Article for the 29th Sensing Forum

Characteristics of Tuning-fork Vibration Rheometer RHEO-VISCO RV-10000

Presented by: Naoto Izumo, Yuji Fukami, and Masahiro Kanno
R&D Division 5, A&D Company, Limited

Organized by: The Society of Instrument and Control Engineers (SICE)

September 27 to 28, 2012

Hitachi Campus, Ibaraki University

Ibaraki, JAPAN

Characteristics of Tuning-fork Vibration Rheometer RHEO-VISCO RV-10000

Naoto Izumo, Yuji Fukami, Masahiro Kanno　A&D Company Limited
Higashi-Ikebukuro, Toshima-ku, Tokyo 170-0013 Japan

Abstract

We've developed a new rheometer for which shear rate can be changed by the sensor plate amplitude in stages, based on the tuning-fork vibration viscometer SV series. Also we report on the physical properties for non-newtonian fluid using the newly developed rheometer RHEO-VISCO RV-10000, which works using the tuning-fork vibration method.

Keywords

Newtonian fluid, Bingham fluid, Dilatant fluid, Thixotropic fluid

1) Introduction

As a means of measuring viscosity, in May 2011, vibration viscometers were recognized as a Japan industrial standard (JIS). Vibration viscometers are also among the viscometers to be calibrated in the Japan Calibration Service System (JCSS). To meet these viscometer standards, A&D has taken the only tuning-fork vibration viscometer in the world for the past 20 years and made it into a product, now sold as the SV Series.

Tuning-fork vibration viscometers have a low resonance frequency of 30 Hz, and the amount of energy they transmit to materials through these slight vibrations is low. For this reason, they have high resolution (minimum digit of 0.01 mPa・s) and consistency, able to perform continuous measurements from a low viscosity of 0.3 mPa・s (equivalent to the viscosity of acetone) all the way up to a high viscosity of 10,000 mPa・s. Because of this, using viscosity variation measurement, the instrument can measure things like the cloud points of nonionic surface-active agents, concentration of alcohol, and cure processes of proteins and adhesives. With this unique vibrational system, researchers, who mostly measure non-Newtonian fluids, often asked us whether it is possible to change the fixed shear rate.

With this in mind, we took the tuning-fork vibration viscometer SV as a base, and developed a rheometer which allowed graded adjustment of the shear rate (the amplitude of the oscillators). We will report on physical properties of non-Newtonian fluids we measured with our newly-developed tuning-fork vibration rheometer, RHEO-VISCO RV-10000.

2) Principles of the tuning-fork vibration rheometer　<u>* 2, 3</u>

With the tuning-fork vibration viscometer, two oscillators are made to resonate in a horizontal direction like a tuning-fork, and the vibrational energy needed to maintain a fixed amplitude for the oscillators is

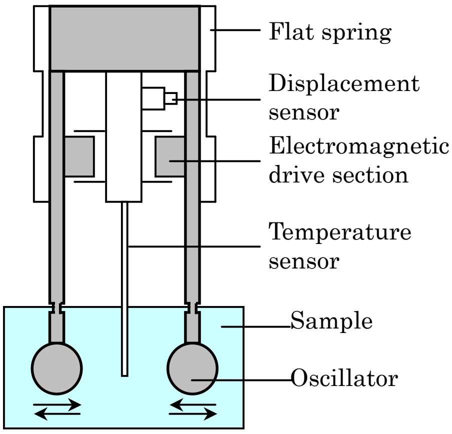


Fig 1. Composition of the viscosity detector

compensated for using electromagnetic energy. In other words, a driving force equivalent to the fluid's viscous resistance is applied, and because this driving force is in proportion to the viscous resistance, the viscosity is sought. Additionally, with a vibrational viscometer, in principle the viscous resistance is sought through viscosity × density. We call this viscosity × density "static viscosity" *4 to differentiate it from kinetic viscosity and viscosity.

With the tuning-fork vibration method, by calculating the equation of motion including the driving force necessary to cause the oscillators to resonate, inertia term, viscosity term, and elasticity term, it can be understood that the power required to drive the oscillators is proportional to viscosity × density.

