A CHARACTERIZATION OF ANISOTROPIC SHEAR FLOW IN CONTINUOUS FIBRE COMPOSITE MATERIALS

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1. ABSTRACT

One of the characteristics of a composite material is that of anisotropy. When aligned continuous fibres form part of the composite the material is highly anisotropic with principal directions along and transverse to the fibres. It is therefore important to be able to characterize such materials with respect to their principal directions. The anisotropic response of a room-temperature continuous-fibre composite material has been investigated with the use of a purpose-built linear oscillator. The composite material has been characterized in both its axial and its transverse directions, and a comparison of the material's axial and transverse dynamic moduli has been made. The results are compared with data obtained from oscillatory tests using a standard rotational viscometer.

INTRODUCTION

One method of determining the viscoelastic properties of a material is to measure the material's response to small-amplitude oscillatory shear. This is usually referred to as dynamic testing. Dynamic testing is more frequently used to test isotropic materials but has recently been used in the characterization of the shear flow of continuous fibre composites [1-3]. These materials are highly anisotropic due to the presence of the aligned fibres. The work on composites has primarily been concerned with the characterization of thermoplastics at around 380 ° C and has incorporated the use of standard rotational viscometers. In order to facilitate experiments at room temperature ICI have provided a model system consisting of carbon fibre impregnated Golden Syrup.

The anisotropic nature of these materials suggests that ordinary rotational viscometers are inappropriate, in that, without modification, they are only able to give an isotropic measure of the dynamic properties of a material. It has been shown by Rogers [4] that dynamic data for both of the shear moduli can be obtained by deliberately off-centering the sample. This has been carried out by Groves [2] and Mackay [3]. However, the anisotropic nature of the material would suggest that linear oscillation along and normal to the fibre direction would give a more direct means of obtaining the dynamic data. To this end a linear oscillator has been designed and built.

APPARATUS

General Description

A linear oscillator has been constructed using the mechanisms of two old rotational rheometers, one to provide the linear oscillatory motion and the other to provide the vertical motion for gap setting. The instrument is shown schematically in Figure 1. The material to be tested is contained between the two parallel plates and the lower plate is made to oscillate at a given frequency and amplitude. The resulting motion of the upper plate, which is constrained by the leaf springs, is recorded. Transducers measure the displacements of the top and bottom plates and the readings are fed into a computer which converts them to amplitude and phase-lag data from which the dynamic viscosity and rigidity are calculated. A facility to rotate the sample in situ has been incorporated in the design so that a comparison of the longitudinal and transverse moduli of the same sample can be made.

Calibration

In order to obtain the restoring constants of the leaf springs a tangential force was applied to the top plate by a string and pulley method with a series of weights. A plot of the displacement of the plate against the load was made and the restoring constant obtained from the slope.

The natural frequency of the top plate was measured using a frequency analyser. This was achieved by hitting the top plate, causing it to vibrate, and measuring the resulting natural frequency. In the table below we give the restoring constants and natural frequencies for the two plate sizes that were used for the experiments.

Plate size (mm^2)	Restoring constant (N/m)	Natural frequency (rads/sec)
39×39	28925	342.26
10×10	28925	288.88

In order to check the linear response of the apparatus we varied the magnitude of the amplitude using the amplitude dial of the converted rotational rheometer used as the drive mechanism. The amplitude of the input wave is plotted as a function of the setting of the dial in Figure 2. This shows a good linear response. Throughout most of the experiments an amplitude of .2mm was used. This amplitude was the smallest that could be used as below this amplitude the wave-form became non-sinusoidal. Strains in the range of 1 to 70% were used throughout the experiments and are comparable with those used in typical oscillatory shear experiments.

For each experiment feeler gauges were used to set the gap and to check that the plates were parallel.

THEORY

The theory for oscillatory shear between parallel plates for a rotational viscometer is given in [5] and is based on linear viscoelasticity. The corresponding analysis for the linear oscillator can be derived in a similar manner and it is sufficient to give the results only. It follows that the dynamic viscosity and rigidity are given by

$$\eta' = -\frac{S\nu \sin c}{\nu^2 - 2\nu\cos c + 1}, \tag{1}$$

$$G' = \frac{\omega S\nu[\cos c - \nu]}{\nu^2 - 2\nu\cos c + 1}, \tag{2}$$

respectively. In these equations S is given by

$$S = \frac{h(K - \omega^2 M)}{L_1 L_2 \omega}. \tag{3}$$

and the amplitude ratio is denoted by ν, c is the phase-lag, ω the frequency, h the gap between the plates, L_1 and L_2 are the dimensions of the plate, K is the restoring constant of the leaf springs and M is the mass of the upper plate. The mass M can be obtained by considering conditions at the systems natural frequency ω_0, i.e.

$$K - \omega_0^2 M = 0. \tag{4}$$

Hence equation (3) can be re-written as

$$S = \frac{hK(1 - (\frac{\omega}{\omega_0})^2)}{L_1 L_2 \omega}. \tag{5}$$

These relationships relating the dynamic viscosity and rigidity to the amplitude ratio and phase-lag enable us to determine the characteristics of the composite for a range of frequencies.

