Int. J. Engng Ed. Vol. 9, No. 6, pp. 503-507, 1993
Printed in Great Britain.
0742-0269/91 $3.00+0.00

Engineering Case Digest

The International Journal of Engineering Education

Engineering Cases are an additional resource that can add new dimensions to learning about engineering. Lectures and problems in engineering science are essential for the student to learn the fundamentals of the craft. Students, however, should be made aware of the real-world relevance of the sciences they are studying, and how they can use them for decisions. The editor's note suggests only one *way that this Case can be used.*

Engineering Cases can be a source of anecdotes for the instructor or a source or real-world engineering problems that the student and instructor can work through together. Where and how Cases are used depends on the course objectives, the nature of the class and the instructor. Cases do not supplant lecture or other teaching methods. Case use is complementary and provides an additional, useful, powerful learning medium.

When using Engineering Cases, students and instructors may find better ways to deal with the technical problems than presented in the Case. This is because an Engineering Case focuses on how an engineer goes about performing tasks and obtaining results. It is not a technical paper! *It is a written account of an engineering activity as it actually occurred, rather than a demonstration of the validity of a particular or 'best' solution. It is intended to be a medium for classroom learning about engineering. Unsuccessful or incomplete efforts attempted before achieving successful results are often included.*

Contributions to the Engineering Case Library or Case Digest are invited. Manuscripts should be sent to Professor Dekker or to the Editor-in-Chief of the International Journal of Engineering Education. *Cases in the area of electronics and computer applications would be especially welcome.*

ECL-68: TAPE RECORDER CAPSTAN SHAFT AT AMPEX CORPORATION

Editor's note

This case was used in a machine design course to complement lectures on journal bearing design. Both students and I found it a more interesting way to deal with the subject than simply lectures and text book type problems.

Part A of the Case presents the technical and economic background for the design of a journal bearing. There is sufficient data that students can undertake the bearing design. Or, with additional dimensions from part B they can analyze the bearing performance.

Part B presents the engineer's design and his concerns about the bearing performance at the lowest speeds. His solution to this difficulty was to machine a pumping groove in the shaft. If students have designed or analyzed the bearing themselves this part of the Case makes an excellent focus for class discussion on journal bearing design and function, especially about full film and partial lubrication.

Questions used for class discussion:

1. Was the engineer's analysis correct with respect to full-film lubrication at the lowest tape speed?
2. How would the absence of full-film lubrication affect bearing performance? How would you test the capstan to decide if you had it?
3. How do you suppose the spiral groove actually affects the performance of the sleeve bearing?
4. How could you analyze for the slippage of the

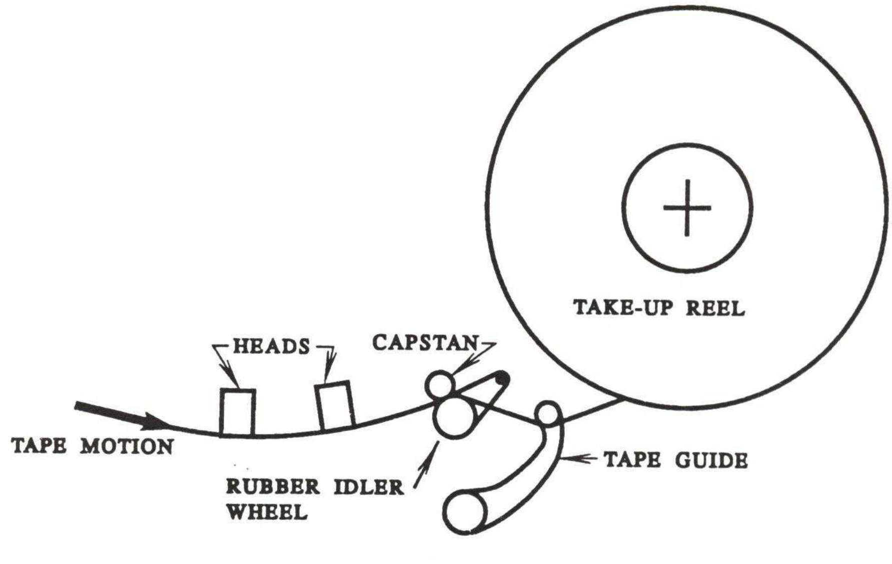

Fig. 1

tape as it passes over the capstan? (Concerning this problem George said, 'As far as I know this has never been figured out, but it's something we would certainly like to know.')

