HEWLETT-PACKARD JOURNAL

TECHNICAL INFORMATION FROM THE -hp- LABORATORIES

CORPORATE OFFICES • 1501 PAGE MILL ROAD • PALO ALTO, CALIFORNIA 94304 • **VOL. 16 NO. 5, JANUARY 1965**

A NEW INSTRUMENTATION-CLASS TAPE TRANSPORT OF SIMPLIFIED DESIGN

A new transport designed for *–hp–* measurement systems achieves high performance with mechanical simplicity

SEE ALSO:
New Transport in Sanborn Recorder, p. 3
Oliver Elected IEEE President, p. 5
–hp– Board Honors Three Engineers, p. 8

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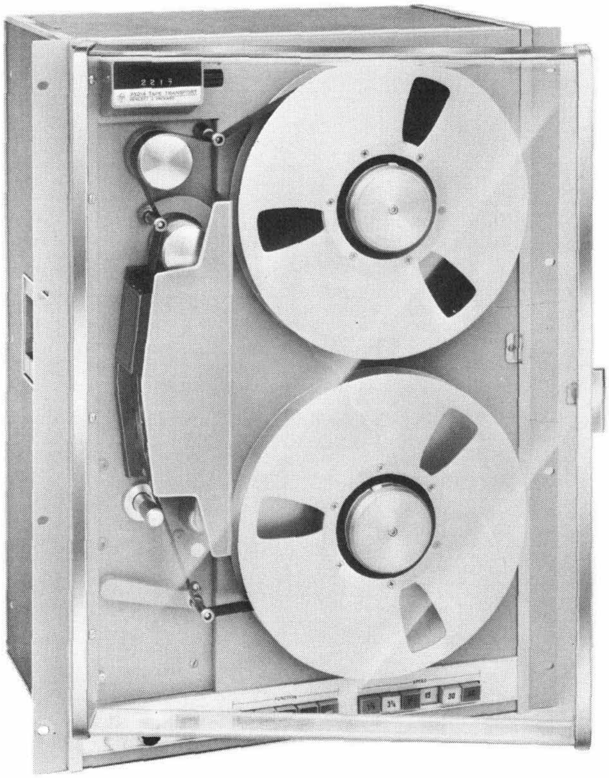


Fig. 1. *New magnetic-tape transport designed for use in –hp– systems. Transport has mechanical simplicity and a high order of mechanical damping for low long-term flutter. Flutter is less than 0.2% p-p at 60 ips. Tape speed accuracy (average value) is within about 0.1%. Transport complies with IRIG requirements.*

For well over a decade, magnetic-tape recording systems have proved of immense value in storing analog (and more recently, digital) information for subsequent measurement and analysis. The ability of tape systems to record simultaneously a number of channels of information and to do so with a high degree of time coincidence, their ability to compress or expand the original time scales, and their ability to replay the information countless times—all these factors have made magnetic-tape systems widely used as instrumentation equipment in many disciplines and many fields.

Along with their enormous advantages, however, high-quality magnetic tape systems have had the undesirable feature of considerable mechanical complexity in the tape-transport portion of the system. This, in turn, led to high cost and to substantial difficulties and "down-time" when mechanical repairs were required. Since several engineering groups in the –hp– organization designed systems that incorporated tape transports, it was decided to undertake in the –hp– laboratories the design of a high-performance transport that would achieve a substantial degree of mechanical simplification. Such a transport would then permit tape-using systems that had improved performance or reduced cost or both.

This program has now produced an instrumentation-quality tape transport that has a mechanical simplicity much superior to that previously attained in this class of device. At the same time it is a transport whose electrical performance surpasses that of most transports and is very nearly equal to that of the most mechanically-complex and costly designs. For example, in the new transport the specified flutter is less than 0.2% peak-to-peak at 60 ips, while average tape speed is specified as accurate within 0.25% under worst conditions and is more typically 0.1%. These performance specifications are equalled only by a very few of the most complicated designs. Another important quantity, cross-talk between adjacent channels, while related to mechanical design although not necessarily to mechanical simplicity, is 15 db or more below that known to have been achieved previously in production equipment.

In contrast to the frequent adjustments typically required in existing designs, the design of the new transport obviates all maintenance adjustments whatsoever during the unit's life (except dusting of tape oxide).

The new transport has 7 or 14 recording channels and bandwidths of 100 kc or 250 kc, depending in each case on options. It has six electrically-selectable speeds from $1\frac{7}{8}$ ips to 60 ips, and the speed selection is achieved with a simple design that does not involve gears, solenoids or sliding belts.

