

Mechanical Damping in Tape Transports*

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Most of the dynamic elements of a tape transport store energy rather than dissipate it; therefore disturbances due to mechanical imperfections will result in the undesirable condition of oscillations of speed which die out slowly. The various physical mechanisms usable for dissipating (damping) this energy are shown along with a quantitative analysis (using electrical analogs) of their effects.

INTRODUCTION

THE length of tape and the rotating elements of a tape transport comprise a mechanical network whose object is to transport the tape from a supply reel, past recording and reproducing transducers (heads), and onto a take-up reel. It is necessary for most applications that the tape speed at the heads be as constant as possible. However, mechanical imperfections of all rotating elements and changes in the power line voltage generate forces and velocities which cause variations of the tape speed. The amount of speed change at the heads due to these forces and velocities depends on the transmission characteristics of this mechanical network of tape lengths and rotating elements.

The energy losses of the mechanical elements are usually small. Because of this, transient disturbances (e.g., tape splices, tape rubbing on a reel, line voltage shifts, etc.) will cause undamped oscillations or "ringing" at the natural resonant frequencies of the network. Additionally, the velocity generated by periodic disturbances (e.g., a "cogging" reel motor, or an eccentric capstan or reel idler, etc.) will be amplified whenever the disturbance frequency falls near a resonant frequency of the mechanical network.

The usual design procedure is to reduce the periodic dis-

turbances by means of increased mechanical accuracy; there are, of course, certain practical limitations to this approach. One can also attempt to place the resonant frequencies so that they do not coincide with the rotational speeds which generate the periodic disturbances. This procedure is valuable but of limited usefulness since the range of possible disturbing frequencies is usually broad, especially for a multi-speed transport. This is illustrated in Fig. 1, using the Ampex Model MR-70 as an example; the rotational speeds and the "cogging" and torque pulses from the reel motors are shown. (Other effects, such as harmonics of rotational speeds and ball-bearing ball speeds may exist, but are not shown.) The rates shown completely cover the

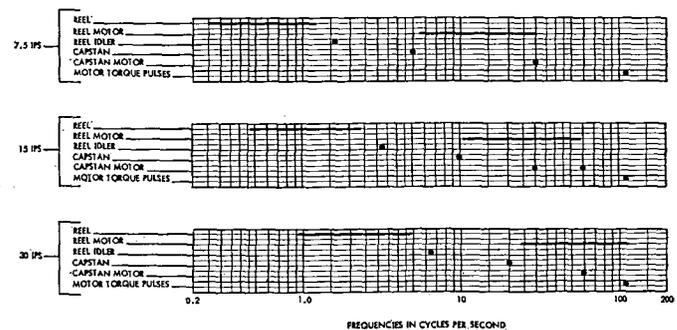


FIG. 1. Frequencies of potential periodic disturbances in the Ampex Model MR-70 tape transport.

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range from 1/4 to 120 cps. Also, the transient disturbances cannot usually be eliminated, and they will excite any resonant condition.

Reduction of the amplitudes of these resonances is possible by providing energy-dissipating elements, called mechanical responsiveness, and corresponding to electrical resistance. Note that electrical dissipators (resistors) are the simplest and most common electrical element; low-loss (high Q) elements are difficult to design. On the other hand, mechanical elements are commonly high-Q, and a dissipator (responsiveness) is comparatively difficult to design. This paper is concerned with the responsiveness of the elements of the transport and the practical application of additional responsiveness elements.

ANALYSIS OF THE TAPE TRANSPORT

Let us first consider a tape transport; for convenience of analysis, we will simplify as much as possible. Fig. 2a

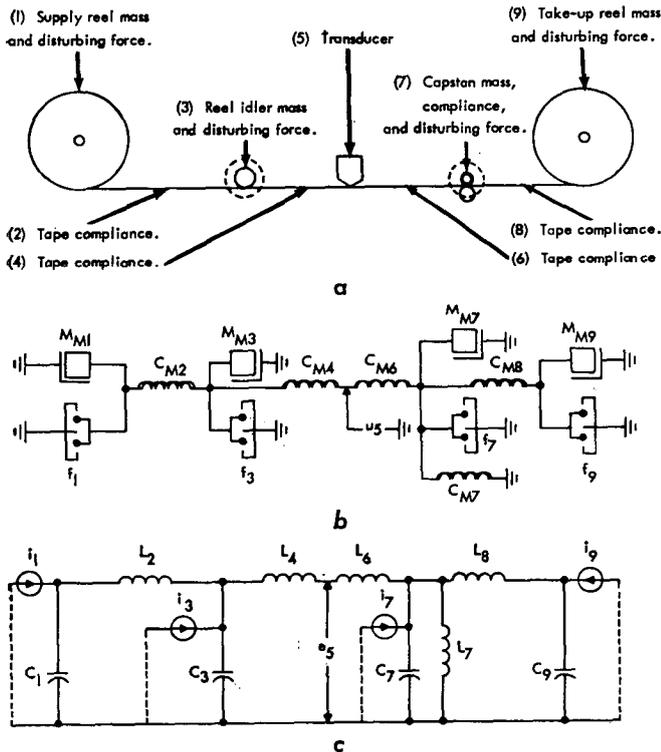


FIG. 2. Representation of a simplified tape transport. a. Physical system. b. Mechanical schematic diagram. c. Analogous electrical schematic diagram.

