood : 5.0 ml.
Temperature : 37 °C
Incubation : 30 min.
II, III : Normal blood
I, IV : Abnormal blood

Fig. IV.3-1 \( \gamma \) vs. no. of carbon molecules in linear normal alkanols (blood rheological properties affected by normal alkanols)
Reaction order

Alkanol: 0.1 ml.
Blood: 5.0 ml.
Temperature: 37 °C
Incubation: 30 min.

I, II, III: Normal blood
I, IV: Abnormal blood

Rate constant

Fig. IV.3-2 C, n vs. no. of carbon molecules in linear normal alkanols (blood rheological properties affected by normal alkanols)
Fig. IV.3-3 A vs. no. of carbon molecules in linear normal alkanols (blood rheological properties affected by normal alkanols)
Fig. IV.3-4 \( \eta_s, \mu \) vs. no. of carbon molecules in linear normal alkanols (blood rheological properties affected by normal alkanols)
**Thixotropic**

**Newtonian**

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Hydrophilic</th>
<th>Amphiphilic</th>
<th>Hydrophobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solubility</td>
<td>∞</td>
<td>∞</td>
<td>9.15</td>
</tr>
<tr>
<td>(g/100g H₂O)</td>
<td>2.78</td>
<td>0.60</td>
<td>0.18</td>
</tr>
<tr>
<td>Alkanol in</td>
<td>0.054</td>
<td>0.054</td>
<td>0.0017</td>
</tr>
<tr>
<td>plasma (g/3g)</td>
<td>0+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alkanol in</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RBC (g/2g)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Estimated</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>partition</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>coefficient</td>
<td>3.83</td>
<td>2.628</td>
<td>30.34</td>
</tr>
</tbody>
</table>

- **Molecular weight (size)**: Increase

**Fig. IV.3-5** Blood rheological properties vs. physical data of alkanols (blood rheological properties affected by normal alkanols)
Temperature: 37°C
Incubation: 30 min.

Fig. IV.3-6 $\gamma$ vs. C₅, C₇, C₉-alkanol concentration (x5)
(→ indicates the coordinate should be used)
Temperature - 37°C; Incubation - 30 min.

Fig.IV.3-7 $\eta_s$, $\mu$ vs. C, C, C,-alkanol concentration (x5)
With regard to the effect of concentration of alkanols in the blood rheology, three alkanols (C\textsubscript{5}, C\textsubscript{7}, and C\textsubscript{9}) which were found more active to change the rheological properties of blood than others have been choosen as examples. The relationship of $\gamma_0$, $\mu$, and $\gamma_s$ vs. the concentration of the alkanols were plotted in Fig.IV.3-6 and Fig.IV.3-7, which have showed the two normal blood samples (II and III) have similar responses to the amphiphilic alkanols, but not for the abnormal ones (I and IV). Furthermore, if looking in detail, even the two similar ones (normal blood II and III) have showed different responses to the same alkanol C\textsubscript{5} (Fig.IV.3-7).

And, no matter whether normal or abnormal, all blood samples are much more sensitive to C\textsubscript{7} alkanol than to others.

To explain these phenomena it will be very difficult from the microscopic viewpoint of blood, since there is too much knowledge indeed needed to develop and to understand the erythrocyte structure. For simplification, let's see the blood from a macroscopic point of view. Blood can be considered as a part water soluble (plasma), and a part water insoluble (erythrocytes) as shown in Fig.IV.3-8.

(a) When the hydrophilic substances (C\textsubscript{1} to C\textsubscript{4}) dissolve in plasma, they may modify the exterior surface of the erythrocyte membrane in some way to strengthen the rouleaux formation. Thus it will cause the increase in
Membrane structure of erythrocytes:

Lipid bilayer mosaic with proteins

Outside cell:
Plasma (H₂O)

Inside cell:
Cytoplasm (Hemoglobin)

C₁⁻C₄

C₁₀⁻C₁₁

C₅⁻C₉

Lipids

Proteins

Insoluble in H₂O

(Two phases system of blood)

Fig. IV.3-8 Mechanisms of linear normal alkanols reacting with erythrocytes; C₁ to C₁₁ indicate the alkanols which have 1 to 11 carbon molecules
thixotropic properties of whole blood.

(b). While the hydrophobic substances \((C_{10} \text{ to } C_{11})\) favorably join in the erythrocyte membrane in loose part to reinforce its strength, and make the red cells much stiffer. In other words, the deformability or flexibility of erythrocytes and rouleaux will decrease, that means the thixotropic properties of blood will increase.

(c). While the amphiphilic substances \((C_{5} \text{ to } C_{9})\) dissolve in blood, their apolar tails will insert in the erythrocyte membrane, and their polar heads will suspend on the exterior surface of the membrane. At low concentrations, they act as a combination of hydrophilic and hydrophobic substances. Once their concentration presented in blood is beyond a certain level at which the membrane is already saturated by the substances. The residual amphiphilic molecules in plasma will continuously attack the membrane. The haemolysis will occur until the intramolecular force between the molecules in plasma and the molecules in the saturated erythrocytes overcomes the intermolecular force which holds the whole membrane as a unit.

(d). The different responses from different bloods to the same alkanol may imply that each individual blood has its own signature (intrinsic ultrastructure of the erythrocyte) and chemical selectivity which were found most favorably to amphiphilic \(C_{7}\). The different Newtonian
behaviors from the haemolysis caused by the attack of C₅ to C₉ may reveal the different size of fragments broken from erythrocytes.
CHAPTER V

CONCLUSIONS

Traditionally, most investigators used apparent viscosities at various constant shear rates to evaluate the rheological property of fluid, it would be okay if the fluid were just shear-rate dependent, or a monotonic system. However, to a multitonic system such as blood—a thixotropic fluid, the traditional method would not be suitable to evaluate its rheological properties, since such a system is just dependent upon the shear rate but also the time.

To correct the traditional method, the Huang model which can be applied to very wide ranges of shear rates and time, emphasizes to use rheological parameters to characterize the flow properties of thixotropic system from its hysteresis loop and torque-decay curve. Once the parameters are determined, the apparent viscosity can be evaluated at any shear rate and at any time of shearing. Thus, the use of the parameters will also eliminate the uncertainty of the apparent viscosity of a sensitive thixotropic system such as blood tested at very low shear rate, obtained by different investigators.

Physiologically, low velocities of blood flow occurring in the microcirculation in capillary or small vessels would be mainly influenced by the presence of
aggregates of the red cells, which in turn depend on the shear rate and, on the history of the blood and the originate of the blood. Low shear rates also exist particularly in pathological conditions such as circulatory shock and thrombosis. The rheological parameters are relevant to the practice of clinical medicine.

The study of open heart surgery during cardiopulmonary bypass is a typical example, which brings together information essential to clinicians and medical workers studying the causes for circulatory diseases, and for engineers who want to apply concepts of the more developed sciences to the so complex problems of medicine. If a simulation study could be made prior to the operation, it might probably have saved the lives of patients who were expired after open heart surgery. In other words, the highly abnormal rheological syndrome which might be of clinical and diagnostic importance could be predicted. A series of tests might help to discover early or silent conditions of hematological disorders or malignancy. The complex clinical tests could be supplemented, and sometimes replaced, by the new rheological methods.

Although changes in rheological parameters may play an important role in clinical medicine or pathophysiology that exists within blood flow, the diagnostic value is sometime difficult to be specific since different causes of illness may lead to same changes in rheological properties. However,
the rheological parameters, in combination with other changes in the blood such as changes in temperature, inducement of chemicals or other physio-chemical factors, serve to narrow the range of diagnosis required.

The rheological study of blood added with different chemicals also imply its applications to other sciences such as pharmocology, toxicology, and ultrastructures of blood, and so on. The effect of temperature on blood thixotropy shows, at least that a living thing containing a thixotropic blood circulating through its organs has its own body temperature, at which the resistance for blood flow is going to be minimum, and at which its physiological functions are operating normally. It further indicates that each individual thixotropic system may have its own thixotropic temperature, at which its flow properties turn to minimum. The temperature study also paves a way to solve certain thermodynamic problems in the thixotropic system.

The study of dynamic behaviors of the torsion head indicates that the rheogram is controlled by the time constant and damping factor of the head, which in turn are determined by the torsion bar constant and the geometrical and physical properties of the head. This provides an information in its installation, of which
the damping factor can be adjustable by changing the viscosity of damping fluid. To minimize the artefact of rheograms, which is mainly dominated by the torsion head provided that the inertia constant and damping coefficient of the tested fluid comparing with those of the head can be neglected, a suitable underdamping factor combining with a particular time constant is necessary if both a single step change and a triangular step change in the rotating part of the viscometer are assigned to a specific rpm range.
CHAPTER VI

RECOMMENDATION

1. Some unusual lumps in hysteresis loop and torque-decay curve were occasionally found from the pathological blood during cardiopulmonary bypass. A simulation approach by assuming the increase of catchamines in blood owing to certain physical or psychological stress that occurred in the patient, was attempted, but failed to produce results. These lumps may imply some very important pathological factors. A further investigation for their solution would probably bring about significant improvements in preventive medicine.

2. Blood, especially for the particular pathological conditions, usually is not easy to obtain. In order to facilitate the research, using the simulated blood from normal people or other living subjects is recommended.

3. It takes almost 5 ml. of blood sample in the present cell for each experiment. A specific pathological blood is hard to acquire. In order to expand its usefulness, to reduce the size of cell (microviscometer) is therefore recommended.

4. The chemicals in blood in vitro are more stable at 4°C than at 37°C. The latter temperature may cause their denaturalization and affect the blood rheology. Also
Reis (43) and Stoltz (44) indicated that the viscosity of blood was much higher at 4°C than that at 37°C. Then the rheological parameters obtained at 4°C in place of 37°C would provide clear and better results. This, in turn automatically involves that a cooling system installed in the rheogoniometer is necessary.

5. There is need for more research to find out if there are any chemicals which are widely involved in our ordinary lives, such as enviromental polluters, pharmaceuticals, and food additives and etc., that present any instantaneous or potential danger to the human blood or our health (38).

6. Though the recovery of hysteresis phenomena in blood is fast, it has been observed that the speed sometimes is different due to different blood samples. This may indicate the memorial property of blood. How to define it? How to find it? What is its relation with respect to other variables existing in blood? All these problems are worhty of a future investigation.

7. To accelerate to obtain the experimental results, an automation of the whole system is absolutely necessary.

8. Systematic dictionaries of the rheological parameter vs. various physical, chemical, and pathological factors which affect blood will bring a great advantage to life sciences.
Appendix 0. Nomenclature

A: Equilibrium value of structural arrangement parameter, dyne-sec-cm⁻².

a: Acceleration constant for a triangular step change, cm-sec⁻².

C: Kinetic rate constant of structural breakdown of rouleaux to individual erythrocytes, secⁿ⁻¹.

G: Torsion bar constant, dyne-cm/micrometer.

I: Moment of inertia of torsion head, dyne-cm-sec²/micrometer.

L: Length of the inner cylinder of the single couette cell, cm.

n: Reaction order of structural breakdown of rouleaux to individual erythrocytes.

R: Radius of the rotating cylinder of the single couette cell, cm.

t: Time, sec.

α: Angular deflection of torsion bar, micrometer.

γₑ: re-component of shear rate, sec⁻¹.

γₒ: re-component of shear stress, dyne-cm⁻².

γ*: Yield stress, dyne-cm⁻².

μ: Newtonian viscosity, dyne-sec-cm⁻².

τ: Torsion head damping coefficient.

Ω: RPM of the rotating cylinder in the single couette cell.
Appendix I.1 - Mathematical Derivation for the Dynamic Behavior of Torsion Head

In a rotating viscometer such as couette, cone and plate and etc., a torque $T(t)$ is transmitted by the tested fluid to the torsion bar due to the angular movement of the bottom shaft (Fig.II.1). For most viscometer design, it is assumed that the torque is proportional to the angular deflection of the torsion bar $\alpha(t)$.

In this derivation, the angular velocity and angular acceleration are also being considered. From the derivation, we can established under what conditions, the assumption of $T(t)$ is linear with respect to $\alpha(t)$ is held for both a single step change and a triangular step change.

Equation of motion of the torsion head

$$I \frac{d^2 \alpha}{dt^2} + \eta \frac{d\alpha}{dt} + G \alpha = T(t)$$

B.C. $\alpha(0) = 0$, $\alpha'(0) = 0$

Define new parameters:

$$\gamma = \left( \frac{I}{G} \right)^{\frac{1}{2}} = \text{--- characteristic time constant}$$

$$\xi = \frac{\eta}{2(IG)^{\frac{1}{2}}} = \text{--- damping factor}$$

Then the equation can be rearranged as follow:
\[ \gamma \frac{d^2 \alpha}{dt^2} + 2 \xi \gamma \frac{d \alpha}{dt} + \alpha = \frac{1}{G} T(t) \]  

(A.I.1-1)

Assume an incompressible Newtonian fluid in the viscometer.

**Equation of motion of the fluid**

\[ \rho \frac{\partial \mathbf{V}}{\partial t} = \mu \frac{\partial}{\partial r} \left[ \frac{1}{r} \frac{\partial (r \mathbf{V})}{\partial r} \right] \]  

(A.I.1-2)

(A). **For a single step change**

**B.C.** \[ V_\theta (r, 0) = 0 \quad ; \quad t = 0 \]

\[ V_\theta (KR, t) = 0 \quad ; \quad t > 0 \]  

(A.I.1-3)

\[ V_\theta (R, t) = R\Omega \quad ; \quad t > 0 \]

The solution of Eq. A.I.1-2 for (A) is shown in (9):

\[ \frac{V_\theta}{R\Omega} = \left( \frac{1}{1-\kappa^2} \right) \frac{r}{R} - \left( \frac{\kappa^2}{1-\kappa^2} \right) \frac{R}{r} + \sum_{n=1}^{\infty} E_n e^{-\beta_n^2 t} Z_n(\theta_n r) \]

(B). **For a triangular step change**

**B.C.** \[ V_\theta (r, 0) = 0 \]  

\[ V_\theta (KR, t) = 0 \]

\[ V_\theta (R, t) = R\Omega(t) = \begin{cases} \alpha R t & ; \quad 0 \leq t \leq t_1 \\ 2\alpha R t_1 - \alpha R t & ; \quad t_1 \leq t \leq 2t_1 \end{cases} \]
where \( a \) is angular acceleration constant of rotating cylinder.