Here we will explain the theoretical model behind the vibration viscometer, abbreviating some intermediate steps. With the structure shown in Fig. 1, when the oscillator vibrates with frequency f, the mechanical impedance Rz which the oscillator receives from the fluid is

$$R_z = A\sqrt{\pi f \eta \rho}$$

and the parameters in the equation are f : vibration frequency (Hz), A : planar dimensions of both sides of the oscillator, η : viscosity of the fluid, ρ : density of the fluid. Then, if the force by which the electromagnetic drive unit gives the oscillator the constant vibration velocity $Ve^{i\omega t}$ is F , then

$$R_z = \frac{F}{Ve^{i\omega t}} = A\sqrt{\pi f \eta \rho}$$

The above equation makes it clear that the power applied by the electromagnetic drive unit is proportional to the static viscosity (product of viscosity η and density ρ)*4. During actual measurements, the instrument controls the torque generated in the electromagnetic drive unit to maintain the constant amplitude of the oscillator against the sample fluid, and uses the fact that the electric current needed for said control is proportional to "viscosity × density", namely, static viscosity. In developing a rheometer (RHEO-VISCO) utilizing a tuning-fork vibration viscometer, maintaining high sensitivity was the most critical issue, so it was difficult to make the natural vibration frequency (the built-in resonance point) adjustable. Instead, the shear rate is changed by adjusting the oscillator amplitude in steps, and from the oscillator surface areas and the torque generated for driving the oscillator at each shear rate, the shear stress is calculated, which in turn is used to arrive at the static viscosity.

In this report, for the sake of convenience, we nondimensionalize values by assuming the sample's

Fig.2 RV-10000

density to be 1.00 g/cm^3, equivalent to water, and express the viscosity by mPa•s. In Fig. 2, we have included an external view of the instrument. The instrument's structure is the same as that of our viscometer. At present, the shear rate range measurable by the RHEO-VISCO is 0.2 to 1.2 mm for oscillator amplitude, and 10 to 2000s^{-1} for shear rate conversion, based on water and JS2000. Because the oscillators on the RV-10000 experience repeated sine-wave vibrations like conventional vibration viscometers do, unlike rotational viscometers, a constant shear rate is not maintained. It is for that reason that the constantly varying shear rate is converted and expressed as an effective value. In other words, one must be aware that the shear rate varies with time. For information on the RV-10000's measurable viscosity range and shear rate, please refer to Fig. 3.