The transport uses standard $10\frac{1}{2}''$ reels which give it a tape capacity of 3600 feet in 1.0-mil tape or 4800 feet in 0.7-mil tape. The tape and speeds are those specified by the Inter-Range Instrumentation Group so that tape interchangeability is achieved. The 7-channel unit uses $\frac{1}{2}''$ wide tape and the 14-channel unit 1″ tape. Care has been taken to achieve an accurate tape-footage counter in which typical accuracy is 2 to 3 inches in 3000 feet, a vast improvement over past practice.

The transport also includes a number of operating conveniences. The reel-holding mechanism, for example, has been specially designed to achieve a simplicity of operation that is otherwise unmatched. The design is such that the reel can be installed on the hub *with one hand* with ease, because a simple automatic-centering mechanism avoids the need for careful alignment of the reel before installation is possible.

A detailed front view of the transport is shown in Fig. 1. The recording heads at the left are shielded which gives them an improvement of 15 db or more in cross talk over the levels usually encountered. The precision 4-digit footage counter is located at the upper left. Tape speeds are selected by the pushbutton switches at the lower right, while operating functions (PLAY, RECORD, etc.) are selected by the pushbuttons at the lower center. A clear-plastic cover closes over the transport's front to minimize accumulation of external dust. The function and speedselecting pushbuttons are accessible with the dust cover closed.

FLUTTER — THE CRITICAL PARAMETER

In the ideal tape transport the tape should move across the heads at a constant and precisely-known speed. The objective in the design of the new transport was to approach the ideal of constant speed as nearly as practicable in a moderate-cost, reliable system.

In tape transports, any medium- or long-term deviation from the desired average speed can be corrected by servo means during reproduction or by inclusion of calibration signals along with the recorded signal. Short-term variation in speed cannot be eliminated in this manner, however, and must be considered among the basic performance characteristics of the system.

Short-term speed variations which are uniform across the tape (i.e., flutter) can be caused by numerous elements in a tape transport mechanism. Eccentricities in the rotating parts of the capstan drive or mechanical filter system will, for example, produce periodic short-term speed errors. Tension variations in the tape supply or tape take-up system will cause errors. Friction between tape and heads or other non-rotating members can cause high-frequency speed variations because of tape roughness and non-uniform friction.

The best-known deleterious effect of flutter is the noise it produces in FM carrier transmissions: when a constant frequency is recorded on the tape, it will be reproduced with some amount of unwanted frequency modulation, depending upon the magnitude of flutter during recording and reproduction. Demodulation of this signal will not result in the ideal pure dc signal, but will consist of a dc signal plus superimposed noise. When a modulated signal is recorded, the noise due to flutter is added to the output signal, and in addition the modulated data signal is both amplitude- and frequency-modulated by the flutter.

REPRESENTATIVE FLUTTER

In the new transport the potential sources of flutter have been carefully dealt with and the resulting levels of flutter are minimal. Figs. 2 (a, b, c) show representative flutter for the new transport at 60 inches per second tape velocity. The vertical scale in each figure represents a speed change of 0.2%/cm. Fig. 2 (a) shows the nature of the flutter in the band between 0 and 200 cps. In this band of frequencies one finds almost all of the flutter components which are caused by rotating mechanical parts and mechanical resonances. It can be seen that the flutter is under 0.1% peak-to-peak.

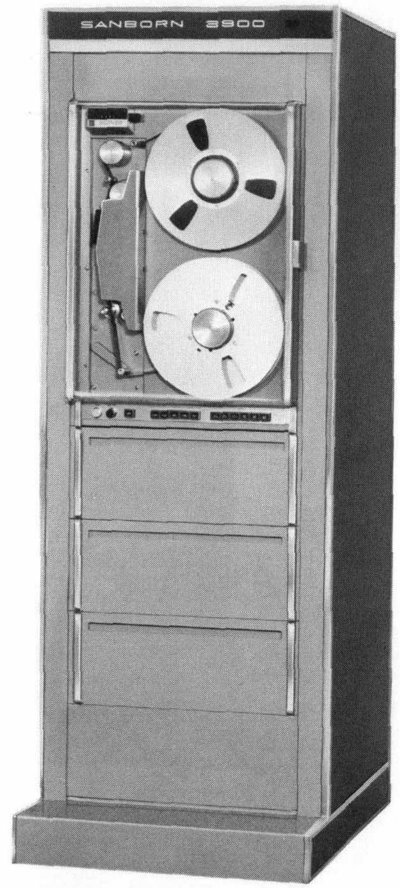
When the bandwidth over which the flutter is observed is increased to 0–1500 cps, the picture is as in Fig. 2 (b). The flutter is approximately 0.2%