EXPERIMENTS AND RESULTS

Testing the Apparatus

The apparatus was tested with a standardized 'Newtonian' fluid, a silicone fluid of viscosity approximately 100 Pa.s. All the tests were carried out at room temperature, i.e. between 18° C and 22° C, and it is known that the dynamic moduli of the material are not very sensitive to temperature changes in this region. The dynamic viscosity and rigidity were measured on the linear oscillator for different gap and plate sizes and the results are shown in Figure 3a. It can be seen that good agreement was obtained. Comparison was also made with measurements from both the Weissenberg Rheogoniometer and the Carri-Med Controlled Stress Rheometer (CSR), Figure 3b, and again good agreement was obtained. It is of interest that this standard 'Newtonian' fluid shows shear-thinning behaviour for all three apparatuses for the high shear rates. Further tests of the apparatus were carried out by varying the amplitude of the oscillation and it was seen that both the phase-lag and the amplitude ratio were independent of changes in the amplitude. The consistency of the above tests justify the use of the linear oscillator as an instrument for measuring dynamic data.

Characterising the model system

Initial results with the model system showed similar behaviour to those of Groves [1]. A typical graph of η' and G' against frequency is shown in Figure 4. In this experiment the 10×10 mm^2 plates were used and a four ply sample was consolidated to 0.5mm before oscillation. The sample was oscillated transversely, starting at the low frequencies and working up in frequencies over a period of about an hour. Figure 5 shows the results from a similar experiment in which the fibres are oscillated longitudinally. It can be seen from comparison of Figures 4 and 5 that there are no significant differences between the transverse and longitudinal data. However, large variations in the results for both transverse and longitudinal oscillatory shear could be obtained by using different samples in identical experiments. In some experiments the initial viscosity of the sample would be of the order 10^7 Pa.s while in others 10^4 Pa.s. This gave rise to several misgivings about the use of the linear oscillator with this material and to the value of the dynamic data obtained.

To examine this in more detail we first looked at the time dependence of the response of the sample. Figure 6 shows a typical viscosity and rigidity against time curve for a four ply sample consolidated to 0.5mm. The sample was placed between the 10×10mm^2 plates and oscillated transversely at a frequency of 31.4 rads/sec over a period of two hours. This graph shows that initially the viscosity decreased dramatically before levelling out and finally beginning to increase at an almost constant rate. This suggests that there is some initial reorganisation of the fibres within the sample. It was observed that as the experiment progressed fibres were ejected longitudinally from the sample. It was also noted that the sample at the end of the experiment appeared to have a smaller resin content, this might be due to a change in the moisture content of the Golden Syrup. Clearly, continued oscillation leads to a degradation of the sample and data taken at the end of each experiment have little or no relevance to the material at the beginning.

In Figure 7 we show two photographs of the longitudinal flow of the fibres out of the gap. In the first photograph the material was oscillated transversely at a frequency of 31.4 rads/sec for two hours and in the second at a frequency of 157.4 rads/sec for the same time. It can be observed that the longitudinal flow was greater at the higher frequency. Also, the symmetry of the longitudinal flow suggests that it was not caused by any misalignment of the plates. Similar longitudinal ejection of the fibres also occurs when the sample is oscillated in the fibre direction.

Repeating the time dependence experiment gave a set of graphs which, although similar in nature, showed considerable variations in the magnitudes of the corresponding data. That is, in addition to the time dependence of each sample which is similar in nature, the actual values of η' and G' obtained varied greatly from sample to sample despite the care taken to produce 'identical' samples. This has been attributed to the variations arising from the manufacture of the model system. The tape from which the sample was prepared showed considerable variations along its length in the amount of resin wetting the fibres. In addition the thickness and fibre alignment varied along the length of the tape. While every care was taken to prepare samples from similar parts of the tape these resulted in differences in the amounts of consolidation taking place during similar experiments. It has been reported that such variations also occur with the real composite though no comparison of the degree of variability between the two systems has yet been made.

To examine the variations of the viscosity and rigidity of the sample with time and to changes in frequency, we carried out an experiment over a three hour period going up and down in the frequency range, Figure 8. The sample consisted of four plies consolidated to 0.5mm and was oscillated transversely between the 10×10 mm^2 plates. A similar response, to that shown in Figure 4 for an 'identical' sample, was obtained during the initial frequency sweep. Subsequent repeated sweeps up and down the frequency range gave a reversible period where the viscosity and rigidity seemed to have settled. During this experiment large amounts of longitudinal fibre displacement was observed suggesting that by the time the sample had settled the material was no longer fully occupying the gap. This suggests that the measurements taken at this time do not relate to those which would be needed to model a real flow situation.

Throughout the series of experiments the wave form of the response of the upper plate was continually monitored. Unlike the sinusoidal wave form that was present throughout all of the experiments with the isotropic materials, the wave forms given by the composite, although regular, were non-sinusoidal. The shape of these wave forms were independent of amplitude and varied between samples. The natural frequency of the apparatus was also apparent and magnified during the experiments using the composite material. It was possible that the strain in these experiments was too high although it has been shown [1] that a fibre reinforced composite in a rotational instrument showed non-linearity at small strains and linearity at larger strains.

CONCLUSIONS

A linear oscillator has been constructed and tested. For isotropic materials it produced data that was in agreement with that obtained from two other instruments. The purpose of the instrument was to give a direct means of determining the dynamic moduli of anisotropic materials.

The experiment carried out on the fibre-reinforced Golden Syrup showed up a number of factors that may have significance for the real material.

1. There was a difficulty in producing 'identical' samples so that although the response of different samples to changes in frequency was similar, the values of the data points showed considerable variations. No distinct differences between transverse and longitudinal behaviour could be made within the large scatter of the results.