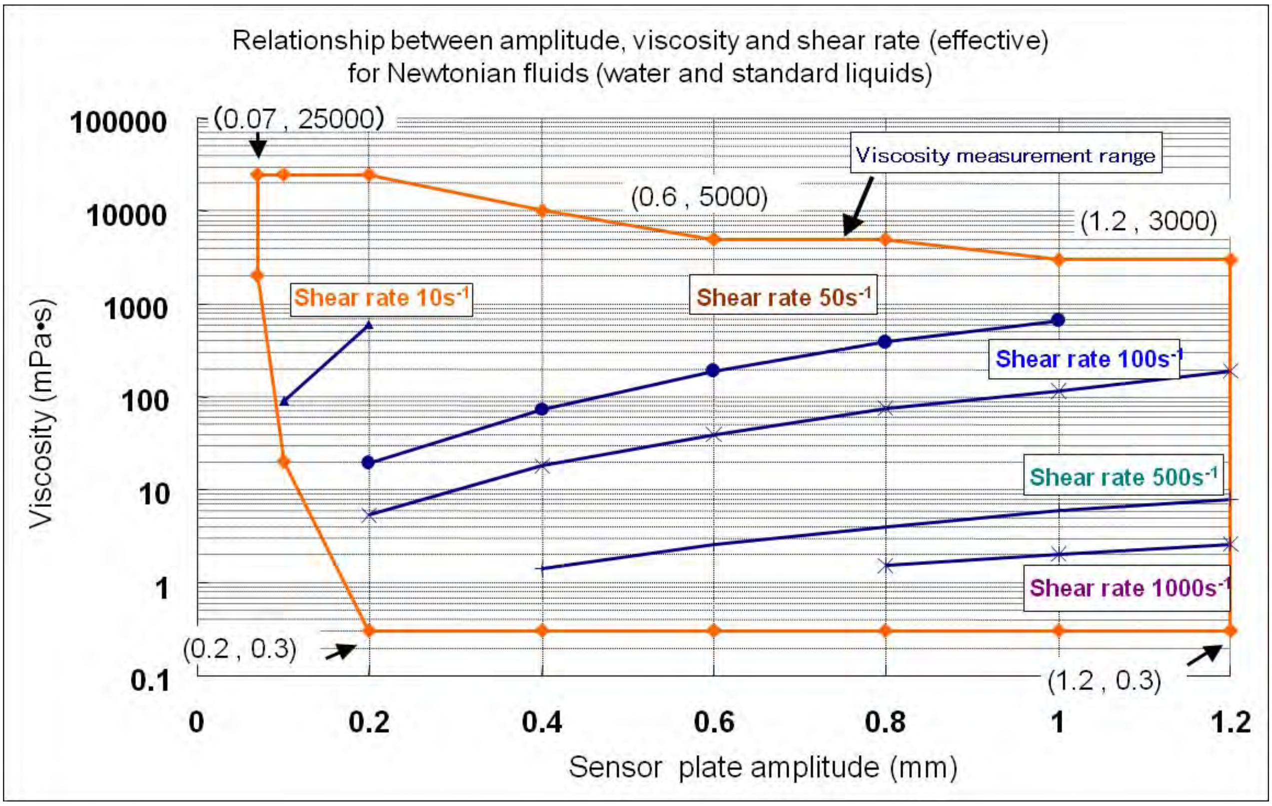


Fig. 3 Relationship between amplitude, viscosity, and shear velocity for Newtonian fluids

3) Sample measurements for the RHEO-VISCO: RV-10000

1. Concerning Newtonian fluids

Here, we explain the measurement results for water and JS2000. Water is a chemically stable substance which can be used as a standard for viscosity measurements, and is determined to have a viscosity of 1.00 mPa・s at 20. Though temperature variation is relatively small, at room temperature there is a change of about -2% for every 1˚C in temperature change, and so temperature must be managed when conducting viscosity measurements. In Fig. 4 and 5, with water and JS2000 as subjects, we plotted viscosity values when oscillation amplitude was changed from 0.2 (0.07) to 1.2 mm by peak to peak (from highest to lowest point) at a temperature of 25˚C.

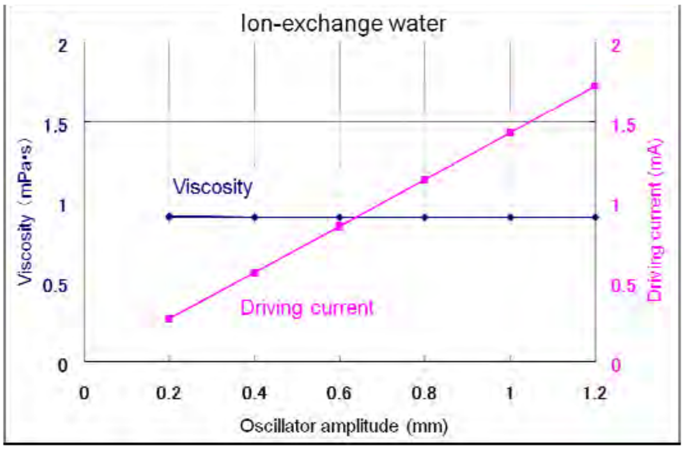


Fig. 4 Ion exchange water:
Amplitude-Viscosity, Driving current

Fig. 5 Standard fluid JS2000:
Amplitude-Viscosity, Driving current

It is shown in Fig. 4 that there is a proportional relationship between amplitude (shear rate) and shear stress for Newtonian fluids. In addition, it can be judged that the JS2000 exhibits good Newtonian properties as a standard viscous fluid.

2. Bingham fluids (skin moisturizing cream)

We now explain measurement results for moisturizing cream. Fig. 6 contains viscosity data from adjusting the oscillator amplitude each minute according to the following values: 0.07 / 0.10 / 0.20 / 0.4 / 0.6 / 0.8 / 1.0 / 1.2mm - roughly Δ0.2 mm intervals - taking one cycle from the minimum amplitude value to the maximum, and then back to the minimum again.

The x axis is time, the left y axis is viscosity, and the right y axis is the oscillating drive (current). Fig. 7 takes Fig. 6's data and makes the x axis the oscillator amplitude, and the y axes viscosity and oscillator drive current. When the amplitude exceeds a certain value, the viscosity drops quickly, revealing its properties as a Bingham fluid. Additionally, the sample's thixotropy can be seen by the fact that even if the shear rate is reduced viscosity does not return to its value when measurement commenced. With moisturizing cream, if its viscosity does not decrease when you rub it between your hands, then its stretchiness will become worse, and it will be more difficult to apply to the skin. Additionally, there is less risk of having the solution seep away if viscosity after applying to the skin is higher. For these reasons, it is thought that this product was designed as a Bingham fluid in order to obtain the above properties.