NEW TAPE TRANSPORT IN SANBORN MAGNETIC DATA RECORDING SYSTEMS

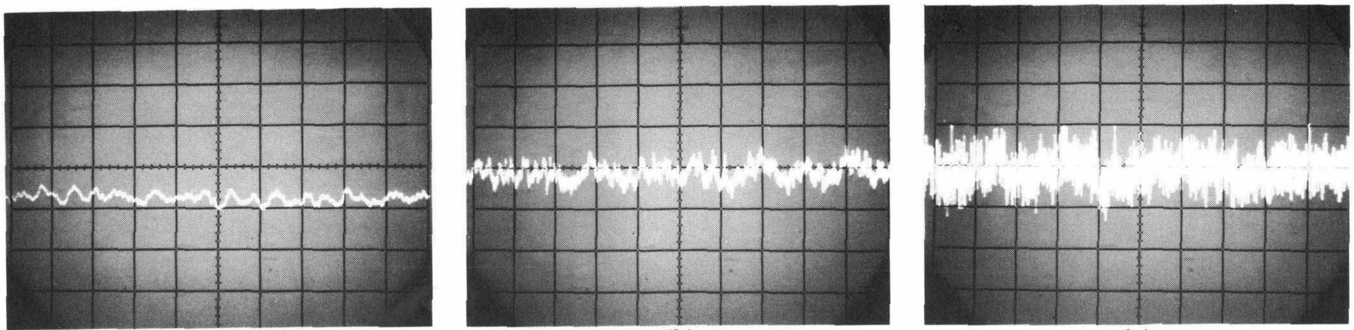
The refined tape transport described in the accompanying article has been incorporated into the magnetic data recording systems produced by the Sanborn Division of Hewlett-Packard. With this transport, the Sanborn systems now achieve the high quality performance (i.e., low flutter and high signal-to-noise ratio) expected of much more elaborate and costly systems.

The Sanborn Magnetic Data Recording Systems that use the new transport conform to IRIG standards with respect to track width, track spacing, FM carrier frequencies, and FM deviation and thus are compatible with other standard tape systems. These systems record and reproduce signals directly within a passband from 100 cps to 100 kc at 60 inches per second (IRIG standard) or to 250 kc (IRIG wideband). With FM electronics, they record and reproduce from dc to 10 kc (IRIG standard) or to 20 kc (IRIG wideband). Pulse circuitry enables digital information to be recorded and reproduced with a rise-time of 4 μsec (at 60 ips). Equalizing or FM frequency-determining networks for each tape speed are on sub-modules that plug on to the transistorized record/reproduce circuit cards.

A change of recording mode for any channel is accomplished by simply changing one circuit card with its plug-in equalizer. A ferrite shield that closes over the tape and recording heads by-passes any fringing magnetic fields to reduce interchannel cross-talk, permitting use of the FM mode on tracks adjacent to direct channels on the same head stack. As in previous Sanborn tape systems, a built-in meter enables the carrier frequency of each FM channel to be monitored so that the system is easily aligned without need for special test instruments.



The electronics of the Sanborn tape systems are designed to be compatible with the pre-amplifiers, transducers, and other accessory items designed for Sanborn's widely-used graphic systems. The new Sanborn tape systems conforming to IRIG standard recording specifications are the Models 3907A (7-track) and 3914A (14-track). The wideband systems are Models 3917A (7-track) and 3924A (14-track).



(a)
0–200 cps

(b)
0–1500 cps

(c)
0–10 kc

Fig. 2. *Oscillograms showing small values of flutter typical of new transport. Bandwidth used for measurement is shown under each oscillogram. Vertical scale is 0.2% p-p in each case. Tape speed is 60 ips.*

peak-to-peak, and most of the components are random. This type of flutter is produced in large part as sliding friction occurs across stationary surfaces; some smaller portion is due to minute irregularities in ball-bearings.

Fig. 2 (c) shows the same recording but with the bandwidth expanded to 0–10,000 cps. The largest part of this high-frequency flutter is due to frictional noises and tape surface granularity. By observation, the flutter is less than 0.5% peak-to-peak. However, if the peaks due to infrequent tape defects are ignored as being the responsibility of the tape and thus beyond the the control of any transport mechanism, then the flutter of the transport itself is reduced. This value of flutter (for this bandwidth of measurement) is very nearly equal to that displayed by the most complex transport systems presently produced.