The complete Case ECL-68 suitable for classroom use and the Case catalogue of other Cases can be obtained from the Engineering Case Library by writing to: Professor Don L. Dekker, Engineering Case Library, Rose Hulman Institute of Technology, Terre Haute, IN 47803, USA.

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TAPE RECORDER CAPSTAN SHAFT AT AMPEX CORPORATION*

J. A. ALIC

Part A

During 1960 and 1961 George Rehklau, a project engineer for Ampex Corporation in Redwood City, California, was working on the development of the mechanical components for a new portable professional reel-to-reel tape recorder, the PR-10. By 1966 the PR-10 series sold from about $1000 to $1400.

George said, 'When we designed the PR-10 we wanted to improve its flutter characteristics, reliability and general mechanical quality. But we were interested right from the beginning in low cost, this is much more important in professional audio equipment than in instrumentation recorders, which may sell for ten or fifteen thousand dollars.'

Flutter is the measure of longitudinal variation in speed of the tape over the heads. George explained that it was measured by recording a 3 kHz tone on the tape and playing it back through an FM frequency discriminator or flutter meter. He said, 'We then send the signal through a sound and vibration analyzer and a graphic level recorder. This gives a spectrum—or spectra-analysis—of the flutter, from a half Hertz to 250 Hertz. Knowing the frequency, we can pinpoint the source of the flutter—for instance, capstan run-out or even the grinding pattern on the capstan. To improve the flutter characteristics of the PR-10 we focused on both capstan and the tape reel hold-backs.'

The capstan meters and drives the tape, as shown in Fig. 1. The capstan is a small-diameter, motor-driven steel shaft against which the tape is held by a rubber idler wheel. George explained that the capstans on all recorders have small ODs so that the capstan speed can be high. Flywheels are used on the capstan shaft to damp out speed fluctuations. High speeds allow flywheels of a reasonable size. The lower limit on practical capstan diameter is set by wear and by manufacturing costs. Tolerances on the shaft must be very tight to minimize flutter. The allowable run-out on the PR-10 shaft was limited to 0.0001 in. (2.5 μm) total indicator reading in 6 in. (152 mm). If the shaft diameter is too small, it will warp and bend easily. The diameter of the PR-10 shaft was 0.3123–0.3125 in. (7.932–7.938 mm).

Various PR-10 models offer tape speeds ranging from $1\frac{7}{8}$ to 15 in./s (47.63–380 mm/s) with the 0.3125 in. capstan. The similar CL-10 models had a capstan of half this diameter for speeds down to $\frac{15}{16}$ in./s (24 mm/s) but the rest of the shaft is the same size as on the PR-10. The drive from motor to capstan shaft is by a flat rubber belt running over

* Original copyrighted in 1966 by the Board of Trustees of Leland Stanford Junior University. Prepared in the Design Division, Department of Mechanical Engineering, Stanford University, by John A. Alic under the direction of Karl H. Vesper with financial support from the National Science Foundation.

stepped pulleys to provide the different speeds. The capstan controls the tape speed, but the motor is connected to each reel through an eddy current clutch (the 'hold-backs'). The feed reel is braked and the tape-up reel is driven, to keep the tape in tension. The objective again is to minimize flutter. Thus the torque on the reels is kept constant, with the result that tape tension varies from about 2 to 6 oz. (0.556 to 1.668) depending on the amount of tape on each reel.

George said 'This change in tension results in a speed error of 15% from the beginning to the end of a reel, caused by slippage of the tape at the capstan and of the drive belt. This is well within the spec of ±25%.'