2. Continued oscillation resulted in degradation of the material with fibres being ejected longitudinally. As far as we know no comparable experiments have been carried out with the real materials.

The overall conclusion of this work is that the use of an oscillatory method to determine the shear moduli of continuous fibre reinforced composites is questionable. Perhaps it is worth noting that continued oscillation is unlikely to be part of any real forming process.

ACKNOWLEDGEMENT

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Figure 1 Schematic of Linear oscillator

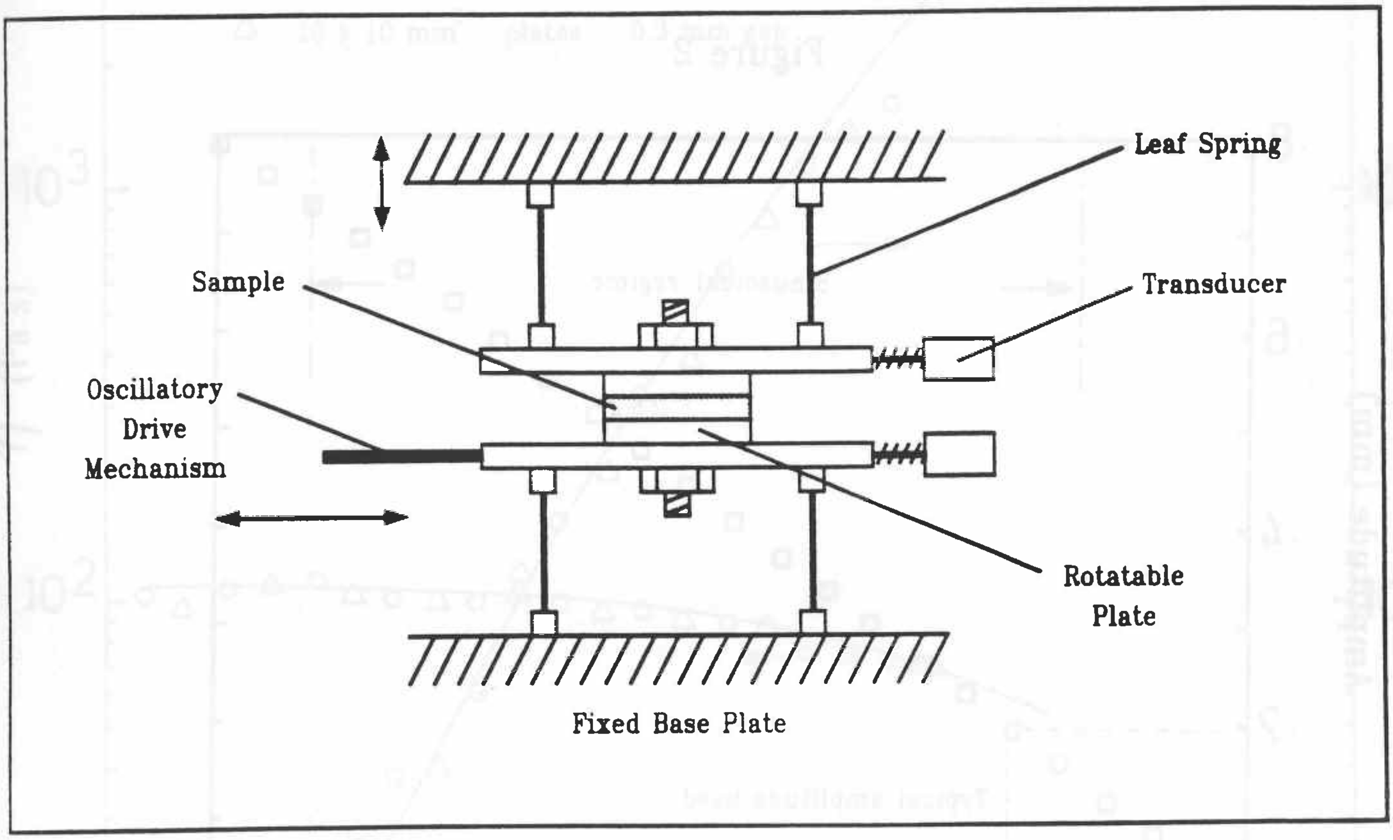
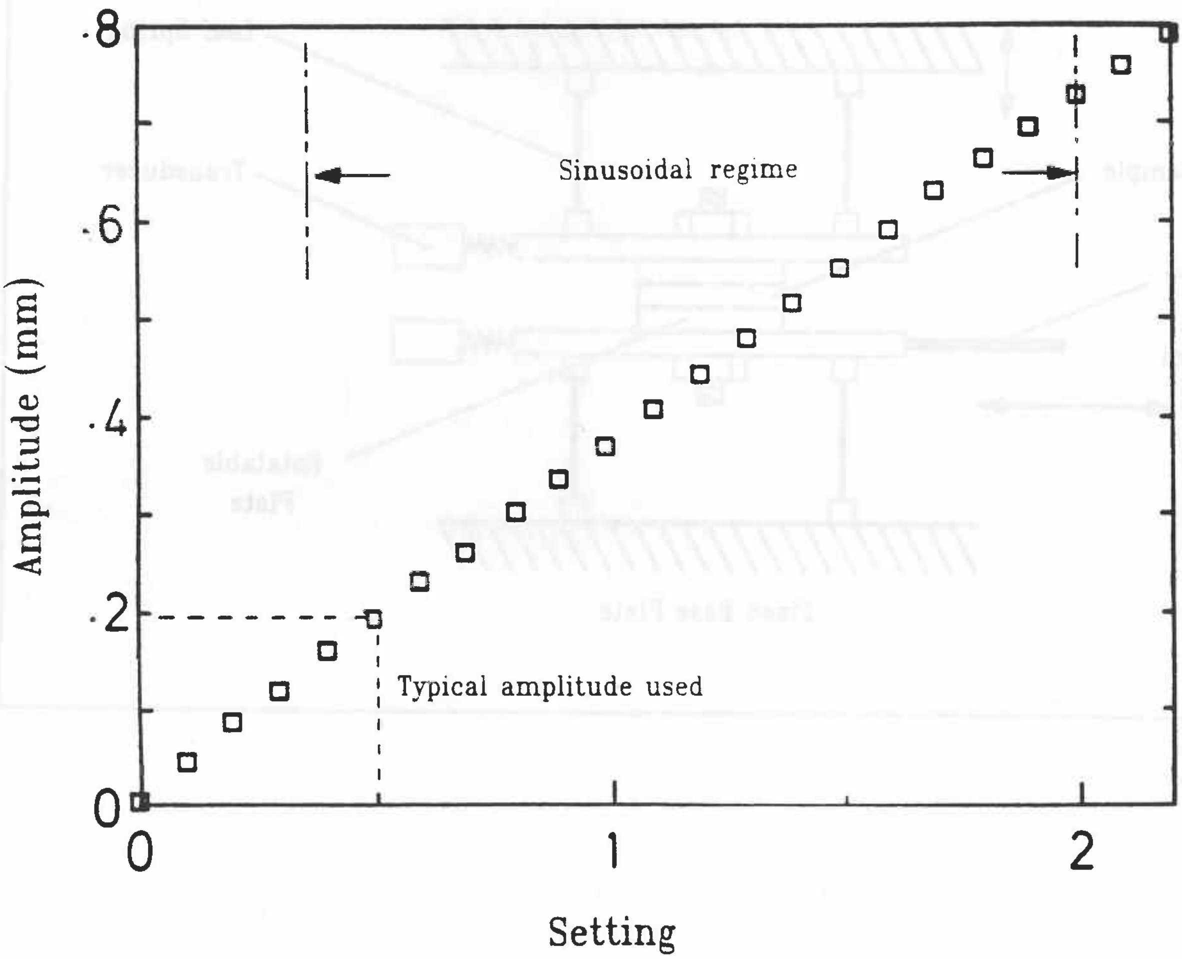
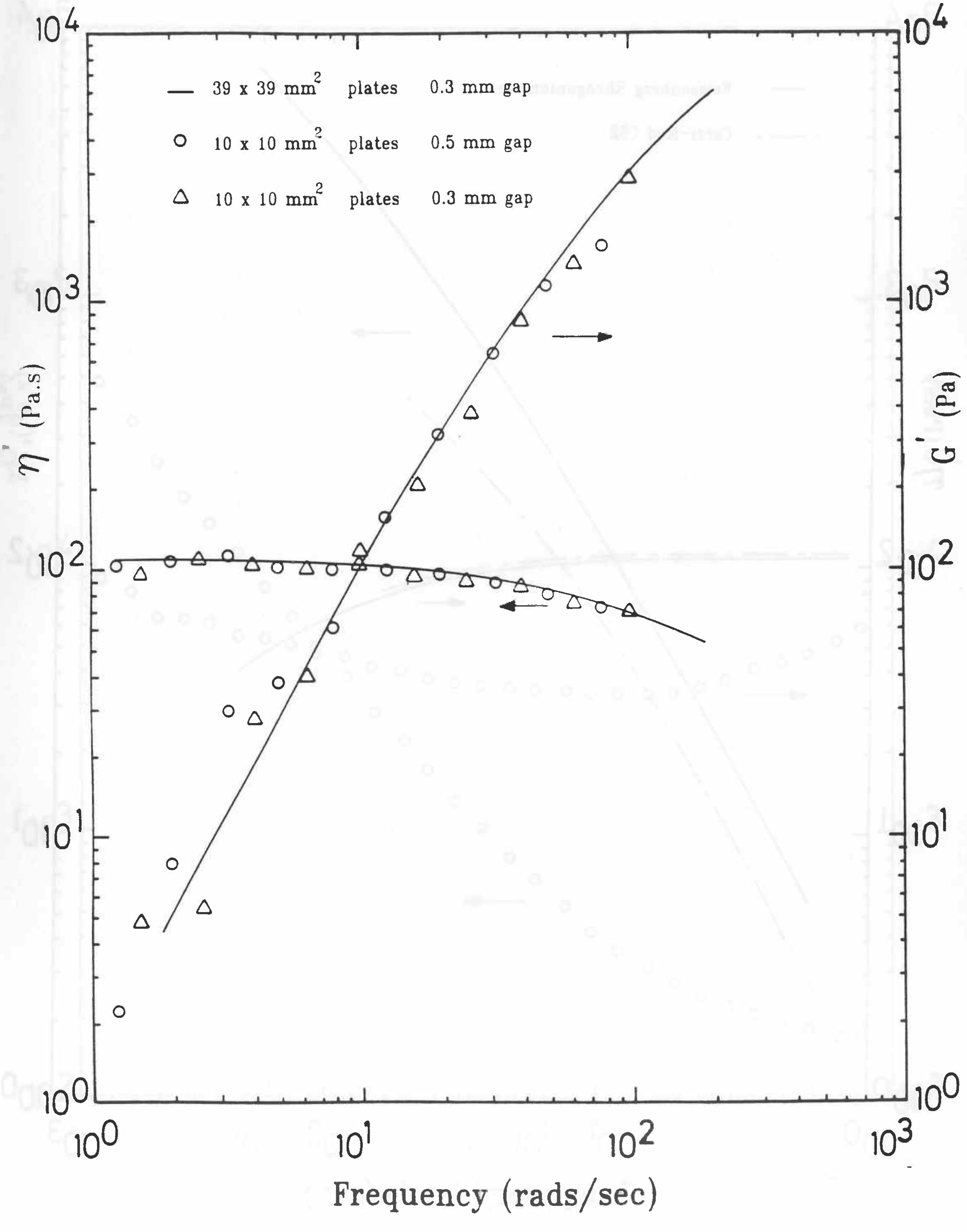