While peak-to-peak measurement is the most useful form of expression for instrumentation purposes, specification is not always made in this way. With some justification it may be argued that, since much of the flutter is irregular in nature, and thus best describable in statistical terms, an rms reading would be appropriate. For some years high-quality sound recorders have routinely been measured for flutter by measuring the flutter components in the band 0–200 cps with an averaging meter calibrated for rms. A figure of $<0.1\%$ has been accepted for professional purposes. By this standard the new transport displays a figure in the region of 0.02 to 0.03% at typical sound-recording tape velocities.

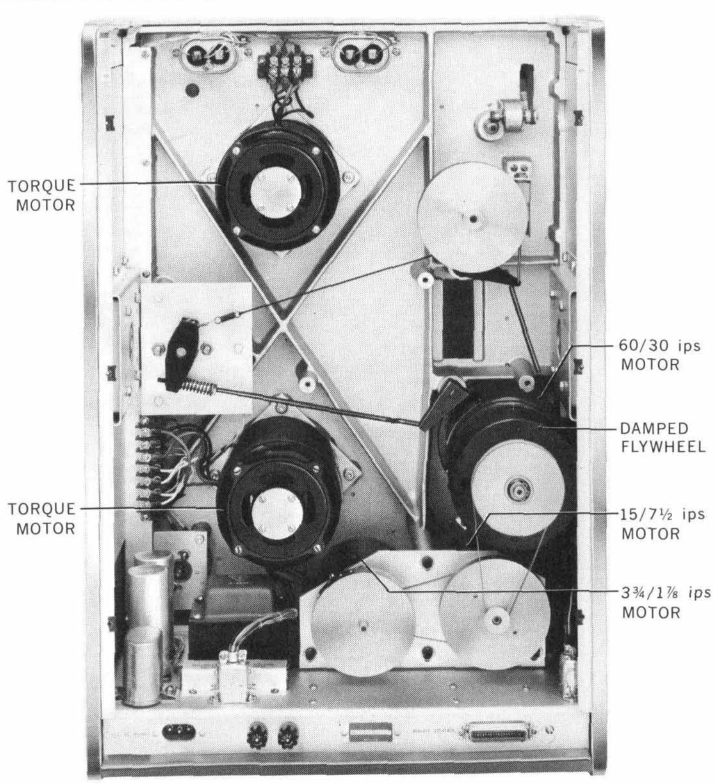


Fig. 3. *View of rear of new -hp- transport showing simplicity of construction and layout. Transport is constructed on a single, large aluminum casting to obtain high strength. Casting is completely machined on tape-controlled mill, assuring uniformity and parts interchangeability.*

DAMPING — THE KEY TO MOTIONAL STABILITY

Designing for the extreme in motional stability (low flutter) resolves into 1) minimizing the sources of tape speed irregularity, and 2) isolating the effect of remaining irregularity sources through *adequate* mechanical filters. It is believed that the damping mechanisms in the new unit are the most extensive and effective ever used in a magnetic tape transport. Their functioning has conferred high motional stability on a mechanism that is nevertheless uncomplicated.

Fig. 4 shows the path of the tape and the elements that are designed to assure smooth tape motion past the heads by isolating this portion of the dynamic system from disturbances from either direction. Disturbances that have been considered and overcome in the design of the transport include those that might originate in the torque motor, in the eccentricity

BRIEF PERFORMANCE SUMMARY

TAPE SPEEDS: 60, 30, 15, 7½, 3¾, 1⅞ in. per sec.

DRIVE SPEED ACCURACY: ±0.25% of nominal capstan speed which is directly proportional to line frequency.

MAXIMUM INTERCHANNEL TIME DISPLACEMENT ERROR: ±1 μsec at 60 ips, between two adjacent tracks on same head.

START TIME: Approximately 4 seconds max.

STOP TIME: 1 second max.

REWIND TIME: Approximately 100 seconds for 2400 feet and 150 seconds for 3600 feet of tape.

OPERATING CONTROLS: Line (Power), Stop, Play, Reverse, Forward (fast), Record; all are pushbutton relays. Receptacle at rear of transport provided for remote control operation.

EXTERNAL SPEED CONTROL: Connections provided.