shows a simplified tape transport—supply reel (1), tape (2), reel idler (turn-around roller) (3), tape (4), transducer (head) (5), tape (6), capstan motor system (7), tape (8), and take-up reel (9). This is a network of torsional masses (1,3,7,9) a torsional compliance (7), and several translational compliances (2,4,6,8). In Fig. 2b these have been converted into an equivalent all-translational system and shown as a mechanical schematic drawing, using mechanical symbols; this schematic can be drawn from the physical

system by inspection. (Vibrations of the elements—e.g., the head—may also occur, but are ignored in this simplification. Also, in this drawing the damping associated with each element is not shown; it will be considered later.) Figure 2c shows the analogous electrical schematic, drawn by inspection using the mobility analogue. Mass becomes capacitance, compliance becomes inductance, responsiveness (the damping property) becomes resistance, force becomes current, and velocity becomes voltage. The principles of analogy are discussed in detail in the literature.¹

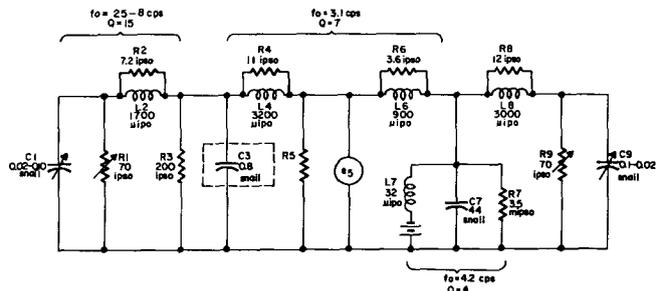


FIG. 3. Electrical analog of an indirect-drive tape transport with 1/4 in. wide tape. When the viscous damper of Fig. 15 is used in place of C3, this analog represents the Ampex Model MR-70 tape transport.

Quantitative study of any system requires measurement of the mechanical values. Metric units are most easily handled in the analogs, and are recommended. We have used the English inch-ounce-second units and, since our suppliers, machinists, etc., are not familiar with metric units, have invented our own set of unit names since a system of units does not exist for mechanical quantities. We have basic units for force, the ounce; for distance, the inch; and for time, the second. The English foot-pound-second system has a mass unit called a "slug," and we have named the inch-ounce mass unit (dimensionally, oz-sec²/in.) a "snail." (The dictionary says the "slug" is "closely related to the snail," if there *must* be a justification.) It is fairly common to express velocity not as "inches per second," but by its initials, "ips." We have likewise named the compliance unit "ipo" (inches per ounce), and the responsiveness unit "ipso" (inches per second-ounce).

Figure 3 shows a simplified schematic of a tape transport, using a mixture of electrical symbols and the mechanical component values. The greatest mass is that of the capstan, 44 snails (C7); the reel idler is much smaller (0.8 snail, C3), and the reel still smaller (0.02 to 0.10 snail, C1). The drive motor is very stiff (low compliance) (32 μipo, L7), and the major compliances are those of the tape itself (1000 to 3000 μipo each, L2, 4, 6, 8). Most of the responsiveness elements are too large to have appreciable damping at the frequencies of concern—C1/L2 with R1 and R2 has a Q of approximately 15 at its resonant frequency of 20 cps; C3/(L4 + L6) with R3, 4, 5, 6 has a Q of approximately 7 at its resonant frequency of 3.1 cps; and C7/L7 with R7 (which is an "added damping"; to be discussed

¹ See especially L. L. Beranek, *Acoustics* (McGraw-Hill Book Co., New York, 1st ed., 1954), Chapter 3, Part VI.

below) has a Q of 4 at its resonant frequency of 4.2 cps. Note that the tape speed *per se* does not enter at all into this network.

MEASUREMENTS WITH AN ANALOG ELECTRICAL NETWORK

The mechanical values may easily be converted to the analogous electrical values, as described by Wolf,² and the response of this electrical network may then be measured.

Such an analog study calls attention to the fact that many variables enter into the performance of a tape transport system. Thus, 1. Disturbances may come from the reeling systems, the reel idler, the heads, and the capstan system; therefore the response from disturbances at each of these inputs should be considered. 2. The speed should be constant at both the recording and the reproducing heads; but the response is different at each head position, requiring separate measurements for the effect at each head. 3. Each element may have disturbances which are of an essentially constant-force nature (e.g., a dragging break or bearing) or of a constant-velocity nature (e.g., an eccentric pulley); responses to velocity and to force inputs are generally different, so that two separate measurements are needed. 4. Many of the elements are variable—e.g., the equivalent mass of the reel of tape changes as the tape is reeled off; the tape compliance changes with different tape thicknesses, widths, and Young's moduli; the compliance of synchronous motors changes with the line voltage; the compliance of a multiple speed synchronous motor is different for each speed.