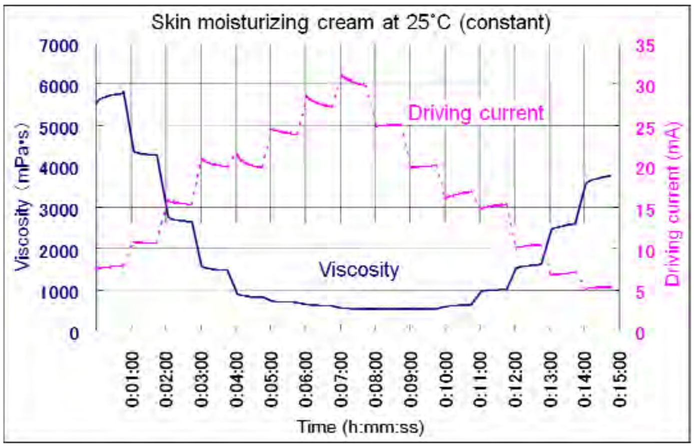


Fig. 6 Moisturizing cream:
Time-Viscosity, Driving current

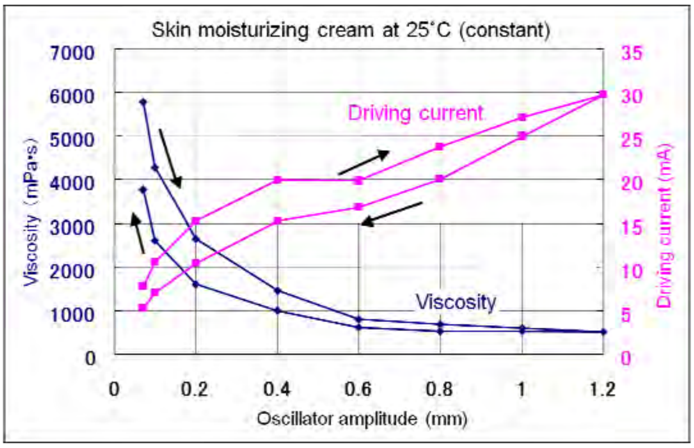


Fig. 7 Moisturizing cream:
Amplitude-Viscosity, Driving currnt

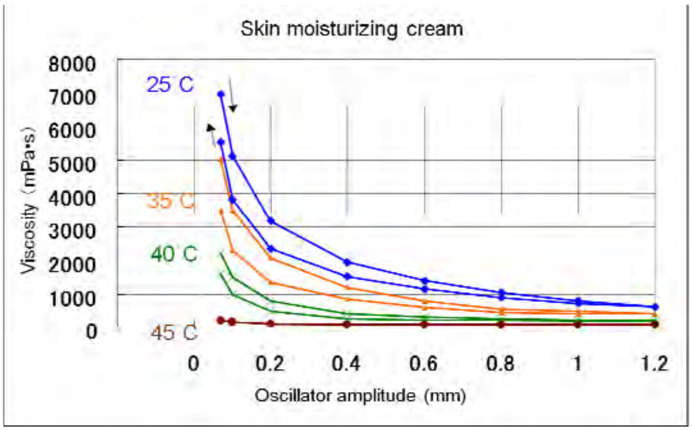
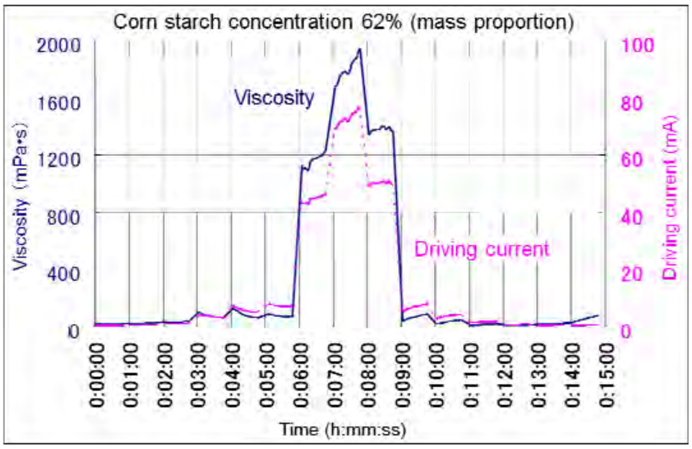


Fig. 8 Moisturizing cream:
Amplitude-Viscosity relative to Temperature change

Fig.8 shows a graph of the effects of changing temperature on moisturizing cream with regards to oscillator amplitude and viscosity. The temperature dependence of viscosity can be seen, as well as the fact that even if temperature is changed, the tendency of viscosity to rise at low shear rates does not change.