MAXIMUM FLUTTER

Speed	Bandwidth	Flutter (p-p)
60 ips	0–200 cps	0.2%
	0–1.5 KC	0.3%
	0–10 KC	0.6%
30 ips	0–200 cps	0.2%
	0–1.5 KC	0.5%
	0–5 KC	0.8%
15 ips	0–200 cps	0.25%
	0–1.5 KC	0.45%
	0–2.5 KC	0.6%
7½ ips	0–200 cps	0.4%
	0–1.25 KC	0.65%
3¾ ips	0–200 cps	0.5%
	0–625 cps	0.8%
1⅞ ips	0–200 cps	0.8%
	0–312 cps	1.2%

of the reel or of the tape pack, in the strumming of the tape as its irregularities or imperfections pass over guides, heads, and rollers, in run-out of rotating parts, in cogging of associated mechanical apparatus, such as the footage counter, in the slight cogging of the capstan drive motor, and in power line voltage transients which could affect all the motors.

Many of the measures which have been taken to reduce flutter in the new design are subtle. In every possible case, for example, diameters are assigned to rotating parts which contact the tape so that their rotational rates do not coincide with natural resonances. The visible features of the transport, which result in low flutter, yet allow fast starting and mechanical simplicity, include these:

1. *The damped arm.* Between the footage counter drum and the idler drum is a swinging arm, which minimizes tension variations and takes up small increments of tape slack. Its motion is damped by an air dash-pot below the deck, air types being considered more trouble-free than oil types.
2. *The idler.* Between the damped arm and the heads is an idler drum which bears a heavy internally-damped flywheel. Its effective mass is large compared with the inertia of the reel, torque

BERNARD OLIVER ELECTED IEEE PRESIDENT

Dr. Bernard M. Oliver, -hp- Vice President of Research and Development, has been elected President of the Institute of Electrical and Electronic Engineers for 1965. He has been a vice president of the IEEE since 1962 and during that time has been on the executive committee that co-ordinated the merger of the former AIEE technical committees with the professional group system developed by the IRE.

He received an AB in electrical engineering from Stanford University and an MSEE from the California Institute of Technology. Following a year as an exchange student in Germany under the auspices of the Institute of International Education, he returned to Cal Tech and earned a PhD in Electrical Engineering magna cum laude.

As a member of the Bell Telephone Laboratories technical staff from 1940 to 1952, Dr. Oliver worked on the development of automatic tracking radar, television, information theory and efficient coding systems. In 1952 he joined Hewlett-Packard as Director of Research and in 1957 was appointed Vice President of Research and Development.

Dr. Oliver holds over 40 U. S. patents in the field of electronics. He is highly active in industry affairs, having been elected a fellow in the IRE in 1954 and a director-at-large in 1958. He has served as chairman of the San Francisco section of the IEEE and on the board of directors of WESCON. He is also a member of the American Astronautical Society.

He has served as a lecturer in electrical engineering at Stanford, is the author of numerous technical articles, several of which have appeared in the *Hewlett-Packard Journal,* and is a regular contributor to the *Proceedings of the IEEE* and other publications. One of his articles, "Radio Search for Distant Races," is among those selected for entombment in the Westinghouse 5000-year time capsule at the site of the New York World's Fair.