Therefore the measurements shown in the remainder of this paper represent but a few of many measurements.

RESPONSE OF A TRANSPORT ANALOG WITH LITTLE DAMPING

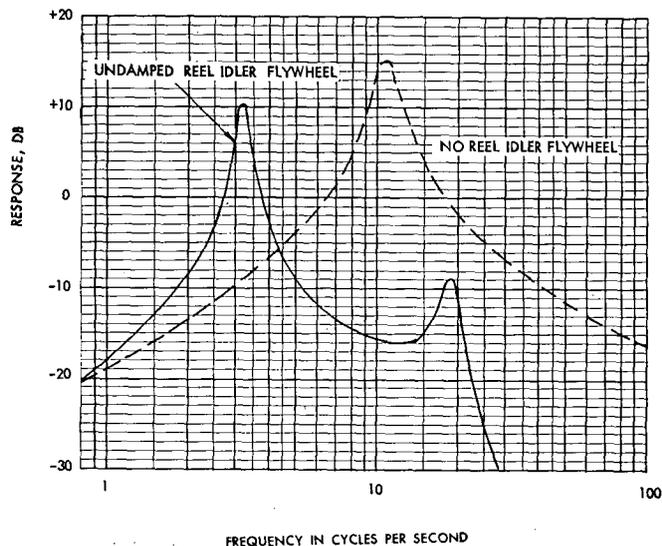


FIG. 4. Frequency response of the analog of the Ampex MR-70 tape transport with 1/4 in. wide tape. Velocity at the recording head due to a force at the supply reel; with no reel idler flywheel, and with an undamped reel idler flywheel.

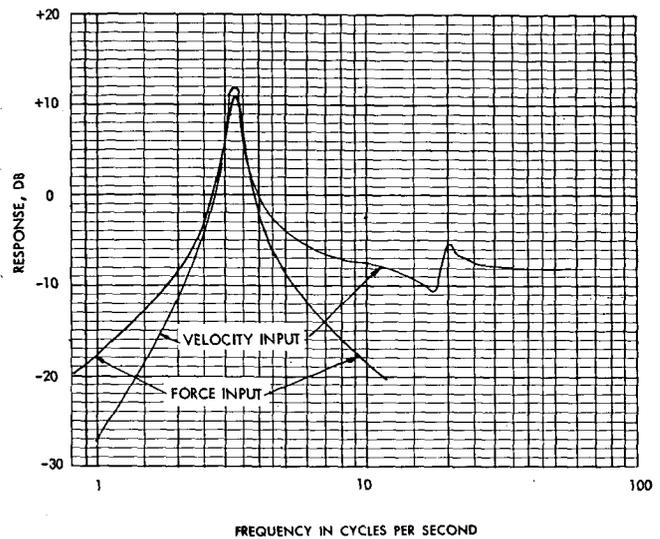


FIG. 5. Frequency response of the analog of the Ampex MR-70 tape transport with 1/4 in. wide tape. Velocity at the recording head due to a force and due to velocity at the reel idler, with an undamped idler flywheel.

Let us consider the frequency response of the velocity at the recording head, when a constant force *vs* frequency is applied at the supply reel—e.g., “cogging” of the reel motor. With no reel idler flywheel (Fig. 4, dashed curve) a large

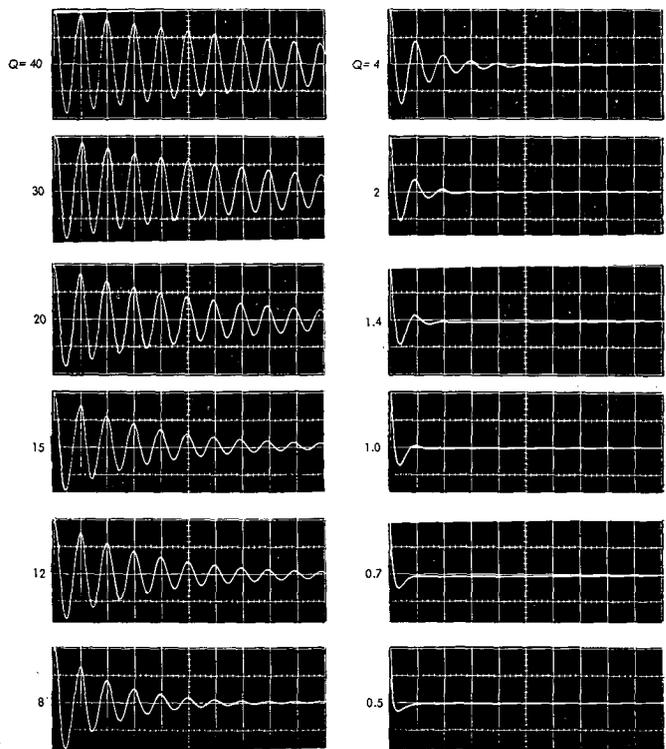


FIG. 6. Oscillograms of damped waves produced by a step voltage change across a resonant circuit, for different values of Q.