The solution of Eq. AI.1-2 for (B) is also shown in (9):

When \( 0 \leq t \leq t_1 \)

\[
V_\theta = a \left( \frac{r}{1-K^2} - \frac{k^2 r^2}{1-K^2} \right) t + \sum_{n=1}^{\infty} \frac{a r}{\beta_n^2} E_n \left( 1 - e^{-\beta_n^2 t} \right) Z_n(\theta_n r)
\]

When \( t_1 \leq t \leq 2t_1 \)

\[
V_\theta = a \left( \frac{r}{1-K^2} - \frac{k^2 r^2}{1-K^2} \right) (2t_1 - t) + \sum_{n=1}^{\infty} \frac{a r}{\beta_n^2} E_n \left( 1 - e^{-\beta_n^2 t_1} + e^{-\beta_n^2 t} \right) Z_n(\theta_n r)
\]

Where \( g = \left[ \frac{p}{\mu} \right]^{1/2} \); \( \theta_n = g \beta_n \)

\[
Z_n(\theta_n r) = J_1(\theta_n K R) Y_1(\theta_n K R) - Y_1(\theta_n r) J_1(\theta_n K R)
\]

with \( J_1(\theta_n r) \) and \( Y_1(\theta_n r) \) being Bessel's functions of the first and second kind respectively.

The eigenvalue satisfy the following relationship:

\[
J_1(\theta_n K R) Y_1(\theta_n R) = J_1(\theta_n R) Y_1(\theta_n K R)
\]

The coefficient of \( E_n \):
\[ E_n = \frac{1}{1-K^2} \left[ Z_n(\theta_n R) - K^2 Z_n(\theta_n K R) \right] - \frac{K^2}{1-K^2} \left[ Z_n(\theta_n R) - Z_n(\theta_n K R) \right] \]

The shear stress distribution and the torque applied to the inner cylinder:

\[ \tau_r = -\mu r \frac{\partial}{\partial r} \left( \frac{V_0}{r} \right) = -\mu \dot{\theta}_0 \quad ; \quad T(t) = 2\pi K R L \left( -\tau_r \right) \bigg|_{r=KR} \]

(A). For a single step change

\[ T(t) = 2\pi K R L \mu \left[ \frac{2\Omega}{1-K^2} - \sum_{n=1}^{\infty} \theta_n E_n e^{-\beta_n^2t} Z_n(\theta_n K R) \right] \]

The transient term may be neglected in most viscometer calculation (9), therefore

\[ T(t) = 2\pi K R L \mu \frac{2\Omega}{1-K^2} = A_0 = \text{Constant} \quad \text{(A.I.1-5)} \]

(B). For a triangular step change

When \( 0 \leq t \leq t_1 \)

\[ T(t) = \frac{4\pi a L K^2 R^2 \mu t}{1-K^2} + 2\pi a L K^2 R^3 \sqrt{\rho \mu} \sum_{n=1}^{\infty} \frac{E_n}{\beta_n} Z_n(\theta_n K R) \left( 1 - e^{-\beta_n^2t} \right) \]
When \( t_1 < t < 2t_1 \),

\[
T(t) = \frac{4\pi \alpha L K^2 R^2 \mu (2t_1-t)}{1-K^2} + 2\pi \alpha L K^2 R^3 \rho \mu \sum_{n=1}^{\infty} \frac{E_n}{\beta_n} Z_o(\theta, kR) \left( 1 - 2e^{-\beta_n t_1} + e^{-\beta_n t} \right)
\]

It was shown (9), if the dimensionless group

\[
N_{HF} = \frac{(1-K^2)R_0 G}{2t_1} \frac{E_1}{\beta_1} Z_o(\theta, kR) \ll 1
\]

the summation terms of \( T(t) \) can be neglected, and since for most viscometers, \( N_{HF} \ll 1 \), so

\[
T(t) = \begin{cases} 
B t & ; \quad 0 \leq t \leq t_1 \\
B (2t_1-t) & ; \quad t_1 \leq t \leq 2t_1
\end{cases}
\]

(A.I.1-6).

where \( B = \frac{4\pi \alpha L K^2 R^2 \mu}{1-K^2} \)

Substitue \( T(t) \) (Eq.A.I.1-5, A.I.1-6) into Eq.A.I.1-1, and using the method of Laplace transformation to solve Eq.A.I.1-1, the following solutions have been obtained:
Case 1. For small $\gamma$ and $\xi$, or $\gamma \to 0$, $\xi \to 0$

Single step change

$$\bar{\alpha}(s) = \frac{A_0}{G S}$$

$$\alpha(t) = \frac{A_0}{G}$$

Triangular step change

$$\bar{\alpha}(s) = \frac{B}{G}$$

$$\bar{\tau}(s) = \frac{B}{G} s^2 \left\{ \begin{array}{ll} \frac{1}{S^2} & ; \quad 0 \leq t \leq t_1 \\ \frac{2 t_1}{S} - \frac{1}{S^2} & ; \quad t_1 \leq t \leq 2 t_1 \end{array} \right.$$ 

$$\alpha(t) = \frac{B}{G} \left\{ \begin{array}{ll} t & ; \quad 0 \leq t \leq t_1 \\ (2t_1 - t) & ; \quad t_1 \leq t \leq 2 t_1 \end{array} \right.$$ 

Case 2. For small $\xi$ or $\xi \to 0$

Single step change

$$\bar{\alpha}(s) = \frac{A_0/G}{S(T^2S^2 + 1)} = \frac{A_0/G}{S} - \frac{(A_0\tau_0/G)S}{T^2S^2 + 1}$$

$$\alpha(t) = \frac{A_0}{G} \left( 1 - \cos \left( \frac{t}{\tau} \right) \right)$$
Triangular step change

\[ \tilde{x}(s) = \frac{B/G}{\tau^2 s^2 + 1} \begin{cases} 
\frac{1}{s^2} & ; \quad 0 \leq t \leq t_1 \\
\frac{2t_1}{s} - \frac{1}{s^2} & ; \quad t_1 \leq t \leq 2t_1 \\
(t - \tau \sin \frac{t}{\tau}) & 
\end{cases} \]

\[ \alpha(t) = \frac{B}{G} \begin{cases} 
2t_1(1 - \cos \frac{t}{\tau}) - (t - \tau \sin \frac{t}{\tau}) & 
\end{cases} \]

Case 3. Overdamped, \( \xi > 1 \)

Single step change

\[ \tilde{x}(s) = \frac{A_0/G}{s(\tau^2 s^2 + 2\xi \tau s + 1)} = \frac{A_0}{G} \left( \frac{1}{s} - \frac{\tau^2 s + 2\xi \tau}{\tau^2 s^2 + 2\xi \tau s + 1} \right) \]

From (45), page 556

\[ \alpha(t) = \frac{A_0}{G} \begin{cases} 
1 - \left( \xi + \sqrt{\xi^2 - 1} \right) e^{-\left( \xi - \sqrt{\xi^2 - 1} \right) \frac{t}{\tau}} & \\
- \left( \xi - \sqrt{\xi^2 - 1} \right) e^{-\left( \xi + \sqrt{\xi^2 - 1} \right) \frac{t}{\tau}} & 
\end{cases} \]

Triangular step change

When \( 0 \leq t \leq t_1 \)

\[ \tilde{x}(s) = \frac{B/G \tau^2}{s^2(s^2 + 2\xi s + \frac{1}{\tau^2})} = \frac{B/G \tau^2}{s^2(s + \frac{1}{\tau}(\xi + \sqrt{\xi^2 - 1}))(s + \frac{1}{\tau}(\xi - \sqrt{\xi^2 - 1}))} \]
From (46), page 203

$$\alpha(t) = \frac{B}{G} \left[ t - 2s \tau - \frac{\tau}{2\sqrt{s^2-1}} \left( 2s^2 - 1 + 2s^{3\sqrt{s^2-1}} \right) e^{-\left( s + \sqrt{s^2-1} \right) \frac{t}{T}} - \left( 2s^2 - 1 - 2s^{3\sqrt{s^2-1}} \right) e^{-\left( s - \sqrt{s^2-1} \right) \frac{t}{T}} \right]$$

When \( t_1 < t < 2t_1 \)

$$\tilde{J}(s) = \frac{B/G}{\tau^2 s^2 + 2\tau \tau s + 1} \left( \frac{2t_1}{S} - \frac{1}{S^2} \right)$$

$$= \frac{2t_1 B/G \tau^2}{S \left[ S + \frac{1}{\tau^2} \left( S - \sqrt{s^2-1} \right) \right]} - \frac{B/G}{S^2 \left( \tau^2 s^2 + 2\tau \tau s + 1 \right)}$$

From (46), page 195

$$\alpha(t) = \frac{2t_1 B}{G} \left\{ 1 + \frac{1}{2s^{3\sqrt{s^2-1}}} \left[ \left( s - \sqrt{s^2-1} \right) e^{-\left( s + \sqrt{s^2-1} \right) \frac{t}{T}} - \left( s + \sqrt{s^2-1} \right) e^{-\left( s + \sqrt{s^2-1} \right) \frac{t}{T}} \right] \right\}$$

$$- \frac{B}{G} \left\{ t - 2s \tau + \frac{s}{2s^{3\sqrt{s^2-1}}} \left[ \left( 2s^2 - 1 + 2s^{3\sqrt{s^2-1}} \right) e^{-\left( s + \sqrt{s^2-1} \right) \frac{t}{T}} - \left( s - \sqrt{s^2-1} \right) e^{-\left( s - \sqrt{s^2-1} \right) \frac{t}{T}} \right] \right\}$$
Case 4. Underdamping, $\xi < 1$

**Single step change**

$$\tilde{x}(s) = \frac{A_0/G}{s(\tau^2s^2 + 2\xi\tau s + 1)}$$

From (46), page 192

$$x(t) = \frac{A_0}{G} \left[ 1 - e^{-\frac{\xi}{\tau}t} \sin \left( \sqrt{1-\xi^2} \frac{t}{\tau} - \phi \right) \right]$$

with $\phi = \tan^{-1} \left( \frac{1-\xi^2}{-\xi} \right)$

**Triangular step change**

When $0 \leq t \leq t_1$

$$\tilde{x}(s) = \frac{B/G}{s^2(\tau^2s^2 + 2\xi\tau s + 1)}$$

From (46), page 201

$$x(t) = \frac{B}{G} \left[ t - 2\xi\tau + \frac{\tau e^{-\frac{\xi}{\tau}t}}{\sqrt{1-\xi^2}} \sin \left( \sqrt{1-\xi^2} \frac{t}{\tau} - 2\phi \right) \right] = \frac{B}{G} \tilde{F}_1(t)$$

When $t_1 \leq t \leq 2t_1$
\[ \tilde{\alpha}(s) = \frac{B/G}{\gamma^2 s^2 + 2 \gamma s + 1} \left( \frac{2t_i}{s} - \frac{1}{s^2} \right) \]

From (46), page 192

\[ \alpha(t) = \frac{2t_i B}{G} \left[ 1 + \frac{e^{-\xi t}}{\tau} \sin\left(\sqrt{1-\xi^2} \frac{t}{\tau} - \Phi\right) \right] - \frac{B}{G} F_{1}(t) \]

**Case 5. Critical damping, \( \xi = 1 \)**

**Single step change**

\[ \tilde{\alpha}(s) = \frac{A_0 G}{s (\gamma^2 s^2 + 2 \gamma s + 1)} \]

\[ \alpha(t) = \frac{A_0}{G} \left[ 1 - (1 + \frac{t}{\tau}) e^{-t/\tau} \right] \]

**Triangular step change**

When \( 0 < t < t_1 \)

\[ \tilde{\alpha}(s) = \frac{B/G}{s^2 (\gamma^2 s^2 + 2 \gamma s + 1)} \]
\[ \alpha(t) = \frac{B}{G} \left( t e^{-t/\tau} + \frac{2}{\tau} e^{-t/\tau} + t - \frac{2}{\tau} \right) = \frac{B}{G} F_2(t) \]

When \( t_1 \leq t \leq 2t_1 \),

\[ \alpha(s) = \frac{B/G}{\gamma^2 s^2 + 2\gamma s + 1} \left( \frac{2t_1}{s} - \frac{1}{s^2} \right) \]

\[ \alpha(t) = \frac{B}{G} \left\{ 2t_1 \left[ 1 - (1 + \frac{t}{\tau}) e^{-t/\tau} \right] - F_2(t) \right\} \]
Appendix I.2 - Mathematical Derivation of the Huang Equation

A brief mathematical derivation of the Huang equation is described as follows (2):

Although the system of a time-dependent, homogeneous, and non-Newtonian fluid is under non-equilibrium conditions during shearing at isothermal state; based on irreversible thermodynamics, it can be assumed that there exists within small mass a state of local equilibrium.

Therefore, the rate of generation of entropy due to the shear stress for a fluid with structural change as modeled by Huang is:

\[ \dot{S} = - \frac{1}{T} \left[ \gamma_{ij} \frac{d\gamma_{ij}}{d\tau} + \gamma_{ij} \frac{d\beta_{ij}}{d\tau} \right] \]  

(AI.2-1)

where \( \gamma_{ij} \) is the strain tensor, \( \beta_{ij} \) is the Huang's molecular rearrangement parameter, \( \gamma_{ij} \) is the stress tensor, \( \tau \) is the time, and \( T \) is the absolute temperature.

Huang then relates the contravariant tensor of first and second order in the above equation to the rate of strain, and the rate of molecular rearrangement parameter by the following phenomenological equations:

\[ \gamma_{ij} = \mu \frac{d\gamma_{ij}}{d\tau} \]  

(AI.2-2)

\[ \gamma_{ij} = - \xi \frac{d\beta_{ij}}{d\tau} \]
where \( \mu \) is the apparent viscosity, and \( \xi \) is the molecular rearrangement coefficient. For a thixotropic fluid, Huang then assumed:

\[
\frac{\partial \beta \dot{\gamma}}{\partial t} = -C_1 \beta \dot{\gamma} \dot{\gamma}^n \quad \text{for} \quad |\dot{\gamma}| > 0 \quad (A1.2-3)
\]

\[
\frac{\partial \beta \dot{\gamma}}{\partial t} = C_2 (\beta^* - \beta \dot{\gamma}) \quad \text{for} \quad |\dot{\gamma}| = 0 \quad (A1.2-4)
\]

where \( \beta^* \) is the equilibrium value of \( \beta \dot{\gamma} \) at \( t = 0 \), and \( C_1 \) and \( C_2 \) are rate constants, and \( n \) is the order of the rate equation.