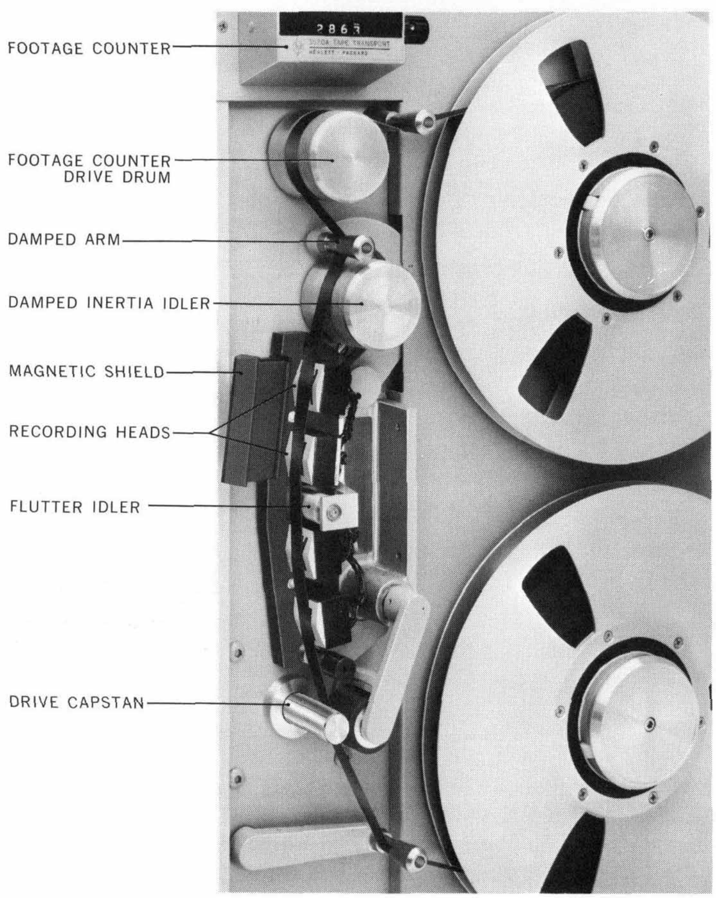


Fig. 4. *Tape path showing various parts of drive and guide system.*

motor, and footage counter drum. This flywheel effectively filters out the remaining small tension variations originating at the supply reel, and the damping reduces the "Q" of the resonant system consisting of the flywheel mass and compliance of the tape over the heads.

3. *The flutter idler.* In the center of the head assembly is a small roller whose mass reacts with the compliance of the tape through friction resistance to reduce high-frequency flutter.

4. *The damped flywheel* (visible in Fig. 3). The substantial irregularities in motion which would otherwise be coupled into the tape through the capstan from the rotational imperfections in the motor drive system are greatly reduced by the damped flywheel. Inside this flywheel is a second free-turning flywheel, which is coupled to the outer wheel by a viscous silicone-oil liquid. A stable liquid of the required viscosity was chosen after extended tests. Near-critical damping of the capstan drive system was achieved. The assembly is sealed, and requires no periodic checking.

5. *The pinch roller.* The pinch roller clamps the tape to the capstan so that tape motion is dominated by the capstan's motion and isolated from effects which occur beyond the capstan. The engaged part of the roller is narrower than the tape so that scrubbing does not occur at the edge where it would produce irregular tape motion.

SIMPLICITY OF TAPE DRIVE

At the outset it was decided that tape speed in the new transport should be selected through a strictly electrical arrangement, i.e., by ordinary switching. This would avoid the complications of such arrangements as multi-speed synchronous motors, solenoid-controlled sliding belts or gear drives, and dc motors under servo control.

In the last decade, responding to demand, several electric motor manufacturers have brought standard two-speed hysteresis synchronous motors to a high state of development. With standardized characteristics and long production runs, these have successively dropped in price until they are less costly than any special motor of comparable performance. High reliability and performance have been achieved, and at a moderate price. Because of this it emerged that the least costly way to achieve six electrically-controlled speeds with superior performance was by use of three well-proved, high-quality two-speed motors. This arrangement was selected and is the basis of the drive system. The mechanical coupling between the motors is an *-hp-* design which involves no servos, no sliding belts or gears, and no solenoids. To change speeds, the arrangement requires only the selection of which of the six motor windings to energize, a selection made by the push-button switches on the front panel. The motors are standard motors which are quickly available and familiar to service people everywhere.

In the past, magnetic tape transports have generally used one or more heavy flywheels in the tape drive system. Many of these, for reasons of space accommodation, are at the ends of rather long shafts. Any shock which tends to deflect the shaft tends to leave a permanent run-out or tends to cause permanent damage to a supporting bearing (commonly dents in the ball races) — or both. Precision of a very high order is required in these assemblies to achieve the extremely low flutter that is demanded. So it takes only a little damage of this kind to disable a tape transport. Damage frequently results simply from wheeling a transport in caster-supported racks. It is often a peculiarly expensive kind of damage, involving replacement of whole capstan assemblies.

The flywheel problem has been overcome in the new transport which is provided with unusually sturdy motor shafts running in generous size ball bearings. Unsupported lengths of shaft are kept short. The result is that, in test, the transport has undergone without harm shocks measured at 50 G. This includes shocks applied in the directions most likely to cause damage. Shock-absorbent packing has, of course, been provided to prevent such shock during shipment, but this degree of sturdiness also insures long trouble-free performance in normal service conditions.

Fig. 3 shows the three-motor drive of the transport. Directly under the capstan is the 30 ips/60 ips motor. For a given power frequency, there is only one capstan size. (A slightly larger capstan is specified for 50-cycle instruments.) This motor is mounted very close to the transport casting, for maximum strength and rigidity. At the rear of the motor is the flywheel constructed so as to provide viscous damping for the entire capstan drive.