² W. Wolf, “An Investigation of Speed Variations in a Magnetic Tape Recorder, with the Aid of Electro-Mechanical Analogies,” *J. Audio Eng. Soc.* 119 (1962).

resonant peak occurs at 12 cps as the tape compliance resonates with the equivalent mass of the supply reel. (This resonant frequency varies with the amount of tape on the reel.) Unfortunately the reel motor "slot rate" frequency passes through this range, and will cause high speed variations (i.e., flutter).

Addition of a flywheel (Fig. 4, solid curve) attenuates the response at this frequency, but produces a new resonance around 3 cps. This new peak falls near the rota-

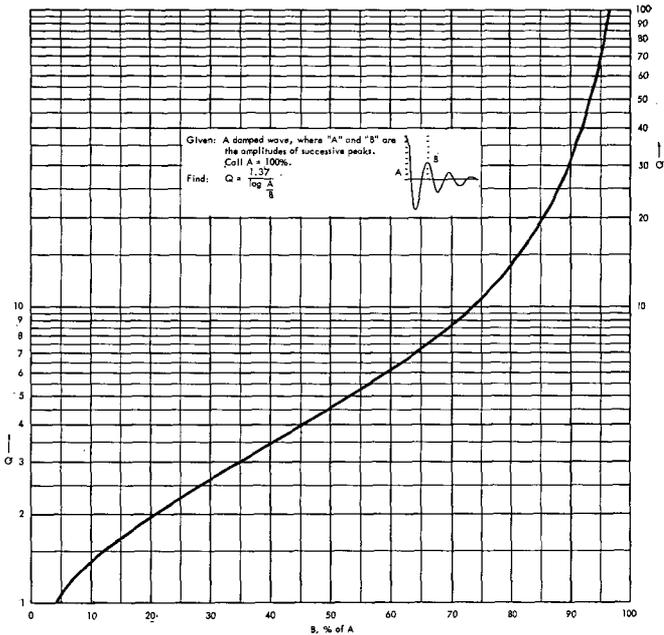


FIG. 7. Q of a damped resonant system as a function of the amplitudes of successive peaks of a damped wave.

tional frequency of the reel idler itself. A still larger flywheel would further lower the resonant frequency so that it would coincide with the reel rotation frequency.

Figure 5 shows the response to force and velocity inputs at the reel idler, when an undamped reel idler flywheel is used. The resonance is seen in this analog to amplify the effect of an eccentricity of the reel idler pulley, or a dragging brake or bearing, by four times. (The Q of the actual mechanical system is really 7—our electrical circuit had too much resistance.) When the reel idler rotation frequency coincides with the resonant frequency—as it does with $\frac{1}{4}$ in. tape at 15 ips—the slightest imperfection of the reel idler will cause large amounts of speed variation (flutter) at 3.2 cps. Moving the frequency is of little help, as some *other* disturbance frequency will then be amplified.

A transient disturbance will cause a damped wave of speed variations to occur. Figure 6 shows examples for different values of Q . A Q of 7, as mentioned above, will damp out to 10% in 5 or 6 cycles, or about 2 seconds for a 3 cps resonant frequency—a considerable time.

This transient disturbance provides a convenient method to measure Q : the damped waveform is recorded on an oscillograph, the ratio of successive peak amplitudes is measured, and Q found from the graph of Fig. 7.

ADDITION OF RESPONSIVENESS

Three-Element Filters

For analytical simplification let us discuss a very simple filter configuration consisting of one L and one C , with addition of an R , as shown in Fig. 8. (Many practical tape transport mechanical networks actually approach this simple case.) Our mechanical systems so far have been comparatively undamped, as shown by the left figure. A responsiveness element can be added in one of four locations in such a network. Each position, however, has some greater or lesser defect:

1. Positions with dc loss

a) R in series with L : a dc drop in voltage occurs when current is transmitted through this filter. Mechanically this means that the output speed is less than the input speed. This is satisfactory if the load is constant, or if some average-speed variation is tolerable.

b) R in parallel with C : a steady state power loss occurs here. Mechanically, this means that for adequate damping of a typical small high speed synchronous motor, the steady load would amount to ten times the available horsepower output of the motor!

2. Positions without dc loss

R in parallel with L , and R in series with C : the transmission of the filter at high frequencies approaches that of an R-C or R-L circuit, impairing the filtering action.