An overall apparent viscosity \( \eta \) can be defined which will relate the shear stress to the rate of strain by considering both the rate of strain effect and the rate of molecular rearrangement effect as follow:

\[
\gamma \dot{\gamma} = \eta \frac{d\gamma \dot{\gamma}}{dt} = \mu \frac{d\dot{\gamma}}{dt} - \xi \frac{d\beta \dot{\gamma}}{dt}
\]

or \( \eta = \mu - \xi \frac{d\beta \dot{\gamma}}{dt} \) (A1.2-5)

If the fluid has a yield stress \( \tau_o \); combining the equations (A1.2-2), (A1.2-3), and (A1.2-5), the Huang equation is obtained:

\[
\gamma \dot{\gamma} = \tau_o \dot{\gamma} + \mu \dot{\gamma} \dot{\gamma} + C A |\dot{\gamma}|^n \dot{\gamma} + \int_0^t c |\dot{\gamma}|^n dt
\]

(Al.2-6)

where \( C = C_1 \), the rate constant; \( A = \xi \beta^* \), the molecular rearrangement parameter; \( \dot{\gamma} \dot{\gamma} = \frac{d\gamma \dot{\gamma}}{dt} \), the shear rate.
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1 PROGRAM BLOOD

2 C*****************************************************************************

3 C THIS PROGRAM WAS WRITTEN BY WALTER FABISIAK. THIS PROGRAM

4 C UTILIZES A NON-LINEAR REGRESSION ALGORITHM DEVELOPED BY

5 C D.W. MARQUARDT(MARQUARDT, D.W., J. SOC. INDUST. AND APPL.

6 C MATH., 11, NO.2, (1963) 431-441). THIS PROGRAM WAS SPECIFICALLY

7 C DESIGNED TO CALCULATE THE BEST ESTIMATES OF THE ADJUSTABLE

8 C PARAMETERS FOUND IN THE HUANG RHEOLOGICAL EQUATION OF STATE

9 C FOR THIXOTROPIC FLUIDS(HUANG, C.R., THE CHEM. ENG. JOURNAL,

10 C 3, 100(1972).

11*****************************************************************************

12 COMMON Y(100),X(100,5),PARAM(10),PRNT(5),CONST(4)

13 DIMENSION INFO(20)

14 124 READ(5,890,END=123)INFO

15 890 FORMAT(20A4)

16 C READING IN THE DATA SET INFORMATION

17 C INFO IS THE NAME OF THE DATA SET BEING USED

18 WRITE(6,891)INFO

19 891 FORMAT(1H1,35X,20A4)

20 5 READ(5,892)CONST(1),CONST(2),CONST(3)

21 892 FORMAT(3F10.3)

22 C CONST(1) IS A CONSTANT USED IN THE MODEL BEING TESTED;

23 CALL FITIT

24 C FITIT IS THE NONLINEAR REGRESSION SUBROUTINE

25 C*****************************************************************************

26 C*****************************************************************************

27 WRITE(6,893)INFO

28 893 FORMAT(/30X,6HEND OF,20A4)

29 GO TO 124

30 123 STOP

31 END

Appendix I.3. Modified Marquardt computer program
for Huang's parameters

(Since this program is very complicated, it is better
to keep the original program in place of a flow chart)
SUBROUTINE FITIT

NONLINEAR REGRESSION SUBROUTINE

THIS SUBROUTINE IS A MODIFICATION OF THE SUBROUTINE

SNOWJO WRITTEN BY R. ROBERTSON (M.S.CHE. 1972, N.C.E.).

MODIFIED VERSION PROGRAMMED BY WALTER FABISLAK

THE FOLLOWING COMMENTS ILLUSTRATE THE OPERATIONAL

SEQUENCE OF THE NONLINEAR REGRESSION SUBROUTINE,

CALL SUBZ(Y, X, PARAM, PRNT, NPRNT, NDATA)

CALL MODEL(Y, X, PARAM, PRNT, FCN, I, RESIDUE)

THE EQUATION TO BE TESTED IS WRITTEN HERE

IT IS SET EQUAL TO FCN(Y HAT)

CALL DERIV(PARTL, X, PARAM, PRNT, FCN, I)

THIS SUBROUTINE IS FOR THE USE OF

ANALYTIC PARTIAL DERIVATIVES

CODING TO MAKE (PARTIAL FCN/PARTIAL PARAM) GOES HERE

MAKE NPARAM OF THEM AND CALL THEM PARTL(J)

READ FIRST CARD OF THE NEXT CASE

COMMON Y(100), X(100, 5), PARAM(10), PRNT(5), CONST(4)

INTEGER IDATA(5), PP(10) Y, X, ICH, OCH

EQUIVALENCE (IBOH, IDATA(1)), (IOCH, IDATA(2)), (IPCH, IDATA(3))

DIMENSION SPARAM(10), DPARAM(10), BPARAM(10), G(10), IPARAM(9),

1, SA(10), PARTL(10), A(10, 11), PMAX(10), SPRNT(5), PMIN(10)

REAL LAMBDA, LENGTH

IF(NPRT = 0)

ICOUNT = 0

IBOUT = 0

READ(5, 900, END=660) NDATA, NPARAM, NFIXED, NVAR, IFPLOT

FORMAT(1013)

READING IN THE PROGRAM CONTROLS

NDATA IS THE NUMBER OF DATA POINTS, THE MAXIMUM

NPARAM IS THE TOTAL NUMBER OF PARAMETERS IN THE MODEL

TO BE TESTED, THE MAXIMUM NUMBER OF PARAMETERS IS 10

NFIXED IS THE NUMBER OF PARAMETERS WITH FIXED VALUES

THE MAXIMUM NUMBER OF FIXED PARAMETERS IS 9, NFIXED

MUST ALWAYS BE LESS THAN NPARAM

NVAR IS THE NUMBER OF INDEPENDENT VARIABLES IN THE

MODEL TO BE TESTED, THE MAXIMUM NUMBER OF INDEPENDENT

VARIABLES IS 5

IFPLOT IS AN OUTPUT CONTROL VARIABLE, A VALUE OF ZERO

GIVES TABULATED RESULTS, A VALUE OF ONE GIVES PLOTTED...
SUBROUTINE 09/26/70 15:35

RESULTS.

IF(NDATA,GT,0) GO TO 2
THE PROGRAM WILL TERMINATE THE PRESENT CASE IF NO DATA
POINTS HAVE BEEN SUPPLIED

WRITE(6,940)
940 FORMAT(/20X,40HCASE TERMINATED: NO DATA POINTS SUPPLIED)
GO TO 660

READ(5,900)NSW1,NSW2,NSW3,NSW4,NSW5,NSW6
900 FORMAT(26HREAD IN THE SENSE SWITCH CONTROLS
SETTING OF THE SENSE SWITCHES(NSW)

NSW EQUAL TO ZERO NOT EQUAL TO ZERO
1 DETAILED OUTPUT ON NO DETAILED OUTPUT ON
2 ONLINE PRINTER ONLINE PRINTER
3 ANALYTIC DERIVATIVES ESTIMATED DERIVATIVES
4 DETAILED PRINTOUTS NSW3 ABBREVIATED PRINTOUTS
5 ON OUTPUT UNIT ON OUTPUT UNIT
6 FORCED BRANCH TO
7 CONFIDENCE REGION
8 CALCULATIONS
9 FORCED BRANCH TO
10 NEXT CASE
11 CONFIDENCE REGION CONFIDENCE REGION
12 DESIRED NOT DESIRED
13 TESTING FOR PLOTTING OR TABULATING OPTIONS
14 IF(IFPLOT.LE,0) GO TO 22
15 READ(5,930)YMIN,SPREAD
16 READING IN THE PLOTTING CONTROLS
17 THE PLOTTING CONTROLS ARE REQUIRED ONLY IF IFPLOT IS SET
18 EQUAL TO ONE.
19 YMIN IS THE VALUE OF THE LEFT SIDE OF THE PLOT.
20 SPREAD IS THE SPREAD OF THE PLOT.
21 930 FORMAT(2F10,0)
22 TESTING FOR MODEL PARAMETERS WITH FIXED VALUES
23 IF(NFIXED,LE,0) GO TO 32
24 READ(5,900)(IPARAM(I),I=1,NFIXED)
25 READING IN THE SUBSCRIPTS OF THE MODEL PARAMETERS
26 HAVING FIXED VALUES.
27 IPARAM(I) IS THE SUBSCRIPT OF THE MODEL PARAMETER
28 HAVING A FIXED VALUE
29 DO 26 I=1,NFIXED
30 IF(IPARAM(I),GT,0) GO TO 26
31 WRITE(6,926)
926 FORMAT(/10X,47HBAD DATA; FIXED PARAMETERS HAVE ZERO SUBSCRIPTS)
32 IBOUT=1
33 26 CONTINUE
34 THE FOLLOWING ARE INPUT CONSTANTS SUPPLIED BY THE PROGRAM

...
101 32 FF=4.
102 C FF IS A VARIANCE RATIO STATISTIC.
103 36 E=.0000005
104 C E IS A CONVERGENCE CRITERION.
105 38 TAU=.001
106 C TAU IS A CONVERGENCE CRITERION
107 40 T=2.
108 C T IS THE STUDENT'S T.
109 51 GAMCR=.45
110 C GAMCR IS THE CRITICAL ANGLE.
111 DELTA=.00001
112 C DELTA IS A MULTIPLIER USED IN THE FINITE DIFFERENCE
113 C DERIVATIVES.
114 ZETA=.1E-30
115 C ZETA IS A CONVERGENCE CRITERION FOR MATRIX INVERSION.
116 LAMBDA=0.01
117 C LAMBDA IS A PROGRAM PARAMETER
118 53 XKDB=1.0
119 C XKDB IS A MULTIPLIER USED TO INCREMENT THE PARAMETERS
120 C********************************************************************************
121 READ(5,901)(PARAM(I),I=1,NPARAM)
122 C READING IN THE INITIAL VALUES OF THE MODEL PARAMETERS;
123 C THEY ARE READ SEVEN TO THE CARD,
124 C PARAM(I) IS THE VALUE OF THE MODEL PARAMETER;
125 901 FORMAT(7F10.0)
126 READ(5,901)(PHIN(I),I=1,NPARAM)
127 C READING IN THE MINIMUM VALUES OF THE MODEL PARAMETERS
128 C PHIN(I) IS THE MINIMUM VALUE OF THE PARAMETER
129 READ(5,901)(PMAX(I),I=1,NPARAM)
130 C READING IN THE MAXIMUM VALUES OF THE MODEL PARAMETERS
131 C PMAX(I) IS THE MAXIMUM VALUE OF THE PARAMETER
132 DO 56 I=1,NDATA
133 56 READ(5,901)(Y(I),X(I,L),L=1,NVAR)
134 C READING IN THE DATA POINTS
135 C Y(I) IS THE VALUE OF THE INDEPENDENT VARIABLE
136 C X(I,L) IS THE VALUE OF THE DEPENDENT VARIABLE
137 C********************************************************************************
138 C CALL SUBZ(Y,X,PARAM,PRNT,NPRNT,NDATA).............
139 C
140 C
141 9999 NSW33=NSW3
142 NTILDA=NDATA
143 XNT=NTILDA
144 NSW44=NSW4
145 NNDATA=NDATA
146 ICOUNT=0
147 IBK=1
148 NSW11=NSW1
149 NSW22=NSW2
150 NSW55=NSW5
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151 IF(IFPFP=IFPLOT)
152 IF(IFPFP=IFPLOT,NEQ,0) GO TO 660
153 59 INAKA=1
154 IF(IFPFP=IFPLOT,LEQ,0) GO TO 61
155 WRITE(6,1007)NDATA,NPARAM,NFIXED,NVAR,IFPFP,GAMMA,DELTA,
156 1 TT,E,TAU,LAMBDA,ZETA
157 907 FORMAT(/5X,8HNDATA = ,13,4X,9HNDATA = ,12,4X,9HNDATA = ,
158 1 I1,4X,7HNVAR = ,11,4X,9HNDATA = ,11,4X,13HNDATA = ,
159 2 IPE10,3,4X,8HDELTA = ,1PE10,3,5X,5HP = ,1PE10,3,4X,8HDELTA = ,
160 3 IPE10,3,4X,8NTAU = ,1PE10,3,4X,9HLAMBDAX = ,
161 4 IPE10,3,4X,9HZETA = ,1PE10,3)
162 60 NS3=NSW3-1
163 NSW3=MAXD(NSW3,0)
164 C START THE CALCULATION OF THE PTP MATRIX
165 DO 62 J=1,NPARAM
166 G(I)=0.
167 DO 62 J=1,NPARAM
168 62 A(I,J)=0,
169 WRITE(6,941)(PMAX(I,J),I=1,NPARAM)
170 941 FORMAT(/5X,18HPARAMETER MINIMUMS,IP5E18.8/(23X,1PE18.8))
171 WRITE(6,942)(PMAX(I,J),I=1,NPARAM)
172 942 FORMAT(/5X,18HPARAMETER MAXIMUMS,IP5E18.8/(23X,1PE18.8))
173 70 WRITE(6,908)ICOUNT,(PARAM(J),J=1,NPARAM)
174 908 FORMAT(/5X,1H(I2,1H) MODEL PARAMETERS ,1PE18.8/(25X,1PE18.8))
175 IF(NSW3,EQ,0) GO TO 73
176 71 IF(IFPFP=IFPLOT,LEQ,0) GO TO 68
177 C THE FOLLOWING STATEMENTS INITIALIZE THE PLOT
178 67 WS=YMIN*SPREAD
179 906 FORMAT(/7X,1PE9.2,90X,1PE9.2,10X,1H+,99X,1H+)
180 68 WRITE(6,910)
181 GO TO 73
182 910 FORMAT(/10X,8HBORED;9X,9HPRED;8X,10HDIF)
183 73 I=1
184 C PHI=0.
185 PHI=0.
186 C PHI IS THE SUM OF THE SQUARES OF THE RESIDUALS
187 PHIN=0.
188 C TESTING FOR ANALYTIC OR ESTIMATED PARTIAL DERIVATIVE
189 OPTIONS
190 72 IF(NSW2,EQ,1) GO TO 602
191 C..........................,
192 CALL MODEL(Y,X,PARAM,PRNT,FCN,I,RESDUE)
193 C THIS IS THE ANALYTIC PARTIALS OPTION
194 C GET PARTIALS AND FUNCTION
195 C..........................
196 C..........................
197 C..........................
198 C..........................
199 75 IF(NFIXED,LEQ,0) GO TO 80
200 IWS=IPAR(I)
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201 77 PARTL(INS)=0.