Figure 2



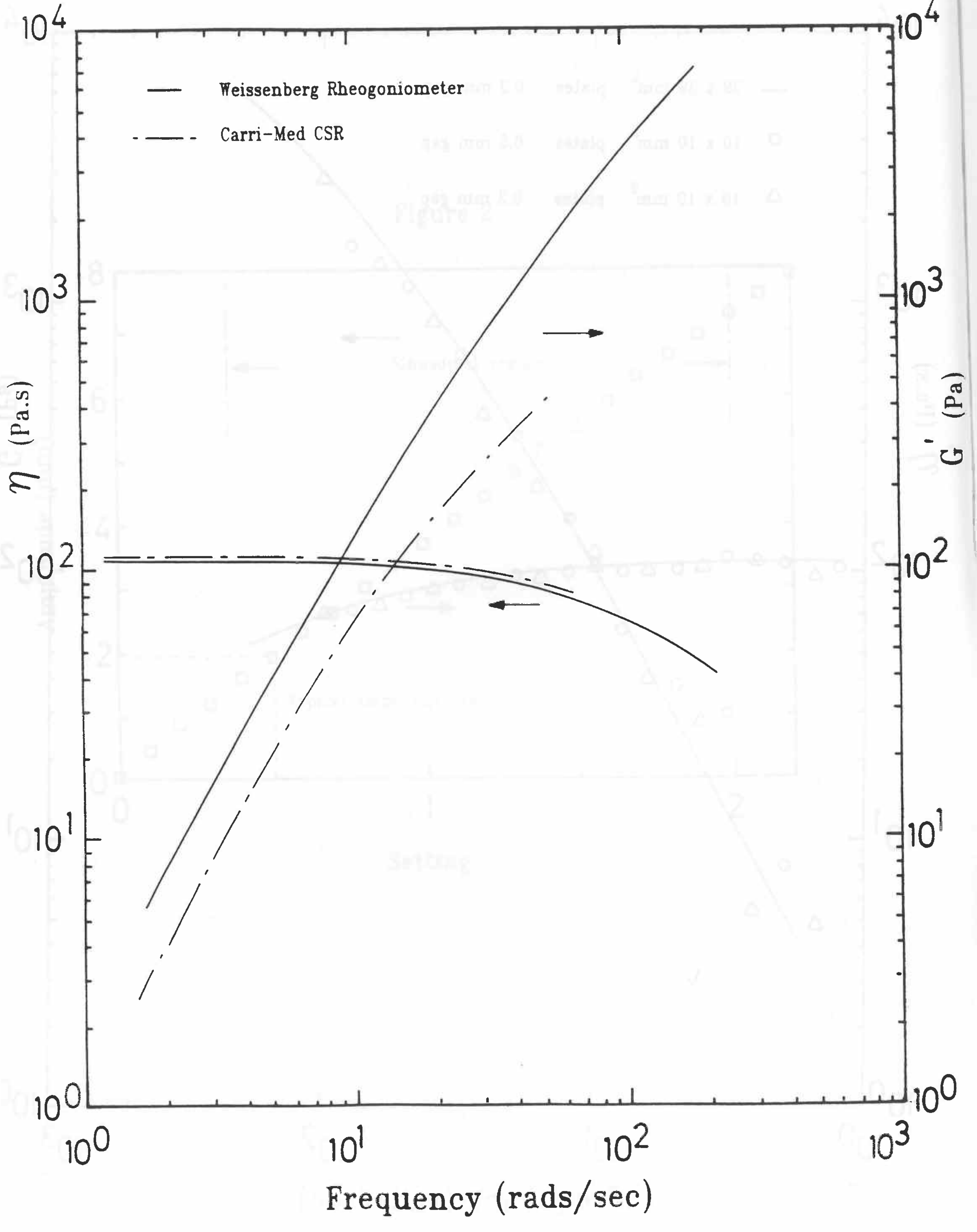
Sinusoidal regime
Typical amplitude used
Amplitude (mm)
Setting
0
·2
·4
·6
·8
0
1
2

Figure 3a



39 x 39 mm^2 plates 0.3 mm gap
10 x 10 mm^2 plates 0.5 mm gap
10 x 10 mm^2 plates 0.3 mm gap
10^4
10^3
10^2
10^1
10^0
η' (Pa.s)
G' (Pa)
10^0
10^1
10^2
10^3
Frequency (rads/sec)