The rubber idler wheel is pressed against the capstan with a force of about 5 lb (22.24 N) by a solenoid. The drive belt tension, which acts in the same direction as the idler load, is about 8 oz (2.224 N). A 2 lb (2.266 kg) flywheel on the end of the capstan shaft also serves as the belt pulley. The tape is $\frac{1}{4}$ in. (6.35 mm) wide and 0.0019 inch (0.048 mm) thick, the mylar or acetate backing being 0.0015 in. (0.038 mm) thick and the remainder is an oxide coating on one side. On the PR-10 the angle of wrap of the tape about the capstan is 15°; George explained that the coefficient of friction of the tape on the capstan depends on the tape, but is generally around 0.2

George said, 'Although matched duplex ball bearings, which are machined and ground in pairs, are used on the capstan shafts of some high-priced recorders, they cost $40–50 a pair and are much too expensive for the PR-10. Other types of ball bearings allow more run-out than we wanted—even Class 7 bearings have a run-out of 0.00015 in. (38.1 μm). We could have tried an oilite bushing or a grooved and graphited bronze bushing, but both rely on boundary layer lubrication and we knew from experience that this would break down intermittently, producing jerking and irregularities.'

'We had never used a sleeve bearing with sustained oil film before, but we decided to do so for the PR-10. This tied in with our low cost objective in two ways, first the bearing would be inexpensive and it allowed us to use a stepless shaft because sleeve bearings are well suited to this. Capstan shafts must be ground to control dimensions and surface finish. We wanted a shaft without any changes in diameter so we could use centerless grinding, which is much less expensive than grinding on centres.'

George continued, 'When we had the basic layout for the machine, we knew we wanted the centres of the bearings to be about $2\frac{3}{4}$ in. (69.85 mm) apart on a $6\frac{1}{2}$ in. (165.1 mm) shaft. The proposed shaft is shown in Fig. 2. We planned to use a split thrust washer in a groove just below the bottom bearing.'

The thrust washer is slit along a diameter so that it can be fitted into the groove. George planned to use two bronze sleeve bearings with their ODs machined spherical so they would be self-aligning. On either side of each bearing would be a felt washer to serve as an oil reservoir. The oil was to be a turbine spindle oil. Mobiloil DTE light, with a viscosity of 150 Sybolt seconds (kinematic viscosity 3.18×10^{-5} m^2/s) at 100°F (38.7°C). This oil is used in all Ampex machines because of its high resistance of oxidation. This is a critical property, since the machines may have to function over a period of years without service.

Next George had to design the bearings themselves, determining a set of parameters that would provide a sustaining oil film at the extremes of shaft speed.

Part B

George Rehklau designed the bearings for the capstan shaft using a set of charts that had been published by *Machine Design* magazine. His calculations showed that at the slow $1\frac{7}{8}$ in./s (47.63 mm/s) tape speed, the bearing would not develop a full oil film. George then thought of cutting a spiral groove into the shaft to pump oil into the bearing. He said, 'We don't know exactly what this does, but the idea was to put the oil under pressure to get a load-bearing film. This is evidently what happens, because we could see the oil bubbling up out of the top on the bearing in test rigs. I had seen spiral grooves before in motor shafts; GE fan motors use them and run for tens of thousands of hours without attention.'

A drawing of the capstan shaft appears in Fig. 3. The bearing is shown in Fig. 4. The bearings, a split thrust washer and felt washers are fitted into a diecast aluminum housing. The longitudinal hole allows oil to return from the upper felt washer to the lower washer after it has been pumped through the bearing by the spiral groove.