Back of the damped flywheel is a centrifugally-controlled over-running clutch. Like the viscous flywheel, this was designed at *-hp-* especially for the new transport. This clutch is coupled tightly to a smaller pulley on the second motor which is of the same type and speeds as the others and provides $7\frac{1}{2}$ and 15 ips tape velocities. The motor carries a solid flywheel to smooth out residual 120-cycle pulsations. The motor is fitted with an over-running clutch which, in turn, is coupled to the third motor. The third motor provides $1\frac{7}{8}$ and $3\frac{3}{4}$ ips tape velocities. The third motor, too, is fitted with a flywheel but no clutch.

The over-running clutches in the drive system operate without continuous dragging and consequently do not wear in use. When driven, of course, such a clutch is firmly engaged. When the clutch is free-wheeling, the clutch shoe is fully disengaged, after the initial part of start-up, by centrifugal force.

DESIGN LEADER

Walter T. Selsted

Walt Selsted joined -hp- in 1963, and headed the group which developed the Model 3520A/3521A Tape Transports. The group is now a part of the -hp- Microwave Division in Palo Alto.

Walt has had extensive experience in the tape transport field and is the originator of more than twenty U. S. and foreign patents, many of which are basic to the recording art. He is a Fellow of the IEEE and of the Audio Engineering Society. He has published more than a score of technical papers.

Walt earned his BSEE at the University of California, Berkeley, where he also was for two years a research engineer on the Manhattan District project at the U. C. Radiation Laboratory. For a dozen years thereafter he directed engineering developments in the magnetic tape recording field, among which were many of the earliest devices for instrumentation applications.

GENERAL

Among the commonest causes of trouble in instrumentation tape recorders has been inadequate maintenance. Under-lubrication, over-lubrication, or other omission of maintenance procedures has been a persistent source of trouble. In recent years, however, improvements have been made in ball bearing design such that there are now available ball bearings of such precision that there is no longer any need to consider the use of sleeve bearings simply for their smoothness of operation. Permanently lubricated, unchanging in axial or end-play alignment after wear, and nowadays adequately precise, modern ball bearings made it possible to eliminate all lubrication procedures in the transport.

Because there are relatively few parts in the transport (see Fig. 3), accessibility is good. Most alignments are automatic, since nearly everything is referenced at the factory to the supporting chassis. Even in replacing so critical an item as the pinch roller or its arm, positioning will automatically be correct if the original shims are installed with the new parts. Head assemblies have plug-in electrical connections and the bases of the head assemblies are lapped to match a machined supporting plate, so no mechanical alignment problems arise during replacement. Brake linings can be replaced in moments, their alignment and adjustment being uncritical because of negative feedback design. In design prove-out the brakes have performed 100,000 high-speed stops without malfunction or significant wear. Torque motors are readily removed and replaced, their alignment being determined by original manufacturing procedures. Replacement of a drive motor takes some care, since a clutch or flywheel must be remounted, but procedures are straightforward, and all are entirely feasible under field conditions.

Specified performance for the new transport, in the *-hp-* tradition, is more conservative than that which is tolerated in checkout before shipment; typical performance is substantially better than specified performance. It has been shown that there is good reason to expect flutter performance to remain excellent in every normal situation over long periods of time with little maintenance and no skilled "tuning up."

In all these ways, design of the new transport has been carried out with the intent that it have high reliability, that it will be easily and quickly restored to service in the field if repair becomes necessary, and that it will require next to no maintenance.

ACKNOWLEDGMENT

The design of the new transport has been enhanced in a marked way by the assistance of William I. Girdner who contributed much to the mechanical design and to the processes used in the production of the transport.

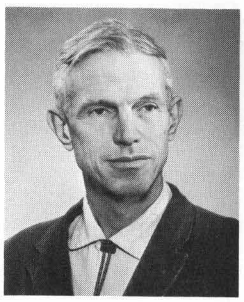
—Walter T. Selsted

SENIOR STAFF ENGINEERS APPOINTED BY *-hp-* BOARD OF DIRECTORS

Three engineers within the Hewlett-Packard organization recently were honored by appointment to the newly-created position of Senior Staff Engineer. This position was established by the Hewlett-Packard Board of Directors to give a clear and unequivocal recognition to those who have made significant contributions to the technical progress of the company. As expressed by –hp– President William R. Hewlett, "It is an unfortunate commentary on modern corporate enterprise that those responsible for a corporation's technological progress frequently do not receive recognition commensurate with their contributions."