3. Dilatant fluid (corn starch water solution: corn starch 62% + water 38%)

The graphs in Fig. 9, 10, 11 show measurement data using a corn starch and water solution. If a spoon is moved rapidly through a corn starch and water solution then resistance will be high, but if the spoon is moved slowly then one will feel little resistance at all. In other words, it is recognized that when shear rate increases, viscosity grows rapidly. It has been confirmed while measuring this corn starch and water solution that when the oscillator amplitude exceeds 0.8 mm, the viscosity quickly increases.



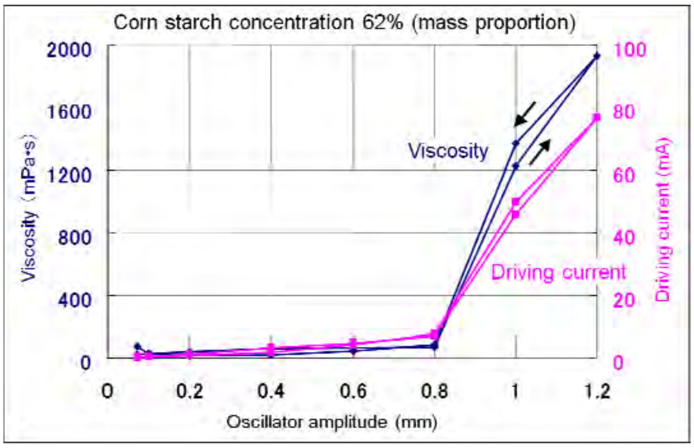


Fig. 9 Corn starch (Concentration 62%): Time-Viscosity

Fig. 10 Corn starch (Concentration 62%): Time-Viscosity

As with Fig. 6, Fig. 9 graphs the oscillator's driving current and viscosity at various amplitudes. Fig. 10 puts oscillator amplitude on the x axis, and viscosity on the y axis. It can be seen that when the oscillator's amplitude exceeds 0.8 mm, the viscosity value, which was previously below 100 mPa・s, quickly rises to 2000 mPa・s.

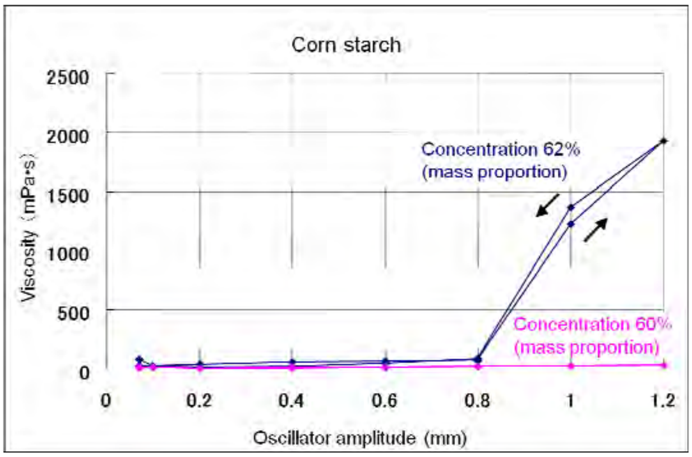


Fig. 11 Cornstarch: Amplitude-Viscosity at different concentration

For Fig.11, we've added a graph showing the same measurement but with the water mass proportion slightly changed. With the newly created 60% corn starch sample, there was no evidence of a rapid rise in viscosity accompanying a rise in shear rate. Measuring the quick elastic response of dilatant fluid as a physical quantity of viscosity is probably a first, and measurement results indicating that just a 2% difference in blend ratio eliminates the phenomenon of rapidly rising viscosity are also quite intriguing.

4. Thixotropic fluid (ketchup)

Lastly, we'll discuss measurement results for tomato ketchup. Tomato ketchup is said to have thixatropic properties, and thus it has a tendency to decrease in viscosity as shear rate increases.

In Fig.12, one can see that as the oscillator's amplitude increases, the initial viscosity of 2000 mPa・s decreases to 900 mPa・s. Fig. 13 shows oscillator amplitude on the x axis and viscosity on the y axis, and the characteristic tendency for viscosity to drop as amplitude is decreased can be seen.