The centerless ground shaft for the PR-10 costs

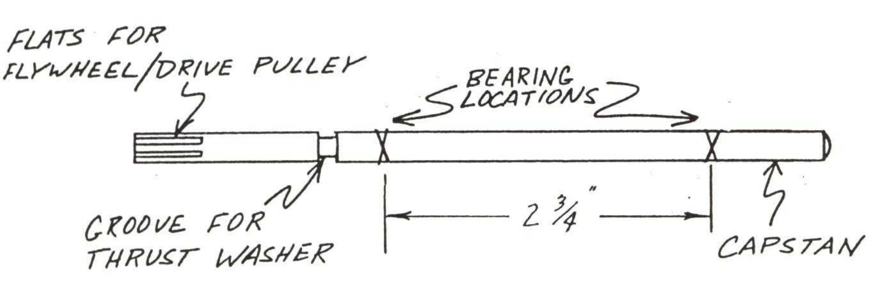

Fig. 2

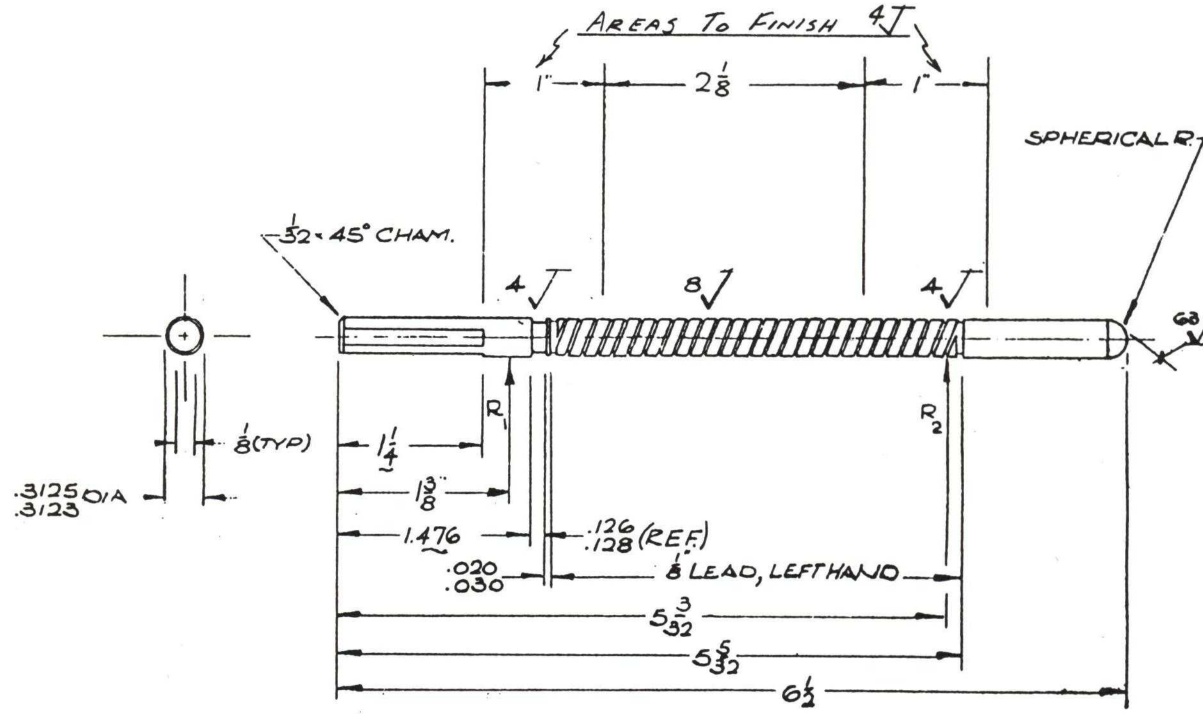
AREAS TO FINISH
SPHERICAL R.
CHAM.
LEAD, LEFTHAND
R1
R2

Fig. 3

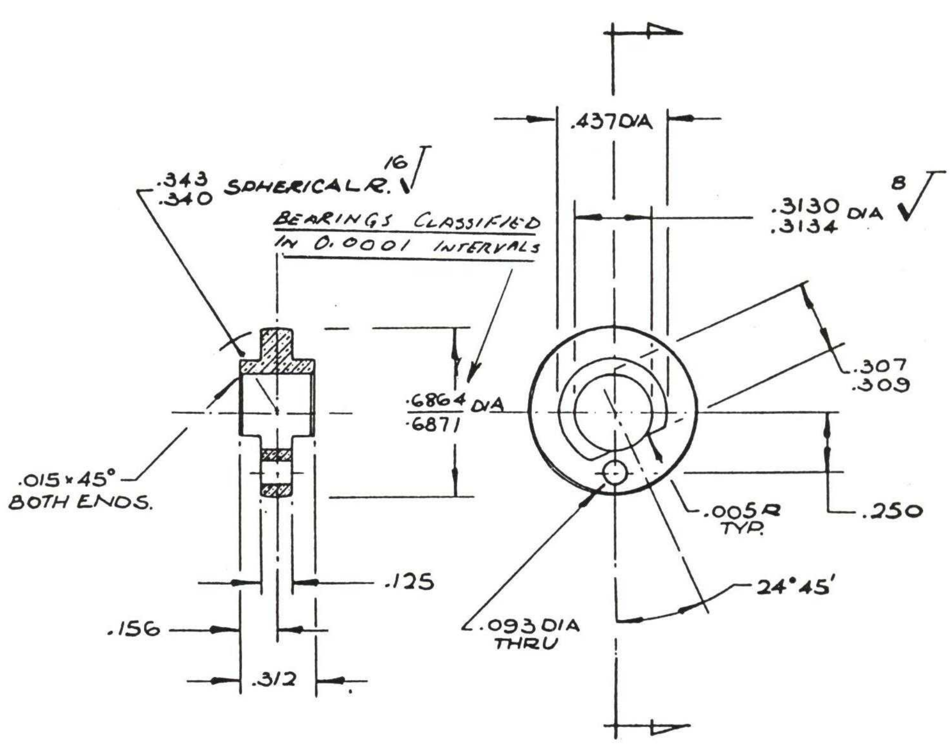
.4370IA
SPHERICAL R.
BEARINGS CLASSIFIED IN 0.0001 INTERVALS
.015 × 45° BOTH ENDS.
.005 R TYP.
.093 DIA THRU
24°45'