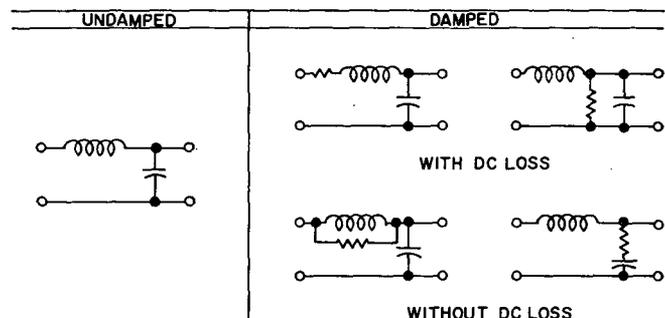


FIG. 8. Simple low-pass filter configurations, without and with damping.

Figure 9 shows two examples of filters with added responsiveness (these have been used in motion picture sound systems³). The effectiveness of these systems is difficult to determine, as no values are given. Figure 9a is for a shunt to ground by a "grease pad," and Fig. 9b is for a responsiveness across a series compliance, using oil driven through a small hole.

Figure 10 shows addition of responsiveness in a tape transport: the usual direct-drive capstan system using a hysteresis synchronous motor (for example the Ampex Model 351) has an equivalent mass of 22 snails, a resonant frequency of 3.5 cps for 15 ips tape speed, and a Q of 10.

³ W. J. Albersheim and D. MacKenzie, "Analysis of Sound-Film Drives," *J. Soc. Motion Picture Engrs.* 37, 452 (1941). The drawings of Figs. 9a and b, and 13a and b are taken from this reference.

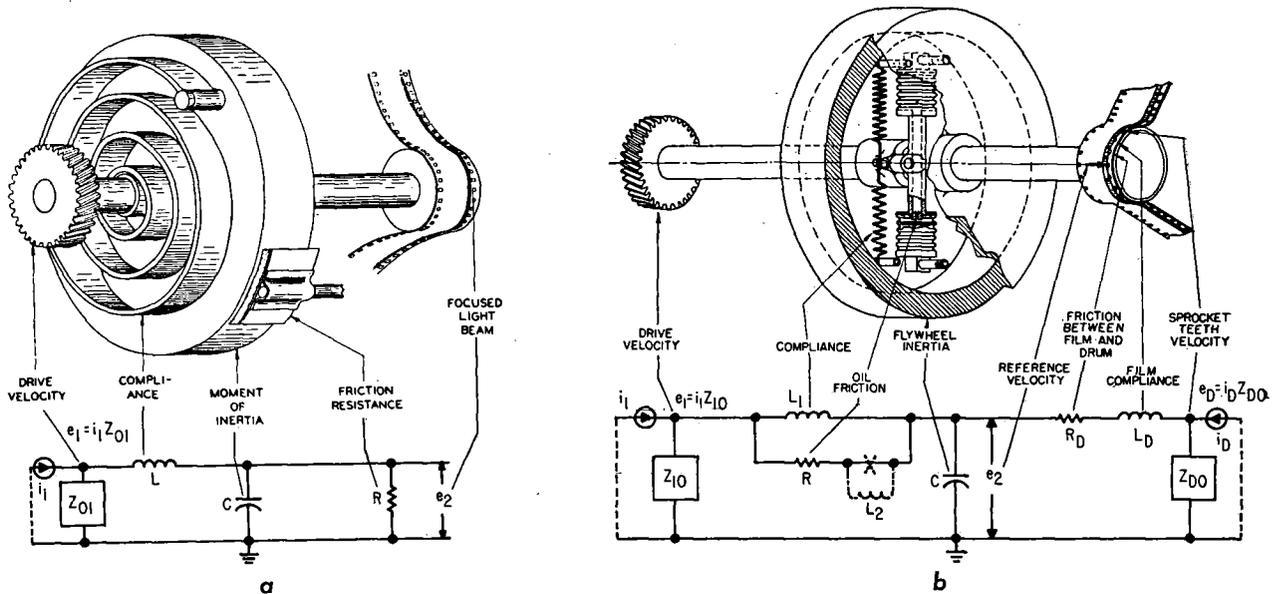


FIG. 9. Examples of mechanical low-pass filters with added responsiveness. *a.* Added shunt responsiveness to ground. *b.* Added responsiveness across a series compliance.

An indirect drive as used on the Ampex Models 300 and MR-70 uses a synchronous motor to drive the capstan flywheel through a rubber tire friction drive. The added series responsiveness damps the system to a Q of 3, with resonant frequency at 6 cps, and an equivalent mass of 50 snails. Although the series responsiveness precludes true synchronism, one must remember that the tape is always coupled to the capstan through a friction coupling, so that true synchronism is never possible in a tape recorder without servo control from the tape. In the MR-70, the hold-back tension is held constant through the reel, so that average-speed variations are minimized. The reduction in Q is of

sufficient advantage to outweigh the disadvantage of slightly decreased speed regulation.