202 C THIS IS THE END OF THE ANALYTIC PARTIALS OPTION

203 C******************************************************************************

204 GO TO 80

205 C******************************************************************************

206 C THIS IS THE ESTIMATED PARTIALS OPTION

207 C MAKE NPARAM OF THEM AND CALL THEM PARTL(J)

208 C THEY ARE MADE FROM X(I,L) AND PARAM(J)

209 602 CALL MODEL(Y;X,PARAM,PRNT,FCN,I,RESDUE)

210 C******************************************************************************

211 606 RWS=RESDUE

212 FSAVE=FCN

213 DO 607 II=1,NPRNT

214 607 PRNT(II)=PRNT(II)

215 J=1

216 608 IF(NFIXED.LE.0) GO TO 618

217 610 DO 612 II=1,NFIXED

218 618 CONTINUE

219 612 DBW=PARAM(J)*DELTA

220 TWS=PARAM(J)

221 PARAM(J)=PARAM(J)+DBW

222 C******************************************************************************

223 CALL MODEL(Y,X,PARAM,PRNT,FCN,I,RESDUE)

224 C******************************************************************************

225 620 PARAM(J)=TWS

226 IF(DBW.EQ.0)DBW=DELTA

227 PARTL(J)=-(RESDUE-RWS)/DBW

228 GO TO 622

229 621 PARTL(J)=0.

230 622 J=J+1

231 IF(J=NPARAM,LE.0) GO TO 608

232 624 RESDUE=RWS

233 FCN=FSIZE

234 DO 625 II=1,NPRNT

235 625 PRNT(II)=PRNT(II)

236 C******************************************************************************

237 C THIS IS THE END OF THE ESTIMATED PARTIALS ROUTINE

238 C******************************************************************************

239 C NOW USE THE PARTIALS TO MAKE THE PARTIALS MATRIX

240 80 DO 82 JJ=1,NPARAM

241 G(JJ)=G(JJ)+RESDUE*PARTL(JJ)

242 DO 82 II=J,J,NPARAM

243 A(II,JJ)=A(II,JJ)+PARTL(II)*PARTL(JJ)

244 82 A(II,JJ)=A(II,JJ)

245 IF(IPLOOT,LE.0) GO TO 318

246 IF(NSH3,EQ.0,OR.1,GT,NDATA) GO TO 314

247 C******************************************************************************

248 C STARTING THE PLOTTING SEQUENCE

249 C PLOTTING Y(I), FCN

250 302 IO=((Y(I)-YMIN)*100./SPREAD)*10
C FORTRAN IV (VER 45) SOURCE LISTING: FITIT SUBROUTINE 05/26/78 15:35:56

251 IPP=((FCN-YMIN)*100./SPREAD)+10
252 IF(10,EQ,IPP) GO TO 808
253 IF(10,GT, IPP) GO TO 812
254 C
255 804 IP1=ICH
256 IP2=IPCH
257 I1=10
258 C
259 I2=IPP
260 C
261 808 IP1=ICH
262 IP2=IPCH
263 I1=10
264 C
265 I2=IPP
266 C
267 812 IP1=IPCH
268 IP2=ICH
269 I1=IPP
270 C
271 C
272 C
273 C
274 C
275 816 IF(I2,LE,111) GO TO 819
276 817 I2=111
277 IP2=IXCH
278 IF(I1,LT,111) GO TO 819
279 818 I1=111
280 I?1=IXCH
281 IP2=IBCH
282 C
283 819 IF(I1,GE,10) GO TO 825
284 822 I1=10
285 IP1=IXCH
286 IF(I2,GT,10) GO TO 825
287 823 I2=1
288 IP2=IBCH
289 825 I1M2=I2-I1-1
290 IF(I1M2,GT,0) GO TO 832
291 820 IP1=ICH
292 823 WRITE(6,928)IP1,IP2
293 928 FORMAT(IH,120A1)
294 928 GO TO 844
295 828 WRITE(6,928)IP1,(IBCH,I1=1,11M2),IP2
296 832 IF(I1M2,GT,0) GO TO 840
297 836 WRITE(6,928)(IBCH,I1=1,11M2),IP1,IP2
298 836 GO TO 844
299 836 GO TO 844
301 840 WRITE(6,928)(IBCH,II=1,I1M1),IP1,(IBCH,II=1,I1M2),IP2
302 CEND OF PLOTTING SEQUENCE
303 C*****************************************************************************
304 844 GO TO 314
305 318 WS=RESDUE
306 IF(NSW3.EQ.0,QR,1,GT,NDATA) GO TO 314
307 308 IF(NPRNT,GT,0) GO TO 312
308 310 WRITE(6,929)(Y(I),FCN,WS
309 925 FORMAT(5X,1P6E18.8/59X,1P2E18,8)
310 GO TO 314
311 312 WRITE(6,925)(Y(I),FCN,WS,(PRNT(JJ),JJ=1,NPRNT)
312 314 WS=RESDUE
313 PHI=PHI+WS*WS
314 IF(I,GT,NDATA) GO TO 313
315 PHI=PHIN+WS*WS
316 GO TO 315
317 313 CONTINUE
318 315 I=I+1
319 IF(I,LE,NI,TA) GO TO 72
320 84 IF(NFIXED,LE,0) GO TO 88
321 85 DO 87 JJ=1,NFIXED
322 IWS=IPARAM(JJ)
323 DO 86 II=1,NPARAM
324 A(IWS,II)=0.
325 86 A(I,IWS)=0.
326 87 A(IWS,WS)=1.
327 88 GO TO (90,704,703),IBKA
328 90 DO 92 I=1,NPARAM
329 92 SAVE SQUARE ROOTS OF DIAGONAL ELEMENTS
330 96 SA(I)=SQRT(A(I,I))
331 DO 106 I=1,NPARAM
332 DO 100 J=1,NPARAM
333 WS=SA(I)*SA(J)
334 IF(WS,GT,0.) GO TO 98
335 96 A(I,J)=0.
336 GO TO 100
337 98 A(I,J)=A(I,J)/WS
338 100 CONTINUE
339 IF(SA(I),GT,0.) GO TO 104
340 102 G(I)=0.
341 GO TO 106
342 104 G(I)=G(I)/SA(I)
343 106 CONTINUE
344 DO 110 I=1,NPARAM
345 110 A(I,I)=1.
346 120 PHI2=PHI
347 C WE NOW HAVE PHI(0)
348 1132 DO 1133 II=1,NPARAM
349 1132 III=II+25
350 DO 1133 JJ=1,NPARAM
FORTRAN IV (VER 45) SOURCE LISTING: FITIT SUBROUTINE 05/26/78 15:35:15

351  A(I,J,J)=A(I,J,J)
352  CONTINUE
353  IF(ICOUNT,NE,0) GO TO 163
354  C**********************************************************************
355  C STARTING THE FIRST ITERATION
356  LAMBDA=0.01
357  DO 161 J=1,NPARAM
358  SPARAM(J)=PARAM(J)
359  SPARAM(J) CORRESPONDS TO PHIZ
360  I=BK1=1
361  WS=NDATA-NPARAM*NFIXED
362  ICOUNT=ICOUNT+1
363  SE=SQRT(PHIN/WS)
364  C SE IS THE STANDARD ERROR OF THE ESTIMATE
365  IF(NSW3,GT,0) GO TO 165
366  IF(NSW2,EQ,0) GO TO 168
367  WRITE(6,911)PHIZ,SE,LENGTH,GAMMA,LAMBDA
368  FORMAT(14X,3HPHIZ,15X,3HS E,12X,6HLENGTH,7X,5HGMMA,7X,
369  6HLAMBDA,10X,24HESTIMATED PARTIALS USED/8X,1P2E18.8,1PE13.3)
370  GO TO 169
371  WRITE(6,912)PHIZ,SE,LENGTH,GAMMA,LAMBDA
372  FORMAT(14X,3HPHIZ,15X,3HS E,12X,6HLENGTH,7X,5HGMMA,7X,
373  6HLAMBDA,10X,22HANALYTIC PARTIALS USED/8X,1P2E18.8,1PE13.3)
374  GO TO 169
375  CONTINUE
376  WRITE(6,939)
377  FORMAT(14X,3HPHIZ,15X,3HS E,12X,6HLENGTH,GAMMA,LAMBDA)
378  DO 114 I=1,NPARAM
379  WRITE(6,937) I, (A(I,J),J=1,NPARAM)
380  IF(NSH2,NE,0) GO TO 161
381  WRITE(6,903)PHIZ,SE,LENGTH,GAMMA,LAMBDA
382  FORMAT(14X,3HPHIZ,15X,3HS E,12X,6HLENGTH,7X,5HGMMA,7X,
383  6HLAMBDA,10X,24HESTIMATED PARTIALS USED/8X,1P2E18.8,1PE13.3)
384  GO TO 169
385  WRITE(6,9099)PHIZ,SE,LAMBDA
386  FORMAT(14X,3HPHIZ,15X,3HS E,12X,6HLENGTH,7X,5HGMMA,7X,
387  6HLAMBDA,10X,22HANALYTIC PARTIALS USED/8X,1P2E18.8,1PE13.3)
388  GO TO 200
389  PHIL=PHI
390  WE NOW HAVE PHI(LAMBDA)
391  DO 170 J=1,NPARAM
392  IF(ABS(DPARAM(J))/(ABS(PARAM(J))+TAU)),GE,E) GO TO 172
393  CONTINUE
394  WRITE(6,923)
395  FORMAT(1H1,50X,19HPASSSED EPSILON TEST)
396  GO TO 700
397  IF(NSH5,EQ,0) GO TO 172
398  IF(NSH4,EQ,0) GO TO 173
399  IF(NSH5,NE,0) GO TO 171
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401  NSW4=NSW4-1
402  GO TO 173
403  WRITE(6,924)
404 924 FORMAT(1H1,30X,40HCASE TERMINATED: REQUIRE MORE ITERATIONS)
405  GO TO 700
406 173 XXX=1,0
407  IF(PHIL,GT,PHIZ) GO TO 190
408  XLS=LAMBD
409  DO 176 J=1,NPARAM
410  BPARAM(J)=PARAM(J)
411 176 PARAM(J)=SPARAM(J)
412  IF(LAMBD,GT,0000001) GO TO 175
413 175 DO 176 J=1,NPARAM
414  PARAM(J)=BPARAM(J)
415 176 SPARAM(J)=PARAM(J)
416  GO TO 60
417 175 LAMBD=LAMBD/10;
418  IBK1=2
419  GO TO 200
420 177 PHIL4=PHI
421  IF(PHIL4,GT,PHIZ) GO TO 184
422 182 DO 183 J=1,NPARAM
423 183 SPARAM(J)=PARAM(J)
424  GO TO 60
425 184 LAMBD=XLS
426 184 LAMBD=XLS
427  DO 186 J=1,NPARAM
428  SPARAM(J)=BPARAM(J)
429 186 PARAM(J)=BPARAM(J)
430  GO TO 60
431 190 IBK1=4
432  XLS=LAMBD
433  LAMBD=LAMBD/10;
434  DO 185 J=1,NPARAM
435 185 PARAM(J)=SPARAM(J)
436  GO TO 200
437 187 IF(PHI,LE,PHIZ) GO TO 196
438 191 LAMBD=XLS
439  IBK1=3
440 192 LAMBD=LAMBD*10;
441 195 DO 193 J=1,NPARAM
442 193 PARAM(J)=SPARAM(J)
443  GO TO 200
444 194 PHIL4=PHI
445  IF(PHIL4,GT,PHIZ) GO TO 198
446 190 IF(PHI,LE,GAMCR) GO TO 192
FORTRAN IV (VER 45) SOURCE LISTING: FITIT

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199 XDB=XDB/2.

DO 1199 J=1,NPARAM
IF(ABS(DPARAM(J))/(ABS(PARAM(J))+TAU)),GE,E) GO TO 195

CONTINUE

DO 1200 J=1,NPARAM
PARAM(J)=SPARAM(J)
WRITE(6,934)

DO 1200 J=1,NPARAM
PARAM(J)=A(I,J)*G(J)+DPARAM(J)

DO 202 I=1,NPARAM
A(I,I)=A(I,I)+LAMBDA
IBKM=1.

CALL GJR(A,NPARAM,ZET,MSING)
GET INVERSE OF A AND SOLVE FOR DPARAM(J)
THIS IS THE MATRIX INVERSION ROUTINE
NPARAM IS THE SIZE OF THE MATRIX
GO TO (415,660), IBKM

GO TO (416,710), IBKM
THIS IS THE END OF THE MATRIX INVERSION.

SOLVE FOR DPARAM(J)
DO 420 I=1,NPARAM
DPARAM(I)=0.

DO 421 J=1,NPARAM
DPARAM(I)=A(I,J)*G(J)+DPARAM(I)

DPARAM(I)=XKDB*DPARAM(I)
DPARAM IS THE INCREMENT OF THE PARAMETER
LENGTH=0.
DTG=0.