Fig. 4

Ampex $1.80 to make, as compared with a cost of $15–18 for stepped shafts ground on centres that are used on other recorders. The groove, which is cut on a lathe, is continued along the length of the shaft between the two bearings because this is the easiest way to make it. George explained that tolerances on the parts of the capstan assembly were determined by assembling machines with different combinations of dimensions and surface finishes and measuring the flutter. From the spectra-analysis satisfactory tolerances for each part were obtained.

George commented, 'The size of the spiral groove was determined by cut and try, but this was the only thing we changed in the capstan assembly during development. When we finished the development work, the Quality Audit group ran life tests on five prototype machines, an average of about 3500 hours each. They ran 1 min cycles of play, stop, rewind, fast forward, rewind, stop, and so on. The sleeve bearings worked fine, and the shafts showed no wear after hundreds of hours.'

The design and development of the PR-10 took 18 months from the first layout to the release of the drawings, of which the last three were spent working almost entirely on the drawings. Several additional prototype machines were built during this period as an aid in checking the drawings.

ERRATA

The following figures from the paper by B. Armstrong-Helouvry and P. Dixon: Elucidating Negative Feedback during the Introduction to Operational Amplifiers were misprinted in Volume 9 number 3, pp. 233–235. The improved figures are reprinted below:

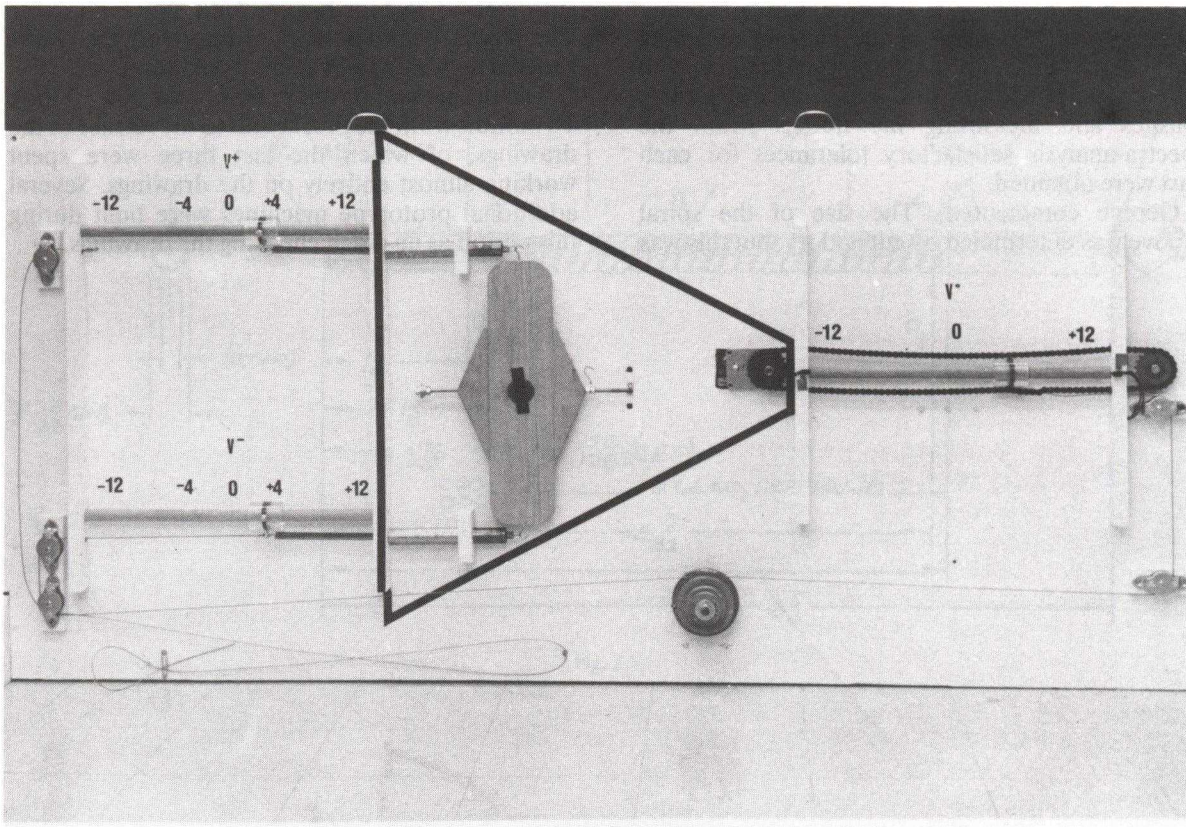

Fig. 2. A lecture hall demonstration of the operational amplifier.

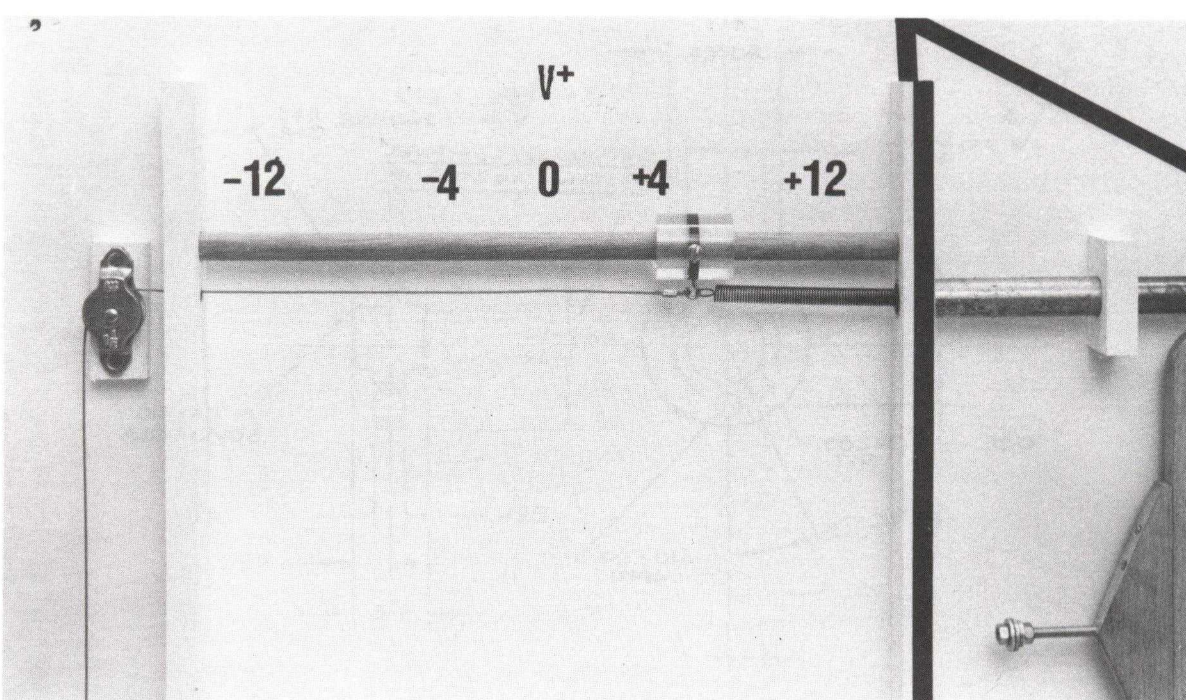

Fig. 3. Detail of the V^+ slider.