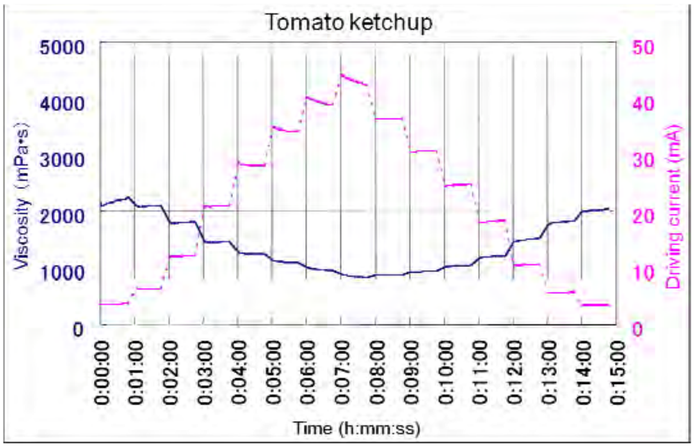


Fig. 12 Tomato ketchup:
Time-Viscosity, Driving current

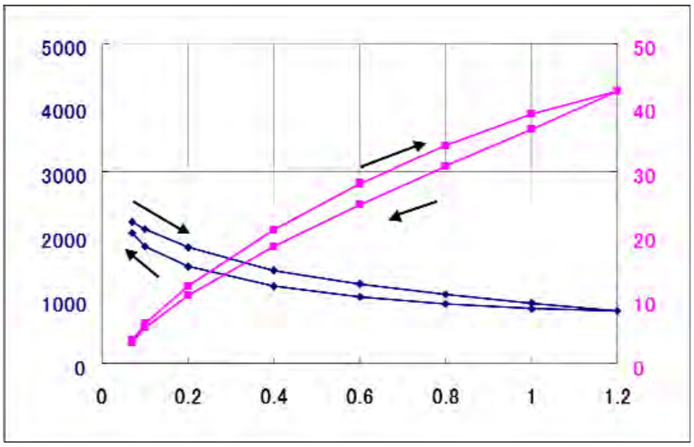


Fig. 13 Tomato ketchup:
Amplitude-Viscosity, Driving current

4) Issues and direction for the future

We have enabled the tuning-fork vibration viscometer to alter the shear rate by changing oscillator amplitude. Through this, it is now possible to gather clear data on characteristic phenomena, such as fluid behavior, for non-Newtonian fluids. By graphing this data, it is easy to quantify understandings of the particular phenomena generated by non-Newtonian fluids. With the vibration design's shear rate, because the oscillator must move with a cyclical, reciprocating motion, it will go back and forth from zero to the maximum value. Because of this, it has the characteristic of expressing the shear rate and shear stress as effective values. Additionally, at present the vibration type, including the tuning-fork vibration type, provides no clear opposite surface to construct shear rate like a rotational type does. Moreover, viscous resistance picked up by the vibration design is expressed as "viscosity × density". Within these characteristics and thinking, it is recognized that there are elements that are counter to existing viscometers and rheometers.

However, for example with the tuning-fork viscometer, there are notable capabilities such as: 1. the sensitivity is high, 2. the dynamic range is wide, 3. it can measure changes in properties from fluid to solid state as viscosity, and it also has advantages such as 4. the energy necessary for measurement is extremely low, and thus 5. the viscometer can measure without changing the physical properties of the measured sample.

Viscosity is a field that is both old and new, but it is certain that advancements in measurement technology are encouraging the development of new materials. As part of this, we hope to consider the special characteristics of vibration designs and aim to raise the capabilities and widen the applications of the design as an analysis tool for non-Newtonian fluids. For this reason, we wish to present our instrument as a more capable instrument for measuring kinetic viscoelasticity from liquids of low viscosity to soft solids of high viscosity, and as a material development tool which can be used in a wide range of industries including magnetic fluids, coatings, inks, petroleum products, polymers, adhesives, abrasives, ceramics, pharmaceuticals, cosmetics, and food products.

References

*1 A&D Website – "Viscometer SV-A series Users' Handbook"

*2 "Revised viscosity" Hiro Kawada – edited by the Weighing Management Society, published by Corona Publishing Co., Ltd.

*3 "Prototype vibration viscometers" - Eichi Fukada, the Society of Polymer Science, Japan, Polymers – January 1957 issue, insert

*4 "Regarding Static Viscosity〔sv〕and Vibration Viscometers", the Society of Instrument and Control Engineers, measurement division, 24^{th} Sensing Forum