DO 250 J=1,NPARAM
LENGTH=LENGTH+DPARAM(J)*DPARAM(J)

DTG=DTG+DPARAM(J)*G(J)
DTG=DTG*G(J)**2 GO TO 699

IF(SA(J),LE,0.) GO TO 1257

DPARAM(J)=DPARAM(J)/SA(J)

IF(PARAM(J)+DPARAM(J),LT,PMIN(J)) DPARAM(J)=ABS(DPARAM(J))
IF(PARAM(J)+DPARAM(J),GT,PMAX(J)) DPARAM(J)=-DPARAM(J)

CONTINUE
KIP=NPARAM-NFIXED

IF(LENGTH+G,J,LE,0.) GO TO 1257
96

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501 IF(KIP,EQ,1) GO TO 1257
502 CGAM=DIG/SQRT(LENGTH+GTG)
503 JGAM=1
504 IF(CGAM,GT,0) GO TO 253
505 251 CGAM=ABS(CGAM)
506 JGAM=2
507 253 GAMMA=57.2957795*(1.5707288+CGAM*(-0.212144+CGAM*0.074261)
508 1-CGAM*.0187293))/SQRT(1-CGAM)
509 GO TO (257,255), JGAM
510 255 GAMMA=180.-GAMMA
511 IF(LAMBDA,LT,1.0) GO TO 257
512 1255 WRITE(6,922)XJ,GAMMA
513 922 FORMAT(1H1,30X,24HPASSED GAMMA LAMBDA TEST,5X,1PE13.3)
514 GO TO 700
515 1257 GAMMA=0.
516 257 LENGTH=SQRT(LENGTH)
517 IBK2=1
518 GO TO 300
519 252 IF(NS3,EQ,0) GO TO 256
520 WRITE(6,905)PHI,LAMBDA,GAMMA,LENGTH
521 905 FORMAT(15X,3HPHI,12X,6HLAMBDA,7X,5HGAMMA,8X,6HLENGTH,1X,)
522 1PE18.8,1P3E13.3)
523 254 WRITE(6,904)(DPARAM(J),J=1,NPARAM)
524 904 FORMAT(5X,20HPARAMETER INCREMENTS,1PE18.8/(25X,1PE18.8))
525 256 GO TO (164,177,194,187),IBK1
526 C CALCULATE PHI
527 300 I=1
528 PHI=0.
529 PHIN=0.
530 C
531 800 CALL MODEL(Y;X,PARAM,PRNT,PCN,I,RESDUE)
532 C
533 IF(RESDUE,GE,1,E33) GO TO 699
534 IF(I,GT,NDATA) GO TO 305
535 PHIN=PHIN+RESDUE*RESDUE
536 305 I=I+1
537 IF(I,E,NHILDA) GO TO 800
538 PHI=PHIN
539 316 GO TO (252,780,704,762,766,772),IBK2
540 C THIS IS THE CONFIDENCE LIMIT CALCULATION
541 C
542 699 WRITE(6,943)
543 943 FORMAT(15X,3HCASE TERMINATED; RESULTS HAVE BLOWN UP)
544 GO TO 660
545 700 DO 702 J=1,NPARAM
546 702 PARAM(J)=SPARAM(J)
547 937 NDATA,NPARAM,NFIXED,NVAR,FF,T,E,TAU
548 933 FORMAT(5X,8HDATA,=,15,4X,9HNPARAM,=,12,4X,9HNFIXED,=,
549 11,4X,7HNVAR,=,11,5X,5HFF,=,1PE10.3,4X,4HT,=,1PE10.3,
550 24X,4HE,=,1PE10.3,4X,6HTAU,=,1PE10.3)
551  IBKA=2
552  NTILDA=NDATA
553  C      THIS WILL PRINT THE Y, YHAT, DELTA Y
554  ICOUNT=ICOUNT+1
555  NSW3=1
556  GO TO 61
557  704  IF(IFPLLOT.LE.0) GO TO 703
558  705  IBKA=3
559  IFPLLOT=0
560  GO TO 61
561  703  CONTINUE
562  706  WS=NDATA-NPARAM+NFIXED
563  IF(WS.LE.0) GO TO 660
564  SE=SRT(PHI/WS)
565  PHIZ=PHI
566  IF(NSW2.EQ.0) GO TO 709
567  707  WRITE(6,903)PHIZ,SE,LAMBDA
568  GO TO 708
569  709  WRITE(6,909)PHIZ,SE,LAMBDA
570  708  DO 1123 II=1,NPARAM
571  111=II+25
572  DO 1123 JJ=1,NPARAM
573  1123 A(II,II)=A(II,II)
574  C      WE NOW HAVE MATRIX A
575  1124 IMH=2
576  GO TO 404
577  C      WE NOW HAVE C=A INVERSE
578  710  DO 711 J=1,NPARAM
579  IF(A(J,J),LE,0) GO TO 713
580  711  SA(J)=SQRT(A(J,J))
581  GO TO 715
582  713  IBOUT=1
583  715  KST=-4
584  WRITE(6,916)
585  916  FORMAT(/40X,11HPTP INVERSE)
586  234  KST=KST+5
587  KEND=KST+4
588  IF(KEND,L.T,NPARAM) GO TO 719
589  KEND=NPARAM
590  719  DO 722 I=1,NPARAM
591  712  WRITE(6,918)I,(A(I,J),J=KST,KEND)
592  918  FORMAT(5X,13,1P5E18.8)
593  IF(KEND,L.T,NPARAM) GO TO 234
594  IF(IBOUT,EQ,0) GO TO 717
595  WRITE(6,936)
596  936  FORMAT(/25X,25HNEGATIVE DIAGONAL ELEMENT)
597  GO TO 660
598  717  DO 718 I=1,NPARAM
599  718  J=1,NPARAM
600  WS=SA(I)=SA(J)
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601 IF (WS, GT, 0.) GO TO 716

602 714 A(I, J) = 0.

603 GO TO 718

604 716 A(I, J) = A(I, J) / WS

605 718 CONTINUE

606 DO 720 J = 1, NPARAM

607 720 A(J, J) = 1,

608 WRITE (6, 917)

609 917 FORMAT (' /23X, 28HPARAMETER CORRELATION MATRIX')

610 KST = 9

611 721 KST = KST + 10

612 KEND = KST + 9

613 IF (KEND, LT, NPARAM) GO TO 722

614 J = 1, NPARAM

615 722 DO 742 I = 1, NPARAM

616 724 WRITE (6, 935) I, A(I, J); J = KST, KEND

617 935 FORMAT ('5X, I3, 2X, 10F10.4')

618 IF (KEND, LT, NPARAM) GO TO 721

619 C GET T*SE*SORT(C(I, I))

620 DO 760 J = 1, NPARAM

621 760 SA(I) = SE*SA(J)

622 1112 DO 1113 II = 1, NPARAM

623 1113 III = II + 25

624 DO 1113 JJ = 1, NPARAM

625 1113 A(II, JJ) = A(III, JJ)

626 1114 CONTINUE

627 740 WRITE (6, 919)

628 919 FORMAT ('/16X, 3HSTD, 19X, 13HONE-PARAMETER, 23X, 13HSUPPORT PLANES) 4X, 14HPARAM, 7X, 5HERO, 13X, 5LOWER, 13X, 5UPPER, 13X, 5LOWER, 13X,

629 25HUPPER)

630 WS = NPARAM - NFIXED

631 DO 780 J = 1, NPARAM

632 780 IF (NFRG, LE, 0.) GO TO 743

633 742 I = 1, NPARAM

634 741 IF (J, EQ, IPNAM(I)) GO TO 746

635 742 CONTINUE

636 743 HJTD = SORT (WS*FF) * SA(J)

637 C STE = SA(J)

638 OPL = SPARAM(J) - SA(J)*T

640 OPU = SPARAM(J) + SA(J)*T

641 SPL = SPARAM(J) - HJTD

642 SP = SPARAM(J) + HJTD

643 WRITE (6, 927) J, STE, OPL, OPU, SPL, SP

644 927 FORMAT ('5X, I2, 1P5E18.8')

645 GO TO 750

646 746 WRITE (6, 913) J

647 913 FORMAT ('5X, I2, 10X, 2HPARAMETER WAS NOT USED')

648 750 CONTINUE

649 C***********************************************************************

650 C NON-LINEAR CONFIDENCE LIMIT CALCULATION
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651 IF(NSW6.EQ.1) GO TO 660
652 WS=NPARAM-NFIXED
653 WS1=NDATA-NPARAM-NFIXED
654 PKN=WS/WS1
655 PC=PHIZ*(1.+FF*PKN)
656 WRITE(6,920)PC
657 920 FORMAT(/IBX,27HNONLINEAR CONFIDENCE LIMITS,10X-
658 1 15HPhi Critical = ,1PE15.8)
659 WRITE(6,921)
660 921 FORMAT(/SX,4HPARA,6X,7HLower B,11X,9HLower phi,9X-
661 1 7Hupper B,11X,9HUpper phi)
662 IFSS3=1
663 DO 790 J=1,NPARAM
664 IBKP=1
665 DO 752 JJ=1,NPARAM
666 752 PARAM(JJ)=SPARAM(JJ)
667 IF(NFIXED.LE.0) GO TO 758
668 754 DO 756 JJ=1,NFIXED
669 IF(J.EQ.IPARAM(JJ)) GO TO 787
670 756 CONTINUE
671 758 DD=-1.
672 IBKN=1
673 760 D=DD
674 PARAM(J)=SPARAM(J)+D*SA(J)
675 IBK2=4
676 GO TO 300
677 762 PH1=PHI
678 IF(PH1.GE.PC) GO TO 770
679 764 D=DD
680 IF(D/DD,GE.5..) GO TO 788
681 765 PARAM(J)=SPARAM(J)+D*SA(J)
682 IBK2=5
683 GO TO 300
684 766 PHID=PHI
685 IF(PHID.LT.PC) GO TO 764
686 IF(PHID.GE.PC) GO TO 778
687 770 D=D/2.
688 IF(D/DD,LE.,001) GO TO 788
689 771 PARAM(J)=SPARAM(J)+D*SA(J)
690 IBK2=6
691 GO TO 300
692 772 PHID=PHI
693 IF(PHID.GT.PC) GO TO 770
694 778 XK1=PHIZ/D+PHII/D*(D=1.)
695 XK2=-(PHIZ*(1.-D)/D+D/(1.+D)*PHII+PHID/(D*(D=1.))
696 XK3=PHIZ-PC
697 BC=SQRT((XK2*XK2-4.*XK1*XK3)/XK2)/(2.*XK1)
698 GO TO (779,784),IBKN
699 779 PARAM(J)=SPARAM(J)-SA(J)*BC
700 GO TO 781
PARAM(J)=SPAR(J)*SA(J)*BC

GO TO 300

GO TO (792,786), IBKN

DD=1.

BL=PARAM(J)

PL=PHI

GO TO 760

BU=PARAM(J)

PU=PHI

GO TO (783,795,785,789), IBKP

WRITE(6,918) J, BL, PL, BU, PU

GO TO 790

WRITE(6,915) J, BU, PU

FORMAT(2X,12,10X,10X,10H0

GO TO 790

WRITE(6,918) J, BL, PL

GO TO 790

WRITE(6,913) J

GO TO 790

WRITE(6,914) J

FORMAT(2X,12,10X,10HNONE FOUND)

GO TO 790

GO TO (791,792), IBKN

DELETE LOWER PRINT

DELETE UPPER PRINT

GO TO 780

GO TO (793,794), IBKP

DELETE BOTH

LOWER IS ALREADY DELETED, SO DELETE BOTH

GO TO 780

CONTINUE

CONTINUE

NSW3=NSW33

COUNT=0

NSW4=NSW44

IFPLOT=IFPP

NDATA=NNDATA

NSW1=NSW11

NSW2=NSW22

NSW5=NSW55

IBOUT=0

READ(5,900) ININ

READING IN THE PROGRAM CONTROL VARIABLE
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751  GO TO (662, 9998, 651), ININ
752  9998  READ (5, 901) (PARAM(JJ), JJ = 1, NPARAM)
753  C  READING IN NEW VALUES OF THE MODEL PARAMETERS
754  GO TO 9999
755  662  RETURN
756  END
SUBROUTINE GJR(A,N,EPS,MSING)

C*******************************************************************************
C GAUSS-JORDAN RUTISHAUSER MATRIX INVERSION
C*******************************************************************************

C*******************************************************************************

DIMENSION A(10,10),B(10),C(10),P(10),Q(10)
INTEGER P,Q

MSING=1
DO 10 K=1,N
10 PIVOT=0.

DO 20 I=K,N
20 IF (ABS(A(I,J))-ABS(PIVOT)) .LT. EPS,10,20

10 PIVOT=A(I,J).
P(K)=I
Q(K)=J
DO 20 J=K,N
20 IF (ABS(PIVOT)-EPS) .LT. EPS,20,40

20 L=P(K)
Z=A(L,J)
A(L,J)=A(K,J)
A(K,J)=Z
DO 30 J=1,N
30 A(I,J)=Z
A(I,L)=A(I,J)
CONTINUE

DO 35 J=1,N
35 CONTINUE
30 IF (J-K) .LE. 10,10,30
31 A(I,L)=A(I,K)
35 C EXCHANGE OF THE PIVOTAL COLUMN WITH THE KTH COLUMN
32 100 A(I,K)=Z
33 90 CONTINUE
34 DO 110 J=1,N
35 JORDAN STEP
36 130 B(J)=1./PIVOT
38 C(J)=1.
39 GO TO 140
40 130 B(J)=-A(K,J)/PIVOT
41 C(J)=A(J,K)
42 140 A(K,J)=0.
43 110 A(J,K)=0.
44 DO 10 I=1,N
45 DO 10 J=1,N
46 10 A(I,J)=A(I,J)+C(I)*B(J)
47 DO 155 M=1,N
48 K=N-M+1
49 REORDERING THE MATRIX
50 IF (PT(K)=K) 160,170,160
51 160 DO 180 I=1,N
52   L=P(K)
53   Z=A(I,L)
54   A(I,L)=A(I,K)
55 180 A(I,K)=Z
56 170 IF(Q(K)=K)190,155,190
57 190 DO 150 J=1,N
58   L=Q(K)
59   Z=A(L,J)
60   A(L,J)=A(K,J)
61 150 A(K,J)=Z
62 155 CONTINUE
63 151 RETURN
64 40 WRITE(2,45)P(K),Q(K),PIVOT
65 45 FORMAT(16H0SINGULAR MATRIX3H I=13,3H J=13,7H PIVOT=E16,8/)
66 MSING=2
67 GO TO 151
68 END
SUBROUTINE SUBZ(Y, X, PARAM, PRNT, NPRNT, NDATA)

COMMON Y(100), X(100,5), PARAM(10), PRNT(5), CONST(4)

NPRNT=1

RETURN

END
SUBROUTINE MODEL(Y, X, PARAM, PRNT, FCN, I, RESIDUE)