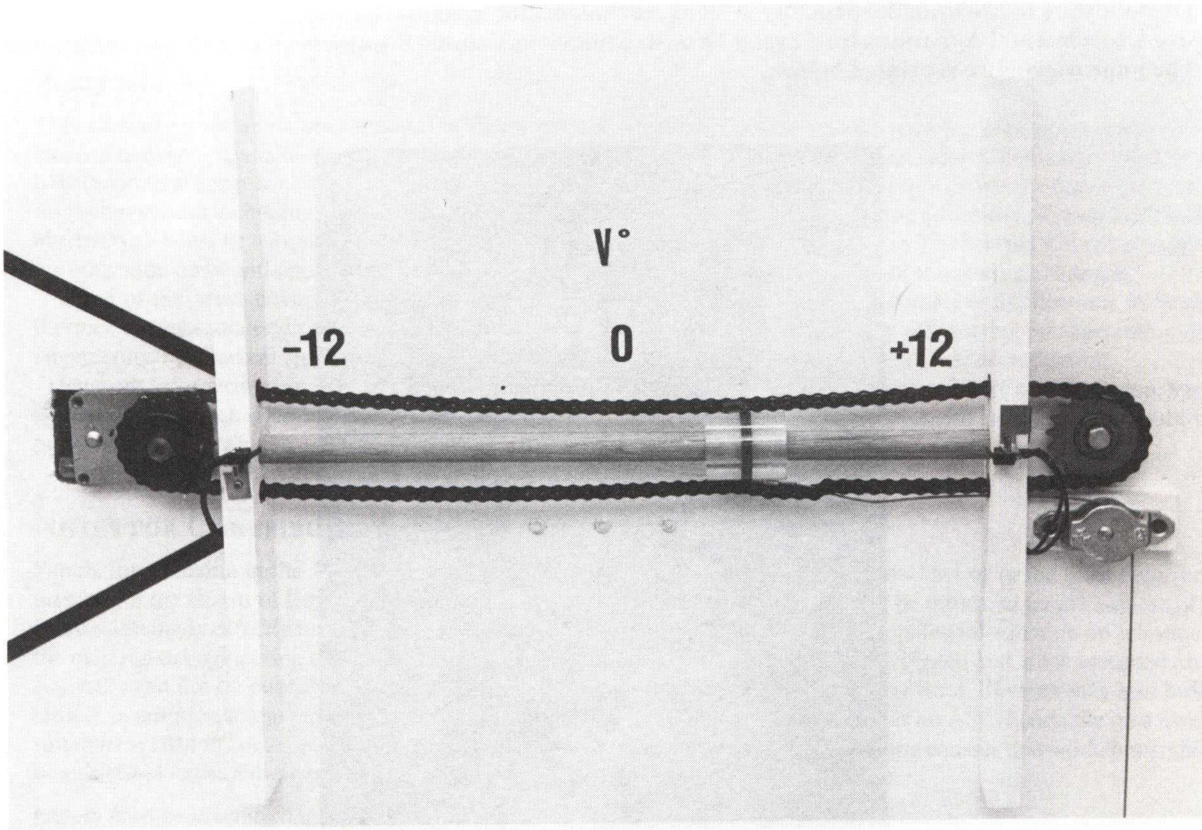

Fig. 4. Detail of the motor, chain drive and V_{out} slider.