FOUR-ELEMENT FILTERS

Cook,⁴ and Wente and Müller,⁵ and Davis⁶ describe four-element filters combining the good features of the response of a damped network, and the loss-free character of an undamped network. The circuit is shown in Fig. 11: an

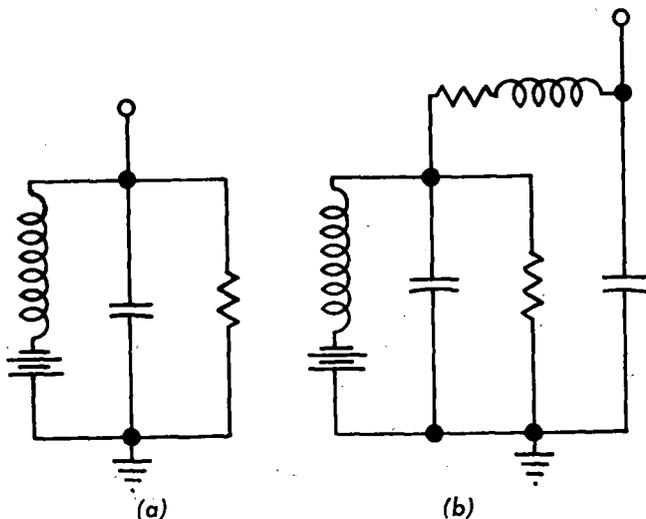


FIG. 10. Analogs of capstan drive systems employing hysteresis in synchronous motors. *a.* A direct-drive system, $Q = 10$ equivalent mass = 22 snails, resonant frequency = 3.5 cps. *b.* An indirect drive system, $Q = 3$ (equivalent mass = 50 snails, resonant frequency = 6 cps).

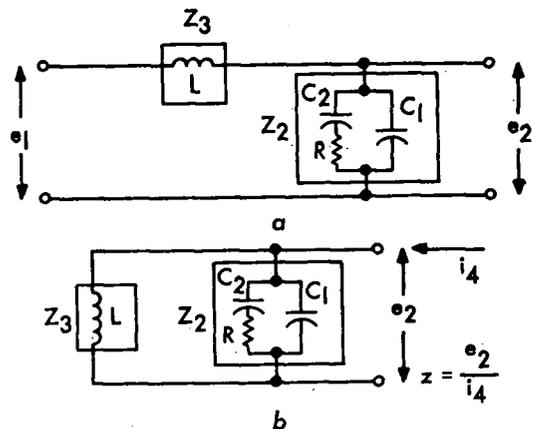


FIG. 11. Circuit of a four element low-pass filter. *a.* Circuit for response, e_2/e_1 . *b.* Circuit for impedance, z/z_0 .

undamped capacitor (mass) C_1 , is shunted by a damped capacitor (mass) C_2 . (The Davis system places a damped

⁴ E. D. Cook, "The Technical Aspects of the High Fidelity Reproducer," *J. Soc. Motion Picture Engrs.* 25, 289 (1935).

⁵ E. C. Wente & A. H. Müller, "Internally Damped Rollers," *J. Soc. Motion Picture Engrs.* 37, 406 (1941).

⁶ C. C. Davis, "An Improved Film Drive Filter Mechanism," *J. Soc. Motion Picture Engrs.* 46, 454 (1946). The drawing of Fig. 13c is taken from this reference.

inductor in series with the main inductor; the principle and results are similar.) Responses are shown in Fig. 12: a very low value of R gives a high Q at the frequency of resonance for $L + (C1$ in parallel with $C2)$; a very high value of R gives a high Q at the frequency of resonance for $L + C1$ only. At the correct intermediate value of R , the response is damped to a minimum.

Figure 13 shows three practical examples of four-element filters used in motion picture sound systems: (a) a damped inertia (viscous damper) with a solid flywheel mounted on bearings, inside an oil-filled shell; (b) a damped inertia (viscous damper) wherein the liquid in the shell is at once the inertia and, by the use of vanes, the responsiveness; and (c) a damped compliance, with a "dash-pot" on an idler system which deflects the film.

The design of such a four-element filter is described by Wentz and Müller,⁵ and by McKnight.^{7,8} To see the effect