Figure 3b



Weissenberg Rheogoniometer
Carri-Med CSR
10^4
10^3
10^2
10^1
10^0
η' (Pa.s)
G' (Pa)
10^0
10^1
10^2
10^3
Frequency (rads/sec)

Figure 4 Transverse Oscillation

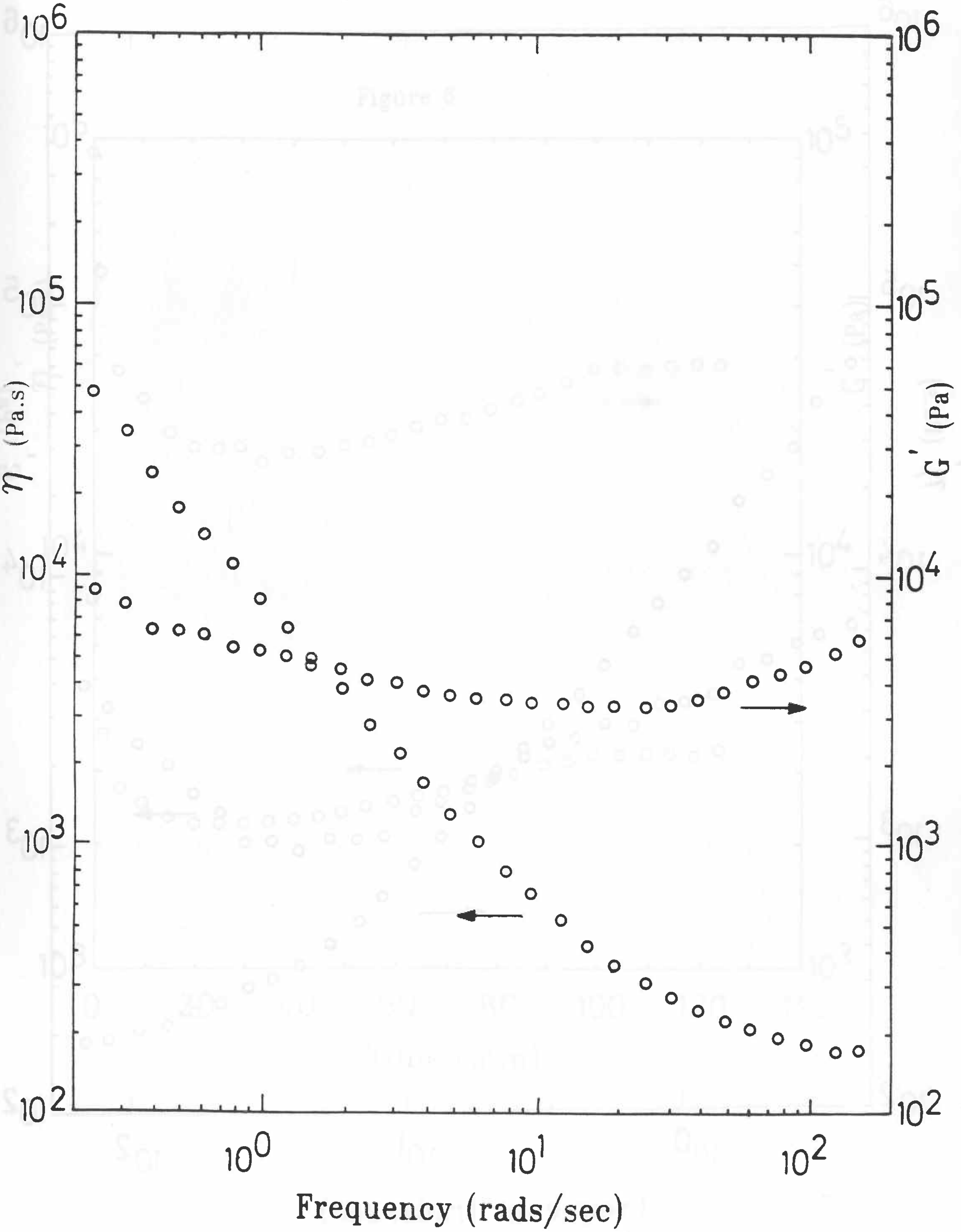


Figure 5 Longitudinal Oscillation

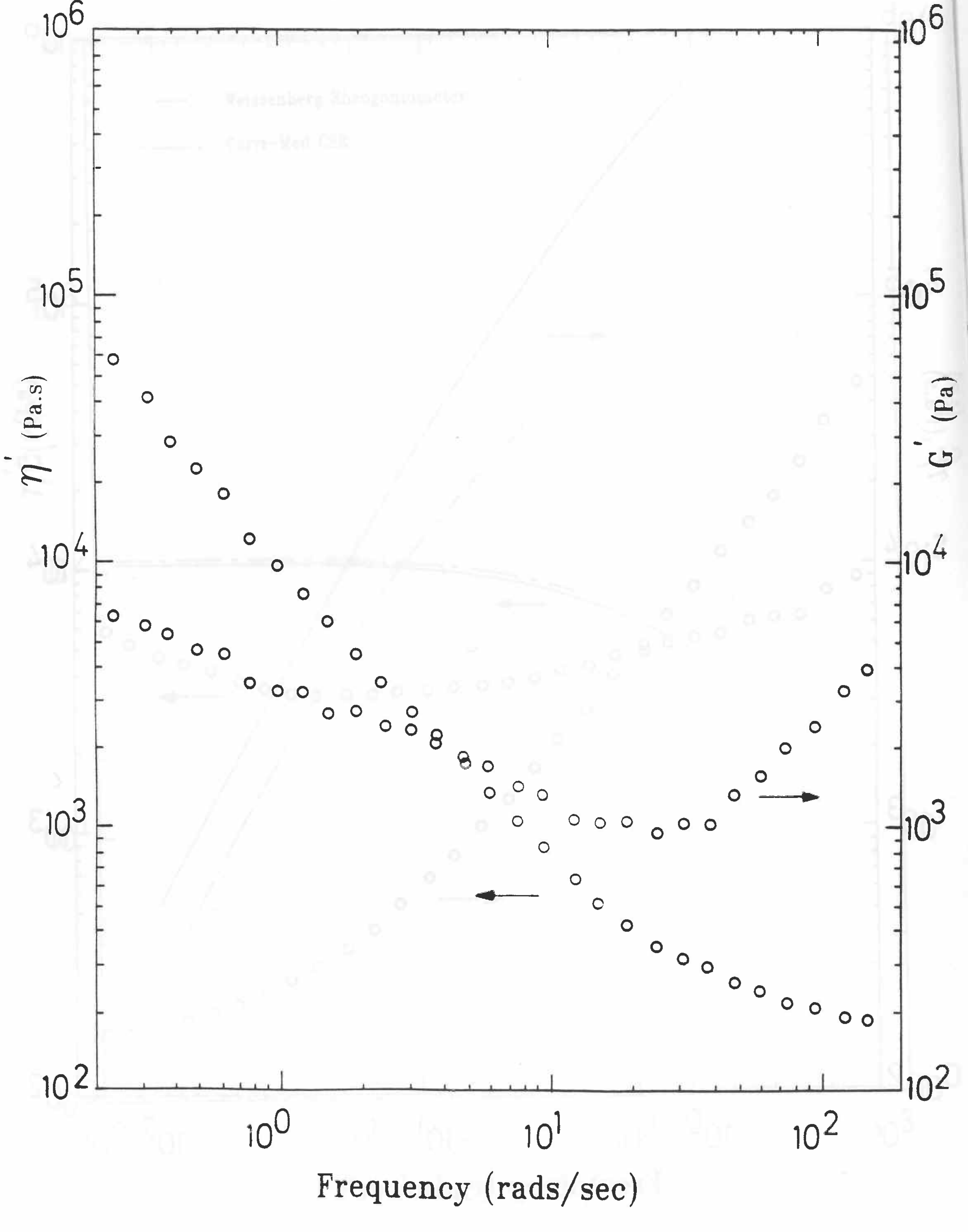


Figure 6