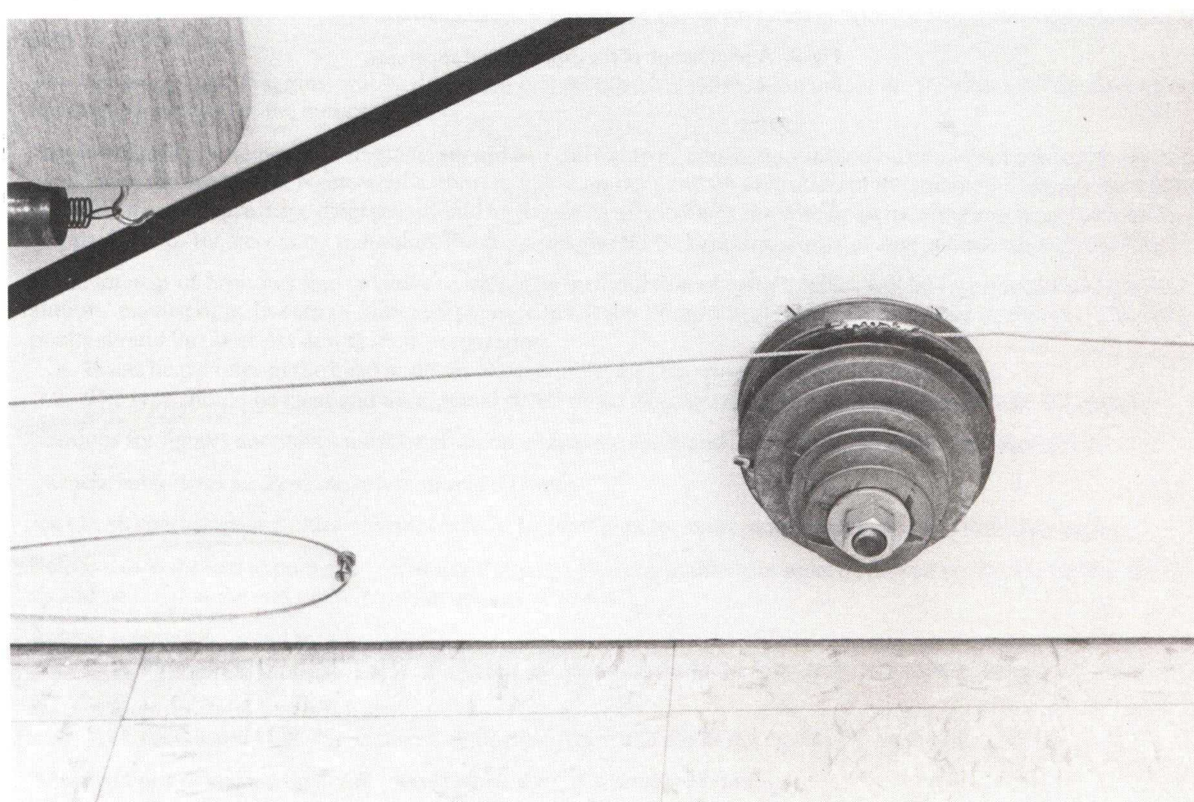

Fig. 6. Cable drums arranged for unit gain.

The following figure from the paper by R. Venkatachalam and A. Ramachandra Reddy: A Simple Inexpensive Experimental Apparatus for Crystal Growth Studies in Volume 9 number 3, p. 255 was misprinted. The improved figure is printed below.

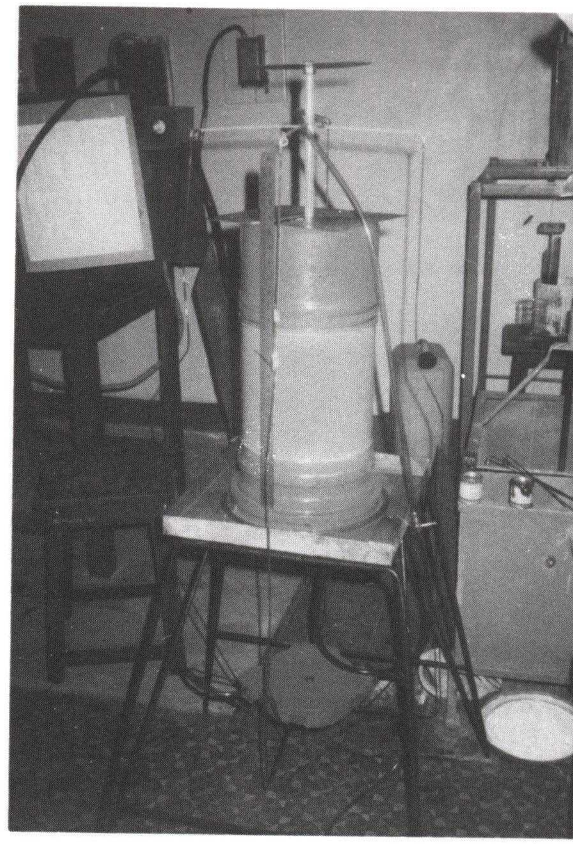

Fig. 9. A photograph of the experimental apparatus.