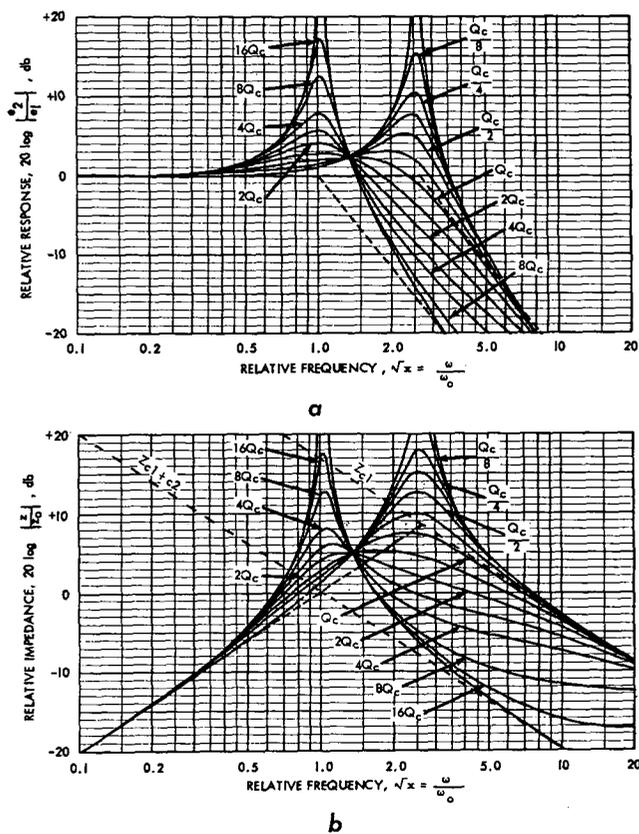


FIG. 12. Response and impedance of a four element low-pass filter as in Fig. 11. $C_2 = 6C_1$. a. Response vs frequency. b. Impedance vs frequency.

of using a viscous-damper on the reel idler, consider Fig. 14 which shows the circuit and values of the viscous damper used in the MR-70 to replace the undamped flywheel ($C3$ of Fig. 3) used in the Models 300 and 351. Figure 15 compares responses measured with an electrical analog for the undamped reel idler flywheel, and for the viscous

⁷ J. G. McKnight, "The Response of Simple Mechanical Networks," (unpublished).
⁸ J. G. McKnight, "Design of a Viscous Damper," (unpublished).

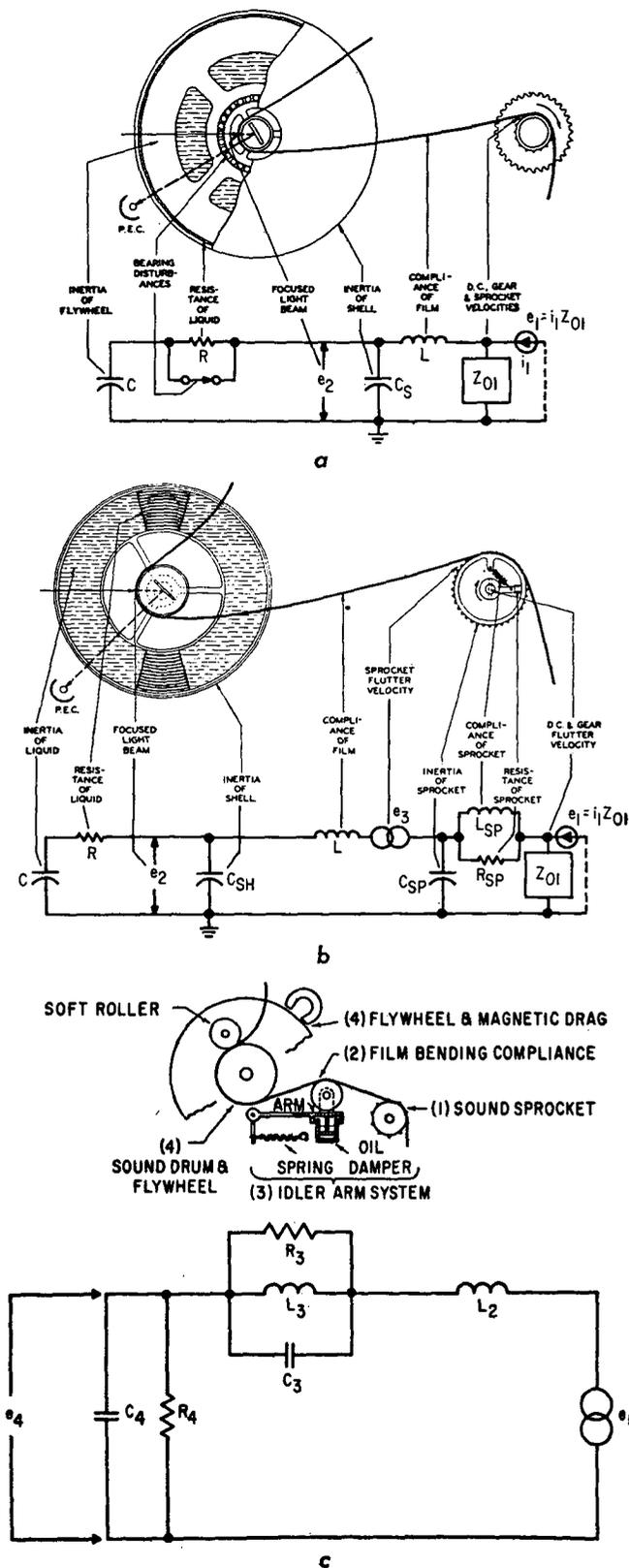


FIG. 13. Examples of mechanical four element low-pass filters. a. Damped inertia (viscous damper) with a solid flywheel. b. Damped inertia (viscous damper) with a liquid flywheel. c. Damped compliance.