Appointment to the new Senior Staff Engineer position is a recognition of substantial contributions already made to Hewlett-Packard's objective of advancing the state-of-the-art in electronic measurements, and also makes the recipient's knowledge and experience available on a broader basis to the entire corporate engineering complement.

The first recipients of this honor are Arthur Miller, who has had a long and influential association with the –hp– Sanborn Division, now in Waltham, Massachusetts, and Brunton Bauer and Arthur Fong, who have had an outstandingly productive affiliation with the parent company in Palo Alto.

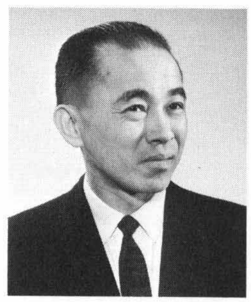


Brunton Bauer

Brunton Bauer joined –hp– in 1941 and has been Chief Development Engineer during most of the time since then. He has been responsible for the design of the majority of –hp–'s audio-range test equipment. His contributions include the 200 series Oscillators and Signal Generators, 300 series Wave Analyzers and Distortion Analyzers — among them the well-known 302A Wave Analyzer —, the 100A-E Frequency Standards, the 350 series Attenuators, the 450A and 451A Amplifiers, and the 700 series Power Supplies. He has made significant contributions to many other –hp– instruments, such as the 410B high-frequency Voltmeter, the 415B SWR Meter, and particularly to –hp–'s first transistorized instruments, the 403A Voltmeter, 466A Amplifier, and 721A Power Supply. He also designed many of the modifications required for special instrument applications, performed basic work in –hp–'s initial electronic counter program, and was consultant on transformer design for –hp–'s PAECO subsidiary.

His most recent project has been a transistorized high input impedance parametric amplifier.

An MIT graduate, Brunton spent several years in the development of communications equipment at Bell Telephone and other laboratories before joining –hp–.

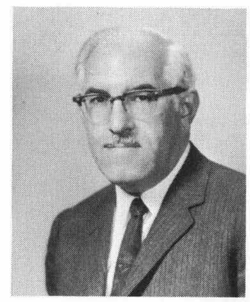


Arthur Fong

Art Fong is best known at –hp– for his work on many of the –hp– microwave signal generators, including the 616A, 614A, 620A, and the 623 and 624 test sets. He also contributed to the design of the 355C/D Attenuators, 360 Coaxial filters, 803A VHF Bridge, 417A VHF Detectors, 650A Test Oscillator, and several microwave components. His most recent responsibility has been the –hp– Model 8551A/851A Microwave Spectrum Analyzer.

During World War II, Art was at the MIT Radiation Laboratories where he was involved in microwave test instrument development. Following that he designed one of the first 88–108 Mc commercial FM receivers at another laboratory. He joined –hp– as a development engineer in 1946, became signal generator group leader in 1953, and was made section head in charge of spectrum analyzer development in 1960.

Art holds several patents on microwave devices and has authored numerous technical articles, several of which have appeared in the Hewlett-Packard Journal. He is vice-chairman of the IEEE Group on Electromagnetic Compatibility, and is a member of Tau Beta Pi, Eta Kappa Nu, Sigma Xi, and the Research Society of America. He holds a BSEE from the University of California and has done graduate work at MIT and Stanford.



Arthur Miller

Arthur "Doc" Miller joined the Sanborn Company in 1936 as a design engineer to work on the amplifiers for the first Sanborn vacuum-tube electrocardiographs and the later 2- and 3-channel "Cardiettes." During the early days of World War II, he contributed to the design of the proximity fuse at John Hopkins University on a part-time basis, commuting between Baltimore and Cambridge, and later worked on underwater sound equipment with an MIT group. During the remainder of the war, he designed radar and other equipment.

Following World War II, Dr. Miller designed the galvanometer and amplifier for Sanborn's first direct-writing ECG. He then adapted this system to data recording for industrial and scientific applications and expanded the concept into a variety of multi-channel systems. He has several patents and has authored numerous articles on recording techniques in the Sanborn Right Angle.

Dr. Miller was made Acting Director of Engineering at Sanborn in 1957 and was promoted to Director of Research a year later. He earned both BS and ScD degrees at MIT. He was chairman of the Boston Section of the IEEE Group on Bio-Medical Engineering and is a member of the Instrument Society of America, the American Association for the Advancement of Science, and Sigma Xi.