**COMMON Y(100), X(100, 5); PARAM(10), PRNT(5), CONST(4)**

* TESTING OF THE THIXOTROPIC MODEL *

PARAM(1) REPRESENTS THE YIELD STRESS

PARAM(2) REPRESENTS THE VISCOSITY

PARAM(3) REPRESENTS A RATE CONSTANT

PARAM(4) REPRESENTS A LUMPED PARAMETER

PARAM(5) REPRESENTS THE ORDER OF THE RATE EQUATION

X(1, 1) IS THE SHEAR RATE AND POSITIVE WHEN USED IN THE UP CURVE OR DOWN CURVE

X(1, 2) IS THE TIME WHEN USED IN THE TORQUE-DECAY CURVE

Determine whether it is representative of the upcurve;

DOWN CURVE, OR THE TORQUE-DECAY CURVE

CONST(1) IS THE MAXIMUM SHEAR RATE FOR THE UP CURVE OR DOWN CURVE

CONST(2) IS THE CONSTANT SHEAR RATE FOR THE TORQUE-DECAY CURVE

CONST(3) IS A PROPORTIONALITY CONSTANT BETWEEN THE SHEAR RATE AND TIME

T = X(1, 1)

PRNT(1) = T

T1 = CONST(1)

T2 = CONST(2)

ALPHA = CONST(3)

**THE FOLLOWING VARIABLES ARE DEFINED TO SIMPLIFY THE MODEL TO BE TESTED**

AONE = PARAM(5) + 1.0

ATWO = ALPHA * AONE

ATHREE = T * AONE

AFOUR = T ** PARAM(3)

AFIVE = T1 * AONE

ASIX = T2 ** PARAM(5)

ASEVEN = PARAM(3) * PARAM(4) * AFOUR

AEIGHT = PARAM(3) * PARAM(4) * ASIX

A9INE = PARAM(3) * ASIX * X(1, 1)

ATEN = PARAM(3) / ATWO

BONE = ATEN * ATHREE

BTWO = 2.0 * AFIVE * ATHREE

BTHREE = ATEN * BTWO

BFOUR = PARAM(4) * AFOUR

BFIVE = PARAM(3) * AFOUR

BSIX = BONE * ALOG(T1)

BSEVEN = BONE / AONE

BIGHT = 2.0 * AFIVE * ALOG(T1)

B9INE = ATHREE * ALOG(T1)

B10NE = ATEN * (BIGHT - B9INE)

CONE = BTHREE / AONE

CTWO = PARAM(4) * ASIX
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51 CTHREE=PARAM(3)*ASIX
52 CFOUR=ALOG(T2)*(1.0-ANINE)
53 C THE FOLLOWING STATEMENTS TEST THE DATA POINT TO
54 C DETERMINE WHETHER IT IS REPRESENTATIVE OF THE UP CURVE;
55 C DOWN CURVE, OR THE TORQUE-DECAY CURVE
56 IF(X(I,2),GT,10.0) GO TO 40
57 IF(X(I,2),GT,2.0;AND,X(I,2),LT,3.0) GO TO 20
58 C THIS EQUATION REPRESENTS THE UP CURVE
59 FCN=PARAM(1)*PARAM(2)*TASEVEN*EXP(-BONE)
60 GO TO 30
61 C THIS EQUATION REPRESENTS THE DOWN CURVE
62 20 FCN=PARAM(1)*PARAM(2)*TASEVEN*EXP(-BTHREE)
63 GO TO 30
64 C THIS EQUATION REPRESENTS THE TORQUE-DECAY CURVE
65 40 FCN=PARAM(1)*PARAM(2)*T2*AEIGHT*EXP(-ANINE)
66 30 RESDUE=Y(I)-FCN
67 RETURN
68 END
SUBROUTINE DERIV(PARTLVX, PARAM, PRNT, FCN, I)

COMMON Y(100), X(100), PARAM(10), PRNT(9), CONST(4)

INSERT THE VARIOUS PARTIAL DERIVATIVES IN THIS SUBROUTINE ONLY IF ANALYTIC PARTIALS ARE TO BE USED

DIMENSION PARTLV(10)

T=X(I,1)

T1=CONST(1)

T2=CONST(2)

ALPHA=CONST(3)

THE FOLLOWING VARIABLES ARE DEFINED TO SIMPLIFY THE MODEL TO BE TESTED

AONE=PARAM(5)+1,0

ATWO=ALPHA*AONE

ATHREE=T*ATWO

AFIVE=T1*ATWO

ASIX=T2**PARAM(5)

ASEVEN=PARAM(3)*PARAM(4)*AFOUR

AEIGHT=PARAM(3)*PARAM(4)*ASIX

ANINE=PARAM(3)*ASIX*X(I,1)

ATEN=PARAM(3)/ATWO

BONE=ATEN*ATHREE

BTWO=2.0*AFIVE-ATHREE

BTHREE=ATEN*BTWO

BFOUR=PARAM(4)*AFOUR

BFIVE=PARAM(3)*AFOUR

BSIX=BONE*ALOG(T)

BSEVEN=BONE/AONE

BIGHT=2.0*AFIVE*ALOG(T1)

BNINE=ATHREE*ALOG(T)

BTEN=ATEN*(BIGHT-BNINE)

BONE=BTHREE/AONE

CTWO=PARAM(4)*ASIX

CTHREE=PARAM(3)*ASIX

CFOUR=ALOG(T2)*(1.0-ANINE)

ONE=PARAM(5)+1,0

ATWO=ALPHA*AONE

ATHREE=T*ATWO

AFIVE=T1*ATWO

ASIX=T2**PARAM(5)

ASEVEN=PARAM(3)*PARAM(4)*AFOUR

AEIGHT=PARAM(3)*PARAM(4)*ASIX

ANINE=PARAM(3)*ASIX*X(I,1)

ATEN=PARAM(3)/ATWO

BONE=ATEN*ATHREE

BTWO=2.0*AFIVE-ATHREE

BTHREE=ATEN*BTWO

BFOUR=PARAM(4)*AFOUR
T F O R T R A N IV (V E R 4 5 ) S O U R C E L I S T I N G : D E R I V S U B R O U T I N E 0 5 / 2 6 / 7 8 1 5 : 3 5 1 5 6 P

51 BFIVE=PARAM(3)*AFOUR
52 BSIX=BOONE*ALOG(T)
53 BSEVEN=BOONE/AONE
54 BHEIGHT=2.0*AFIVE*ALOG(T)
55 BNINE=ATREE*ALOG(T)
56 RNI INE=ATREE*ALOG(T)
57 BTEN=ATEN*(BHEIGHT-BNINE)
58 CONE=BTREE/AONE
59 CTHO=PARAM(4)*ASIX
60 CTHREE=PARAM(3)*ASIX
61 CFOUR=ALOG(T2)*(1.0-ANINE)
62 C THE FOLLOWING STATEMENTS TEST THE DATA POINT TO
63 C DETERMINE WHETHER IT IS REPRESENTATIVE OF THE UPCODE;
64 C DOWNCURVE, OR THE TORQUE-DECAY CURVE
65 IF(X(1,2),GT;10.0) GO TO 40
66 IF(X(1,2),GT;2.0;AND,X(1,2),LT;3.0) GO TO 20
67 C THE FOLLOWING PARTIAL DERIVATIVES ARE FOR THE UPCODE
68 PARTL(1)=1.0
69 PARTL(2)=T
70 PARTL(3)=BFOUR*EXP(-BOONE)*(1.0-BOONE)
71 PARTL(4)=BFIVE*EXP(-BOONE)
72 PARTL(5)=ASEVEN*EXP(-BOONE)*(ALOG(T)-BSIX+BSEVEN)
73 GO TO 30
74 C THE FOLLOWING PARTIAL DERIVATIVES ARE FOR THE DOWNCURVE
75 20 PARTL(1)=1.0
76 PARTL(2)=T
77 PARTL(3)=BFOUR*EXP(-BTHREE)*(1.0-BTHREE)
78 PARTL(4)=BFIVE*EXP(-BTHREE)
79 PARTL(5)=ASEVEN*EXP(-BTHREE)*(ALOG(T)-BTEN+CON E)
80 PARTL(5)=-BSEVEN*ATWO*EXP(-ATREE)
81 GO TO 30
82 C THE FOLLOWING PARTIAL DERIVATIVES ARE FOR THE TORQUE-
83 C DECAY CURVE
84 40 PARTL(1)=1.0
85 PARTL(2)=T2
86 PARTL(3)=CTWO*EXP(-ANINE)*(1.0-ANINE)
87 PARTL(4)=CTREE*EXP(-ANINE)
88 PARTL(5)=HEIGHT*EXP(-ANINE)*CFOUR
89 30 CONTINUE
90 RETURN
91 END
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DIMENSION TAV(50), FN(50), EV(50), AS(50), ASR(50), GS(50), TTS(50),
TSS(50), GA(50, 50), GR(50, 50), TTR(50, 50), TSR(50), QK(50),
2GC(50), GV(50), W(50), WN(100), YW(100), HS1(100), HS2(100), WR1(100),
JS2(50), AR1(50), AR2(50), AS1(50), WR2(100), DGC(50),
4DLTS(50), DLAS(50), DLTSR(50), DLASH(50), DLQQ(50), DLGS(50), DLGV(50),
5DLV(100), DLWW(100), DLWW(100), DLWW(100), DLWW(100),
6DLAS1(50), DLAS2(50), DLAR1(50), DLAR2(50),
7DLAS(50), DLAS(50), DLAS(50), DLAS(50),
8EQUIVALENCE (T(1), TSS), (T(22), AS)
9EQUIVALENCE (W(1), TSR), (W(22), ASR)
10EQUIVALENCE (Y(1), GC), (Y(22), GV)
11EQUIVALENCE (DLW(1), DLTS), (DLW(22), DLASR)
12EQUIVALENCE (DLW(1), DLTSR), (DLW(22), DLASR)
13EQUIVALENCE (DLYW(1), DLGC), (DLYW(22), DLGV)
14EQUIVALENCE (HS1(1), DLTS), (HS1(22), DLAS)
15EQUIVALENCE (HS2(1), DLTSR), (HS2(22), DLA2)
16EQUIVALENCE (HR1(1), DLTSR), (HR1(22), DLAR1)
17EQUIVALENCE (HR2(1), DLTSR), (HR2(22), DLAR2)
18633 FORMAT (///, 30X, 'RELATIONSHIP OF INPUT SHEAR RATES VS. TIME!'/)
19634 FORMAT ('15X, TIME(SEC), 10X, D L, T, 8X, D L .Sh.R., (STEP CHANGE)!, 4X,
201DL, SH, R. (TRIANGULAR STEP CHANGE)!!/)
21365 FORMAT (13X, 'FOR TA=0,0, E=0,0, DL .T. = TIME/2*T1!', 1)
221 FORMAT (6F10.4)
2311 FORMAT (2F10.3, 3F10.4)
2498 FORMAT (I10, F10.4)
2592 FORMAT (16.9F8.4)
26100 FORMAT (110, 3F10.4)
27311 FORMAT ("C", ///, 10X, 'RI=' F10.4, 4X, 'R2=' F10.4, 4X, 'B=' F10.4, 4X,
281 'TK=' F10.4, ///)
29321 FORMAT (10X, 'NR=' I10, 5X, 'NI=' I10, 5X, 'S=' F10.4, 5X, 'MM=' I10, 5X,
301 'NN=' I10, ///)
3133 FORMAT ("C", ///, 10X, 'U=' F10.4, 4X, 'A=' F10.4, 4X, 'W=' F10.4, 4X, 'T1=' F10.4)
32405 FORMAT ('141, 30X, 'TA=0,0, 1X, 'SEC', 10X, 'E=0,0!///)
33406 FORMAT ('141, 30X, 'TA=' F10.4, 1X, 'SEC', 10X, 'E=0,0!///)
34291 FORMAT ('141, 20X, 'DEFINITION:!!/
3566 FORMAT ('141, 10X, 'T1=' F10.4, 1X, 'SEC', 10X, 'TSS(1)=' F10.4, 'DYNE/CM-
361 CM', 10X, 'TSR(MAX)=' F10.4, 'DYNE/CM-CM')
37666 FORMAT ('141, 10X, 'TA=' F10.4, 1X, 'SEC', 5X, 'E=' F10.4, 5X, 'GS(1)=' F9.4,
381 'SEC', 5X, 'GV(MAX)=' F9.4, 1X, 'SEC'/)
39202 FORMAT (10X, 'R1=RADIUS OF THE STATIONARY CYLINDER, CM')
40203 FORMAT (10X, 'R2=RADIUS OF THE ROTATING CYLINDER, CM')
41205 FORMAT (10X, 'R = ARBITRARY RADIUS BETWEEN R1 AND R2, CM')
42208 FORMAT (10X, 'A = ACCELERATION CONSTANT OF THE ROTATING CYLINDER')
43209 FORMAT (10X, 'B=LENGTH OF THE COUVEETE')
44210 FORMAT (10X, 'Q=TIME, SEC')
45219 FORMAT (10X, 'T1=TIME AT MAXIMUM SHEAR RATE, SEC')
46220 FORMAT (10X, 'NI=S=SECTIONAL CONSTANT FOR TIME, 0')
47221 FORMAT (10X, 'NR=SECTIONAL CONSTANT FOR RADIUS, 0')
48222 FORMAT (10X, 'UA, UB, UC=DELTA FUNCTIONS IF (UA, ETC.) 0,0,1')
49211 FORMAT (10X, 'G=SHEAR RATE, 1/SEC')

Appendix I. 4. Computer program for the dynamic behavior of torsion head
FORTRAN IV (VER 45) SOURCE LISTING:

110

51 2121 FORMAT (10X,'AS=DEFLECTION OF THE TORSION BAR AT A CONSTANT',1X,
52 1 'ROTATING RATE,W0,MICRO')
53 2122 FORMAT (9X,'AR=DEFLECTION OF THE TORSION BAR DURING A LINEAR',1X,
54 1 'ACCELERATION OF THE',12X,'ROTATING CYLINDER',MICRO')
55 214 FORMAT (10X,'U=NEWTONIAN VISCOSITY,POISE')
56 215 FORMAT (13X,'W0=CONSTANT REVOLUTION RATE OF THE ROTATING CYLINDER,1X,
57 11/SEC')
58 216 FORMAT (10X,'TK=TORSION BAR CONSTANT,DYNE.CM/MICRO')
59 2171 FORMAT (9X,'TSR=THEORETICAL SHEAR STRESS,DYNE.CM.CM')
60 2172 FORMAT (10X,'ASR=ARTIFICIAL SHEAR STRESS,DYNE.CM.CM')
61 313 FORMAT (10X,'TA=F10.4,F10.4,E=0.0/)
62 402 FORMAT (30X,'STEADY STATE FLOW AT CONSTANT ROTATING RATE',1X,
63 1'AFTER A STEP CHANGE')
64 4.31 FORMAT (10X,'TIME',13X,'SHEAR RATE',10X,'THEO.SHEAR STRESS',10X,
65 1'ARTI-SHEAR STRESS/')
66 5:31 FORMAT (/,'/0X',12X,'DL,T,,12X,'DL,SH.RATE',9X,'DL,THEO.SH.STRESS',9X,
67 1'DL,ARTI-SH.STRESS/')
68 4.32 FORMAT (10X,F10.4,10X,F10.4,15X,F10.4,15X,F10.4)
69 4.33 FORMAT (10X,F10.4,10X,F10.4,15X,F10.4,15X,F10.4)
70 4.4 FORMAT (30X,'TIME',13X,'SHEAR RATE',10X,'THEO.SHEAR STRESS',10X,
71 1'AFTER A STEP CHANGE')
72 501 FORMAT ('3',10X,'PLOT OF SHEAR STRESSES (Y-AXIS) VS. TIME
73 1 AFTER A STEP CHANGE')
74 504 FORMAT ('3',10X,'PLOT OF SHEAR STRESSES (Y-AXIS) VS. SHEAR RATE
75 1 DURING A LINEAR ACCELERATION AND DECELERATION')
76 505 FORMAT ('3',10X,'PLOT OF SHEAR RATES (Y-AXIS) VS. TIME (X-AXIS)')
77 600 FORMAT (50X,'UNDERDAMPING')
78 601 FORMAT (50X,'CRITICAL DAMPING')
79 602 FORMAT (50X,'OVERDAMPING')
80 216 FORMAT (10X,'TA=TIME CONSTANT OF THE TORSION HEAD,SEC')
81 207 FORMAT (10X,'E=DAMPING COEFFICIENT,0')
82 3.51 FORMAT (10X,'DL,T,(DIMENSIONLESS TIME=TIME/10SEC)/TIME-CONST,TAI')
83 3.52 FORMAT (10X,'DL,S,R,(DIMENSIONLESS SHEAR RATE=SHEAR RATES (STEP)/
84 1,12X,'CHANGE/TRIANGULAR STEP)/(CONST./MAX.) SHEAR RATE (AFTER A',/
85 2,13X,'STEP CHANGE/DURING A TRIANGULAR STEP CHANGE)')
86 3.53 FORMAT(10X,'DL,(THEO/ARTE) S.S.(DIMENSIONLESS SHEAR STRESS)',/
87 113X,'(THEORETICAL/ARTIFACT)=SHEAR STRESS (THEORETICAL/ARTIFACT)',/
88 213X,'/THEORETICAL-SHEAR-STRESS-AT-MAX-SHEAR-RATE')
89 901 FORMAT (10X,'GSC(1)=SHEAR RATE FOR A STEP CHANGE')
90 902 FORMAT (10X,'GVC(MAX)=MAX. SHEAR RATE DURING A LINEAR ACCELERATION
91 1AND DECELERATION',12X,'1TRIANGULAR-STEP-CHANGE')
92 903 FORMAT (10X,'TTI=TOTAL TIME FOR A TRIANGULAR STEP CHANGE')
93 904 FORMAT (10X,'ITSS(1)=THEORETICAL SHEAR STRESS FOR A STEP CHANGE')
94 905 FORMAT (10X,'ITSS(MAX)=THEORETICAL-MAX. SHEAR STRESS FOR A TRIANGULAR
95 1AR STEP CHANGE')
96 1234 FORMAT (10X,'MM=NO. OF TA!')
97 1235 FORMAT (10X,'NN=NO. OF E!')
98 WRITE (6,201)
99 WRITE (6,202)
100 WRITE (6,203)
```
101 WRITE (6,205)
102 WRITE (6,206)
103 WRITE (6,209)
104 WRITE (6,210)
105 WRITE (6,211)
106 WRITE (6,2121)
107 WRITE (6,2122)
108 WRITE (6,214)
109 WRITE (6,215)
110 WRITE (6,216)
111 WRITE (6,2171)
112 WRITE (6,2172)
113 WRITE (6,219)
114 WRITE (6,220)
115 WRITE (6,221)
116 WRITE (6,222)
117 WRITE (6,206)
118 WRITE (6,207)
119 WRITE (6,1234)
120 WRITE (6,1235)
121 WRITE (6,901)
122 WRITE (6,902)
123 WRITE (6,903)
124 WRITE (6,904)
125 WRITE (6,905)
126 WRITE (6,3051)
127 WRITE (6,3050)
128 WRITE (6,3052)
129 WRITE (6,3053)
130 1980 READ (5,1) U,R1,R2,B,TK,A
131 READ (5,11) NR,NI,W0,S,T1
132 9876 READ (5,100) NM, (TAV(MTA),MTA=1,MM)
133 999 READ (5,982) NN, (EV(NE),NE=1,NN)
134 WRITE (6,301). R1,R2,B,TK
135 WRITE (6,302) NR,NI,S,MM,NN
136 WRITE (6,303) U,A,W0,T1
137 RK=R1/R2
138 PI=3.1416
139 CS=4*PI*R1*R2+B*(U*W0/((1.0-RK*RK)*TK)
140 CR=4*PI*R1*R2+B*(U*A/((1.0-RK*RK)*TK)
141 CT=TK/(2*PI*R1*R2)
142 DO 1000 MTA=1,MM
143 TA=TAV(MTA)
144 DO 1000 NE=1,NN
145 E=EV(NE)
146 DO 2 I=1,NI
147 Q=S*(1-I,0)
148 QT=Q/TA
149 QA=Q
150 QB=QA-T1
```
FORTRAN IV (VER 45) SOURCE LISTING:

151  QC=QA-2*T1
152  TI=2*T1
153  J=(NI+1)/2
154  UA=QA
155  UB=QB
156  UC=QC
157  IF (UA-0,0) 40,40,41
158  40  UA=0.0
159  GO TO 42
160  41  UA=1.0
161  42  IF (UB-0,0) 50,56,54
162  50  UB=0.0
163  50  GO TO 52
164  51  UB=1.0
165  52  IF (UC-0,0) 60,60,61
166  60  UC=0.0
167  60  GO TO 62
168  61  UC=1.0
169  62  E=EV(NE)
170  70  X=SQRT(1.0-E*E)
171  71  XT=X*QT
172  72  P=ATAN(-X/E)
173  73  EC=EXP(-E*QT)
174  74  CASE THREE, TA IS NOT EQUAL TO ZERO, E<1.0, UNDERDAMPING
175  AS=CS*(1.0-(EC*SIN(XT-P))/X)
176  AA=CR*(G-2*E*TA+(TA*EC/X)*SIN(XT-2*P))
177  AD=CR*(2*P+1.0+(EC*SIN(XT-P))/X)
178  CR=0.0
179  AR=AA*(UA-UB)+AD*(UB-UC)
180  ATS=CT*AS
181  ATR=CT*AR
182  75  GO TO 80
183  76  EC=EXP(-Q/TA)
184  77  CASE FOUR, TA IS NOT EQUAL TO ZERO, E=1.0, CRITICAL DAMPING
185  AS=CS*(1.0+Q/TA)*EC
186  AA=CR*(F+EC*Q-2/TA)
187  AD=CR*(2*Q-1.0-(1.0+Q/TA)*EC)
188  78  AR=AA*(UA-UB)+AD*(UB-UC)
189  ATS=CT*AS
190  ATR=CT*AR
191  79  GO TO 90
192  80  XP=E*X
193  81  XN=E-X
194  82  EP=EXP(-XP*QT)
195  83  EN=EXP(-XN*QT)
196  CASE FIVE, TA IS NOT EQUAL TO ZERO, E>1.0
FORTRAN IV (VER 45) SOURCE LISTING:

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201 AS=CS*(1.0-(XP*EN-XN*EP)/(2*X))
202 QE=Q-2*E*TA
203 TE=TA/(X+2)
204 DF=2*E-E-1.0+2*E*X
205 DN=2*E-E-1.0-2*E*X
206 AA=CR*(GE+TE*(DP*EP-DN*EN))
207 AD=2*T1*CR*(1.0+(1/(2*X)))*(X*EN-EP*EN)-
208 1CR*(GE+TE*(DP*EP-DN*EN))
209 AR=AA*(UA-UB)+AD*(UB-UC)
210 ATS=CT+AS
211 ATR=CT+AR
212 80 ASS(I)=ABS(ATS)
213 ASR(I)=ABS(ATR)
214 C THEORETICAL SHEAR STRESS AND SHEAR RATE
215 DO 2.M=1,NR
216 R=R1+(M-1)*0.1+(R2-R1)
217 SUMS=0.0
218 GS(M)=2*R1*R1+WO/((1.0-RK*RK)*R*R)+SUMS
219 TTS(M)=U*GS(M)
220 TSS(I)=ABS(TTS(1))
221 SUMA=0.0
222 GA(M,I)=(2*R1*R1+A/((1.0-RK*RK)*R*R))*Q+SUMA
223 SUMP=0.0
224 GD(M,I)=(2*R1*R1+A/((1.0-RK*RK)*R*R))*(-QC)+SUMP
225 GR(M,I)=GA(M,I)*(UA-UB)+GD(M,I)*(UB-UC)
226 GV(I)=GR(1,I)
227 K=I+NI
228 GV(K)=GR(1,I)
229 TTR(M,I)=U*GR(M,I)
230 TSR(I)=ABS(TTR(1,I))
231 QC(I)=QT
232 L=I+NI
233 QQ(L)=QQ(I)
234 2 CONTINUE
235 DO 266 I=1,NI
236 J=(NI+1)/2
237 TT1=2*I1
238 DLTS(I)=TSS(I)/TSS(1)
239 DLASS(I)=ASS(I)/TSS(1)
240 DLTSR(I)=TSR(I)/TSR(J)
241 DLASR(I)=ASR(I)/TSR(J)
242 DLOO(I)=QQ(I)/TT1
243 DLGS(I)=GS(1)/GS(1)
244 DLGC(I)=DLGS(I)
245 DLGV(I)=GV(I)/GV(J)
246 266 CONTINUE
247 WRITE (6,30)
248 WRITE (6,666) TA,E,GS(1),GV(J)
249 WRITE (6,66) TT1,TSS(1),TSR(J)
250 IF (E-1.0) 700,711,712
FORTRAN IV (VER 45) SOURCE LISTING:

251 700 WRITE (6,600)
252   GO TO 677
253 711 WRITE (6,601)
254   GO TO 677
255 712 WRITE (6,602)
256 677 WRITE (6,402)
257 C WRITE (6,4031)
258 C DO 3 I=1,NI
259 C Q=S*(I-1,0)
260 C QQ(I)=Q
261 C L=I+NI
262 C QQ(L)=QQ(I)
263 C GC(I)=GS(1)
264 C WRITE (6,4032) QQ(I),GC(I),TSS(I),ASS(I)
265 C 3 CONTINUE
266 WRITE (6,5031)
267 DO 363 I=1,NI
268 Q=S*(I-1,0)
269 QQ(I)=Q/TA
270 L=I+NI
271 DLGC(L)=DLGC(I)
272 WRITE (6,4032) QQ(I),DLGC(I),DLTSS(I),DLASS(I)
273 363 CONTINUE
274 WRITE (6,404)
275 C DO 4 I=1,NI
276 C Q=S*(I-1,0)
277 C QQ(I)=Q
278 C L=I+NI
279 C QQ(L)=QQ(I)
280 C GV(I)=GR(1,I)
281 C K=I+NI
282 C GV(K)=GR(1,I)
283 C WRITE (6,4032) QQ(I),GV(I),TSR(I),ASR(I)
284 C 4 CONTINUE
285 DO 464 I=1,NI
286 Q=S*(I-1,0)
287 QQ(I)=Q/TA
288 DLGV(I)=GV(I)/GV(J)
289 L=I+NI
290 DLGV(L)=DLGV(I)
291 WRITE (6,4032) QQ(I),DLGV(I),DLTSS(I),DLASS(I)
292 464 CONTINUE
293 NP=2*NI
294 WRITE (6,30)
295 C CALL XYPLOT (NP,QQ,W)
296 C WRITE (6,30)
297 C CALL XYPLOT (NP,QQ,DLW)
298 WRITE (6,501)
299 WRITE (6,30)
300 C CALL XYPLOT (NP,QQ,WW)
```
301  C WRITE (6,30)
302   CALL XYPLOT (NP, DLGV, DLWH)
303   WRITE (6,504)
304   WRITE (6,30).
305   CALL XYPLOT (NP, GG, DLWW)
306   WRITE (6,504)
307  1000 CONTINUE
308  6351 WRITE (6,30)
309   WRITE (6,633)
310   WRITE (6,634)
311  6352 DO 351 I=1,NI
312   Q=S*(I-1,0)
313   QQ(I)=Q/TT1
314   DLGC(I)=GS(I)/GS(1)
315   DLGV(I)=GV(I)/GV(J)
316   L=I+NI
317   QQ(L)=QQ(I)
318   WRITE (6,4032) Q,QQ(I),DLGC(I),DLGV(I)
319  351 CONTINUE
320   WRITE (6,30)
321  3522 NP=2*NI
322   G=S*(I-1,0)
323   QQ(I)=G/TT1
324   CALL XYPLOT (NP, QQ, DLYW)
325   WRITE (6,505)
326   READ (5,100) MM, (TAV(MTA),MTA=1,MM)
327   DO 1001 MTA=1,MM
328   DO 1001 I=1,NI
329   Q=S*(I-1,0)
330   QA=0
331   CB=QA-T1
332   CC=QA-2*T1
333   UA=QA
334   UB=QQ
335   UC=QC
336   IF (UA-0,0) 43,43,44
337   43 UA=0,0
338   GO TO 45
339   44 UA=1,0
340   45 IF (UB-0,0) 53,53,54
341   53 UB=0,0
342   GO TO 55
343   54 UB=1,0
344   55 IF (UC-0,0) 63,63,64
345   63 UC=0,0
346   GO TO 65
347   64 UC=1,0
348  C CASE ONE TA=0,0,E=0,0
349   65 AS=CS
350   AA=CR+QA
```
FORTRAN IV (VER 45) SOURCE LISTING:

351 AD=CR*(-QC)
352 AR=AA*(UA-UB)+AD*(UB-UC)
353 ATS=CT*AS
354 ATR=CT*AR
355 AS1(I)=ABS(ATS)
356 AR1(I)=ABS(AR)
357 CASE TWO, TA IS NOT EQUAL TO ZERO, E=0.0
358 TA=TAV(HTA)
359 QT=Q/TA
360 AS=CS*(1.0-COS(QT))
361 AA=CR*(C-TA*SIN(QT))
362 AD=CR*(2*T1*(1.0-COS(QT))-(Q-TA*SIN(QT)))
363 AR=AA*(UA-UB)+AD*(UB-UC)
364 C NATURAL FREQUENCY
365 FN(MTA)=1.0/(2*PI*TA)
366 ATS=CT*AS
367 ATR=CT*AR
368 AS2(I)=ABS(ATS)
369 AR2(I)=ABS(AR)
370 1.01 CONTINUE
371 WRITE (6,405)
372 WRITE (6,402)
373 WRITE (6,5031)
374 DO 703 I=1,NI
375 Q=S*(I-1.0)
376 QQ(I)=Q/TT1
377 LI=I+NI
378 QQ(L)=QQ(I)
379 DLGS(I)=GS(I)/GS(I+1)
380 DLGC(I)=DLGS(I)
381 DLGC(L)=DLGC(I)
382 DLAS1(I)=AS1(I)/TSS(I)
383 WRITE (6,4032) QQ(I),DLGC(I),DLTSS(I),DLAS1(I)
384 703 CONTINUE
385 WRITE (6,404)
386 DO 704 I=1,NI
387 Q=S*(I-1.0)
388 QQ(I)=Q/TT1
389 LI=I+NI
390 QQ(L)=QQ(I)
391 DLGV(I)=GV(I)/GV(J)
392 DLGV(L)=DLGV(I)
393 DLAR1(I)=AR1(I)/TSR(J)
394 WRITE (6,4032) QQ(I),DLGV(I),DLTSS(I),DLAS1(I)
395 704 CONTINUE
396 WRITE (6,30)
397 CALL XYPLOT (NP,QQ,KS1)
398 WRITE (6,501)
399 WRITE (6,30)
400 CALL XYPLOT (NP,DLGV,WR1)
FORTRAN IV (VER 45) SOURCE LISTING:  

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401 WRITE (6,505)
402 DO 709 MTA=1,MM
403 TA=TAV(MTA)
404 WRITE (6,406) TA
405 WRITE (6,402)
406 WRITE (6,5031)
407 DO 705 I=1,NI
408 Q=S*(I-1,0)
409 QQ(I)=Q/TA
410 L=I+NI
411 QQ(L)=QQ(I)
412 DLGC(I)=DLGS(I)
413 DLGC(L)=DLGC(I)
414 DLAS2(I)=AS2(I)/TSS(I)
415 WRITE (6,4032) QQ(I),DLGC(I),DLTSS(I),DLAS2(I)
416 705 CONTINUE
417 WRITE (6,404)
418 DO 706 I=1,NI
419 Q=S*(I-1,0)
420 QQ(I)=Q/TA
421 L=I+NI
422 QQ(L)=QQ(I)
423 DLGV(I)=GV(I)/GV(J)
424 DLGV(L)=DLGV(I)
425 DLAR2(I)=AR2(I)/TSR(J)
426 WRITE (6,4032) QQ(I),DLGV(I),DLTSR(I),DLAR2(I)
427 726 CONTINUE
428 WRITE (6,30)
429 CALL XYPLT(NP,OG,WS2)
430 WRITE (6,501)
431 WRITE (6,30)
432 CALL XYPLT(NP,DLGV,WR2)
433 WRITE (6,505)
434 WRITE (6,30)
435 CALL XYPLT(NP,OG,WR2)
436 WRITE (6,505)
437 709 CONTINUE
438 GO TO 1980
439 9666 STOP.
440 END
DEFINITION:

R1 = RADIUS OF THE STATIONARY CYLINDER, CM
R2 = RADIUS OF THE ROTATING CYLINDER, CM
R = ARBITRARY RADIUS BETWEEN R1 AND R2, CM
A = ACCELERATION CONSTANT OF THE ROTATING CYLINDER
B = LENGTH OF THE COUETTE
Q = TIME, SEC
G = SHEAR RATE, 1/SEC
AS = DEFLECTION OF THE TORSION BAR AT A CONSTANT ROTATING RATE W0, MICRO
AR = DEFLECTION OF THE TORSION BAR DURING A LINEAR ACCELERATION OF THE
    ROTATING CYLINDER, MICRO
U = NEWTONIAN VISCOSITY, POISE
W0 = CONSTANT REVOLUTION RATE OF THE ROTATING CYLINDER, 1/SEC
TK = TORSION BAR CONSTANT, DYNE-CM/MICRO
TSR = THEORETICAL SHEAR STRESS, DYNE/CM, CM
ASR = ARTIFICIAL SHEAR STRESS, DYNE/CM, CM
T1 = TIME AT MAXIMUM SHEAR RATE, SEC
N1,S = SECTIONAL CONSTANT FOR TIME, 0
NR = SECTIONAL CONSTANT FOR RADIUS, 0
UA, UB, UC = DELTA FUNCTIONS IF (UA, ETC.) 0,0,1
TA = TIME CONSTANT OF THE TORSION HEAD, SEC
E = DAMPING COEFFICIENT, 0
NH = NO. OF TA
NN = NO. OF E
GS(1) = SHEAR RATE FOR A STEP CHANGE
DV(MAX) = MAX. SHEAR RATE DURING A LINEAR ACCELERATION AND DECELERATION
    TRIANGULAR STEP CHANGE
TT = TOTAL TIME FOR A TRIANGULAR STEP CHANGE
TSS(1) = THEORETICAL SHEAR STRESS FOR A STEP CHANGE
TSR(MAX) = THEORETICAL MAX. SHEAR STRESS FOR A TRIANGULAR STEP CHANGE
DL, T = (DIMENSIONLESS TIME = TIME/10 SEC)/TIME-CONST, TA
    FOR TA = 0,0, E = 0,0, DL,T = TIME/2*T1
DL,S,R, (DIMENSIONLESS SHEAR RATE = SHEAR RATES (STEP
    CHANGE/TRIANGULAR STEP)/(CONST, MAX.) SHEAR RATE (AFTER A
    STEP CHANGE/DURING A TRIANGULAR STEP CHANGE)
DL,(THEOR/ARTIF).S.S, (DIMENSIONLESS SHEAR STRESS
    (THEORETICAL/ARTIFACT) = SHEAR STRESS/(THEORETICAL/ARTIFACT)
    /THEORETICAL SHEAR STRESS AT MAX. SHEAR RATE
### Appendix II.1-A Hematological Parameters During Cardiopulmonary Bypass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample</th>
<th>N</th>
<th>X</th>
<th>S.D.</th>
<th>P</th>
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<tr>
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<td>6</td>
<td>14.7</td>
<td>1.3</td>
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<td>1.2</td>
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<tr>
<td>3</td>
<td>11</td>
<td>8.1</td>
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<td>-</td>
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#### $\gamma$

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Appendix II.I-B  Comparison of Rheological Parameters Between 13 Patients Who Survived and Two Patients Who Expired After Cardiac Surgery

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Rh.P. : Rheological parameters.

\( \bar{X} \) : Mean value of 13 survivors.
Appendix II.2 Rheological Parameters from the Effect of Temperature on Blood

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Appendix II.3 Rheological Parameters from the Effect of Alkanols on Blood

**Note:**

- $C_1$ to $C_4$: No. of Pure Blood Sample (Control).
- 1 to 11: The number indicates the carbon number of the alkanol which has been added to 5.0 ml. of the pure blood sample.
- 0.1 to 0.005: ml. of the pure alkanol added to 5.0 ml. of the pure blood sample.
- Incubation: at 37°C for 30 minutes.
- $S$: Sample.
- $V$: ml. of alkanol added to the control.

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Appendix III. Equations for the Calculation of Shear Rate and Shear Stress on a Double Couette

The double couette was shown in Fig.III.1-2.

Assuming an incompressible Newtonian fluid flows at steady state in \( \theta \) -direction only i.e. \( V_r = V_z = 0 \)

Equation of motion of the fluid in \( \theta \) - direction

\[
0 = \frac{d}{dr} \left[ \frac{1}{r} \frac{d}{dr} (r V_\theta) \right]
\]  

\text{(A.III-1)}

(A) Inner couvette \( r_1 \leq r \leq r_2 \)

B.C. \( V_\theta (r_1) = 2\pi r_1 \Omega \) with \( \Omega [=] \text{rad/sec} \)

\[ V_\theta (r_2) = 0 \]

The solution of Eq.AIII-1 is

\[
V_\theta (r) = \frac{2\pi r^2 \Omega}{r_2^2 - r_1^2} \left( \frac{r_2^2}{r} - r \right)
\]

\[
\dot{\gamma}_{r\theta} \bigg|_{r=r_2} = r \frac{d}{dr} \left( \frac{V_\theta}{r} \right) \bigg|_{r=r_2} = -\frac{4\pi r^2 \Omega}{r_2^2 - r_1^2} \text{ sec}^{-1}
\]

\[
\tau_{r\theta} \bigg|_{r=r_2} = -\mu \dot{\gamma}_{r\theta} \bigg|_{r=r_2}
\]

\[
T_2 = 2\pi r_2 L \tau_{r\theta} \bigg|_{r=r_2} = 4\pi \mu L \Omega \frac{r_1^2 r_2^2}{r_2^2 - r_1^2}
\]
(B). Outer couette; \( r_3 \leq r \leq r_4 \)

**B.C.** \( V_\theta (r_3) = 0 \)
\( V_\theta (r_4) = 2 \pi r_4 \Omega \)

The solution of Eq.AIII-1 is

\[
V_\theta (r) = \frac{2 \pi r_4^2}{r_4^2 - r_3^2} (r - \frac{r_3^2}{r})
\]

\[
\gamma_{\theta r} \bigg|_{r=r_3} = r \frac{d}{dr} \left( \frac{V_\theta}{r} \right) \bigg|_{r=r_3} = \frac{4 \pi r_4^2 \Omega}{r_4^2 - r_3^2} \sec^{-1}
\]

\[
\tau_{\theta r} \bigg|_{r=r_3} = -\mu \gamma_{\theta r} \bigg|_{r=r_3}
\]

\[
T_3 = 2 \pi r_3 L \left( -\tau_{\theta r} \right) \bigg|_{r=r_3} = 4 \pi L \mu \Omega \frac{r_3^2 r_4^2}{r_4^2 - r_3^2}
\]

(C). Design condition

In order to have the same \( \dot{\gamma}_{\theta r} \) and same \( \tau_{\theta r} \) on the surfaces at \( r_2 \) and \( r_3 \), the double couette should have:

\[
\gamma_{\theta r} \bigg|_{r=r_2} = -\gamma_{\theta r} \bigg|_{r=r_3} \quad \text{so that} \quad \tau_{\theta r} \bigg|_{r=r_2} = -\tau_{\theta r} \bigg|_{r=r_3}
\]

or

\[
\frac{r_1^2}{r_2^2 - r_1^2} = \frac{r_3^2}{r_4^2 - r_3^2}
\]
(D). Calculation of shear stress from total torque

\[ T = T_2 + T_3 = \text{Total torque applied to both} \]

\[ = 4\pi u l \Omega \left( \frac{r_1^2 r_2^2}{r_2^2 - r_1^2} + \frac{r_3^2 r_4^2}{r_4^2 - r_3^2} \right) \quad r_2 \text{ & } r_3 \text{ surfaces} \]

\[ \frac{T_2}{T} = \frac{r_2^2}{r_2^2 + r_3^2} \]

\[ \text{or} \]

\[ T_2 = T \left( \frac{r_2^2}{r_2^2 + r_3^2} \right) = 2\pi l r_2^2 \left( \tau_{r\theta} \right) \bigg|_{r=r_2} \]

\[ \therefore \left( \tau_{r\theta} \right) \bigg|_{r=r_2} = \left( -\tau_{r\theta} \right) \bigg|_{r=r_3} = \frac{T}{2\pi l (r_2^2 + r_3^2)} \]

(E). Calculation of total torque from the measurement of

Y in X-Y recorder

Let \( R \) = setting of range of the maximum deflection in micro of the transducer meter.

\( Y_m \) = the reading in Y of the X-Y recorder corresponding to the maximum angle deflection of the torsion bar.

\( Y \) = reading of Y at the X-Y recorder.

\( G \) = torsion bar constant.

\( \alpha \) = angle deflection of torsion bar.

\[ T = G \cdot \alpha = G \cdot R \cdot \frac{Y}{Y_m} \]
so,

\[
\left. (\mathcal{L}_r) \right|_{r=r_2} = \left. (\mathcal{L}_r) \right|_{r=r_3} = \frac{G \cdot R \cdot Y / Y_m}{2 \pi L (r_2^2 + r_3^2)}
\]

\[
\left. (\dot{\mathcal{L}}_r) \right|_{r=r_2} = \left. (\dot{\mathcal{L}}_r) \right|_{r=r_3} = -\frac{4\pi r_2^2 \Omega}{r_2^2 - r_3^2}
\]

For \( \Omega \), see next Appendix.
Appendix IV. Calculation of the RPM of viscometer in Weissenberg Rheogoniometer, Model 18

Input shaft

1500 rpm (motor)

\[
\frac{99999 \times 60}{256 \times 200 \times 5} = 585.93 \text{ rpm}
\]

(control panel)

Couette

\[\Omega \text{ rpm}\]

\[\Omega^?\]

Note:

1. Constant speed of motor is 1500 rpm.

2. Control panel sets at 99999 with high switch 5 (low switch 1) giving the new impulse driven motor at the above speed (585.93 rpm).

3. \(\Omega_o\) is determined by the gear box setting (see Weissenberg manual, Appendix 1).

so,

\[
\Omega = \frac{585.93}{1500} \Omega_o \text{ (rpm)}
\]

\[
= \frac{585.93}{1500} \Omega_o \times \frac{2\pi}{60} \text{ sec}^{-1}
\]
Appendix V. Bibliography


29. Lew, E., Membrane Transport in Red Cells, 197-219, 1977


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