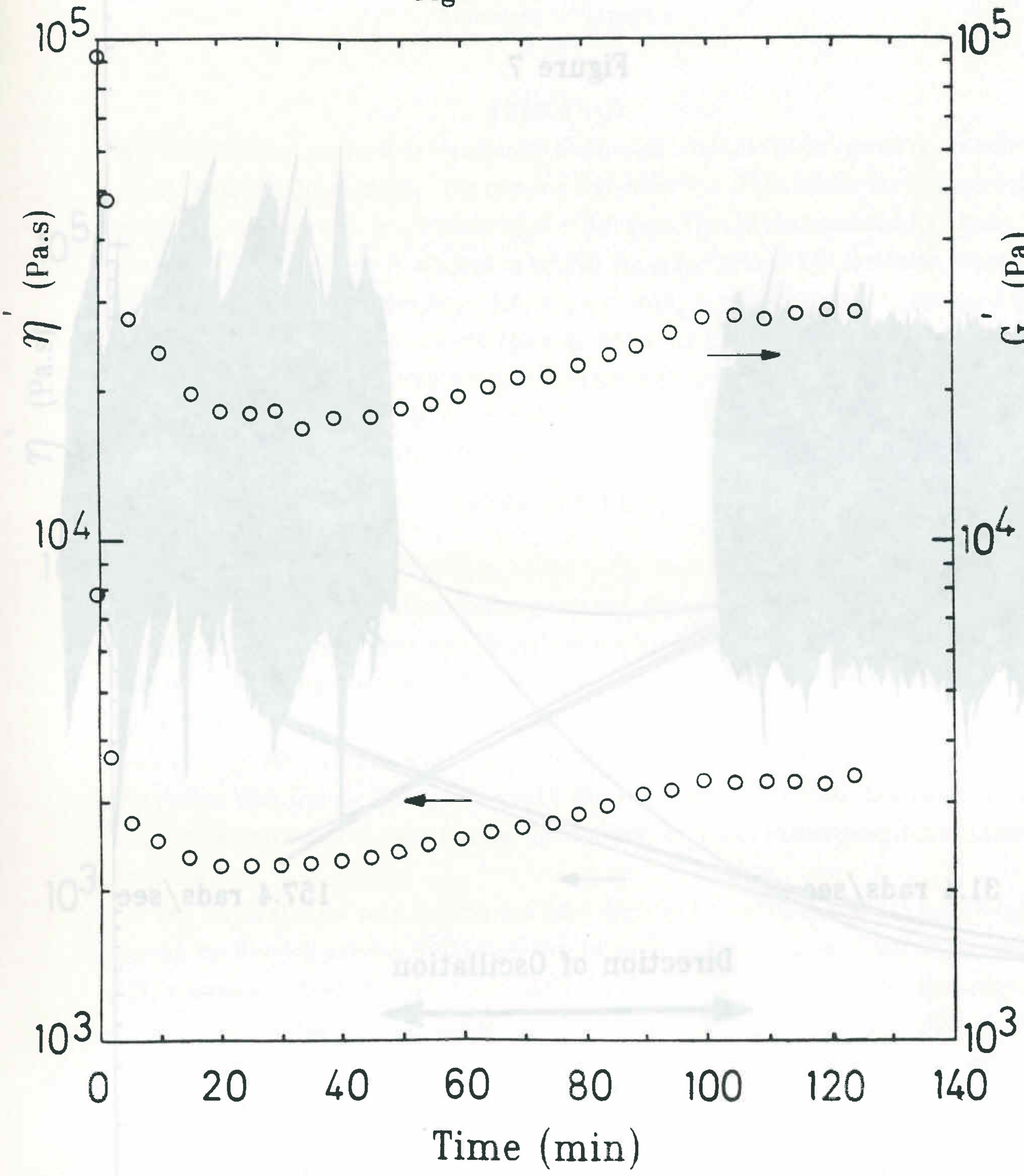
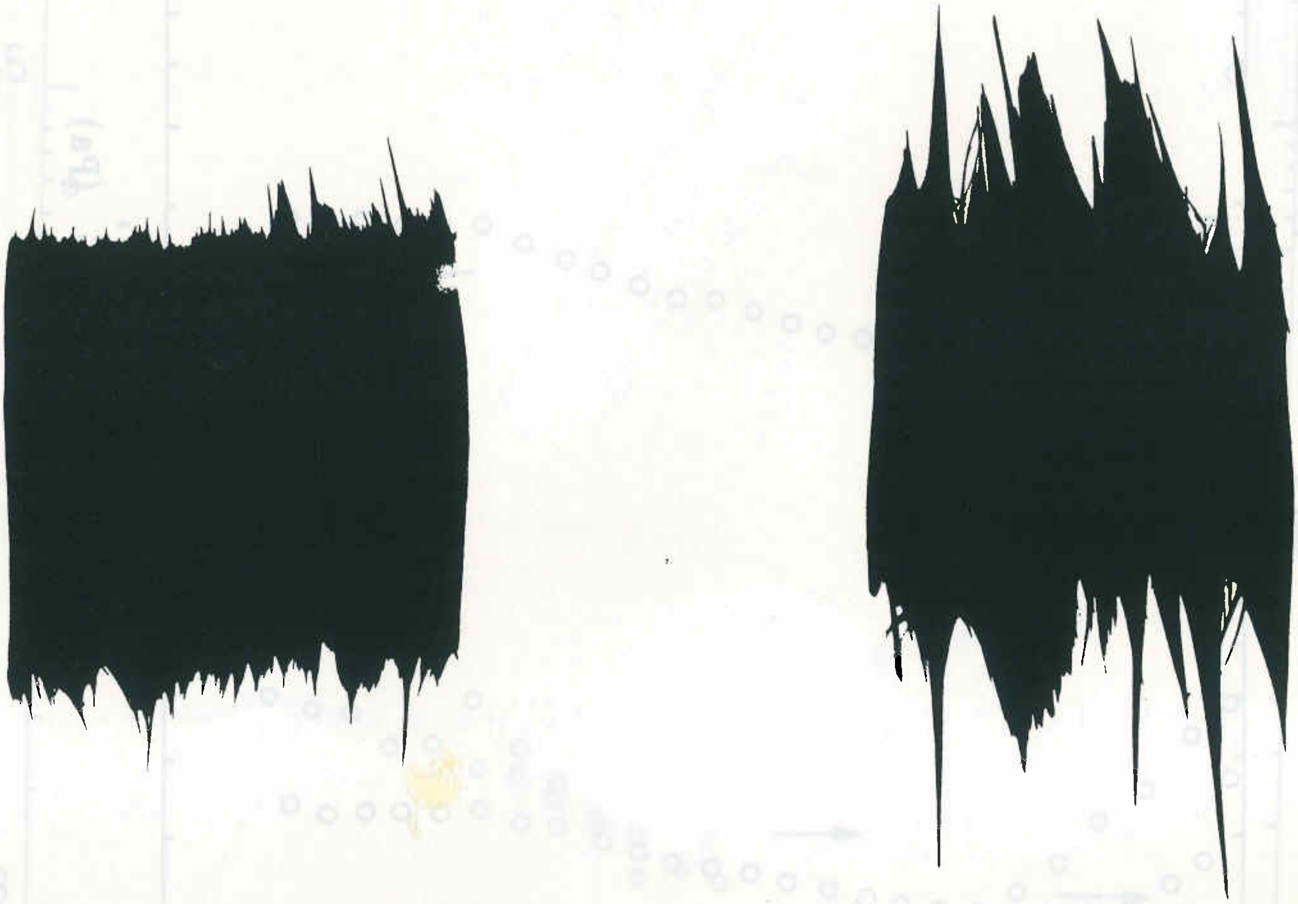


Figure 7



31.4 rads/sec

157.4 rads/sec

Direction of Oscillation

Figure 8