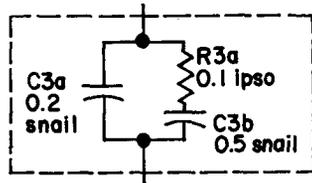


FIG. 14. Viscous damper to replace the reel idler flywheel (C3) in the transport analog of Fig. 3.

damper. Resultant velocity at the record head is shown for a force at the supply reel, a force at the reel idler, and a velocity at the reel idler. (In this case, the total inertia of the viscous damper equals that of the solid flywheel.)

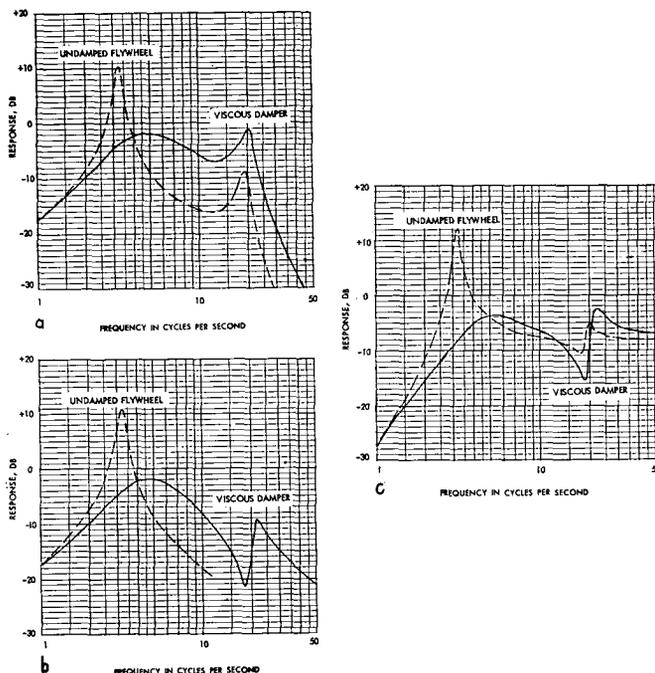


Fig. 15. Frequency response of the analog of Ampex MR-70 tape transport with 1/4 inch wide tape, with an undamped flywheel, and with a viscous damper on the reel idler. Velocity at the recording head due to: a. a force at the supply reel. b. a force at the reel idler. c. a velocity at the reel idler.

The response at resonance for all three disturbances is seen to be decreased 12 to 16 db (i.e., one-fourth to one-sixth) when the viscous damper is used. The response at

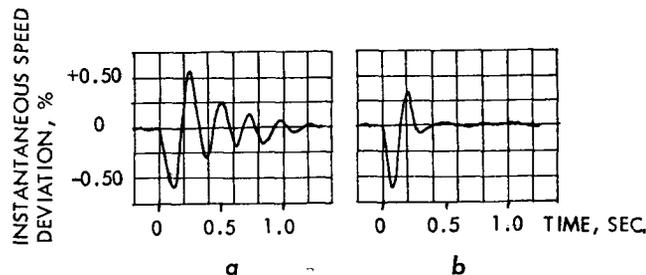


FIG. 16. Measured speed deviation vs time for an impulse at the supply reel, MR-70 tape transport with 1/2 inch wide tape. a. Undamped flywheel on reel idler, Q = 4.5. b. Viscous damper on reel idler, Q = 1.7.

higher frequencies is slightly impaired, but still adequate.

The measured effect on an Ampex MR-70 transport with 1/2 in. tape is shown in Fig. 16. In this measurement the condition with the undamped reel idler flywheel (Fig. 16a) had a Q of 4.5. When the viscous damper was substituted (Fig. 16b) the Q fell to 1.7. The improvement in case of an impulsive disturbance at the supply reel is obvious.

CONCLUSIONS

We have shown that the mechanical system of a tape transport consists mainly of elements with low dissipation, and that the high Q resonances resulting will almost certainly coincide with one of the many possible disturbances, resulting in large speed variations (flutter) at one frequency or another. A change of mass or compliance may avoid coincidence of resonances with the worst of the disturbances, but a better solution is to add a responsiveness (damping) element to reduce the response at resonance. An example of a practical damper is shown which provides a response reduction of four to six times.

THE AUTHOR



John G. McKnight was born in Seattle in 1931. He received a B.S. in electrical engineering from Stanford University in 1952.

He has been with Ampex Corporation since 1953, with the exception of the years 1945-56 when he was assigned to the engineering staff of the U. S. Armed Forces Radio Service in New York. The Ampex Corporation appointed him manager of the advanced audio section of the Professional Audio Division in 1959, and staff engineer in the Ampex Audio Division in 1961.

Mr. McKnight's work has been in research and engineering on the dynamics of tape transports as well as on magnetic recording, especially as it concerns the recording of music. He is an amateur musician, and has presented and published papers on energy distribution in music, noise considerations and measurement in magnetic recording, equalization in magnetic recording, stereophonic recording, and transport speed variations (flutter).

He is a governor of the Audio Engineering Society and a member of the Recording and Reproducing Standards Committee of the IEEE and the Magnetic Tape Subcommittee of the NAB Recording and Reproducing Standards Committee, a Fellow of AES and a Senior Member of IEEE.