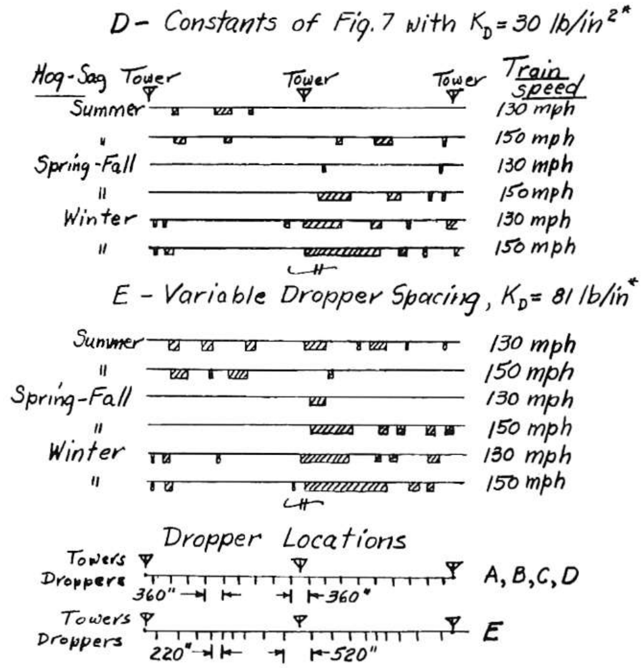

Fig. 25 Effect of changes from values A used in Fig. 7 (Section 3.1) for a single pantograph

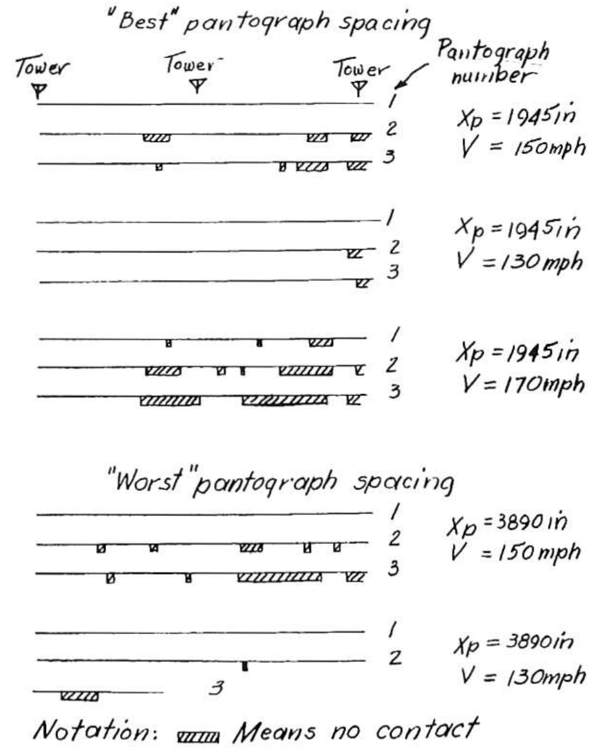

Fig. 26 Effect of reduced dropper stiffness on loss of contact. "Best," from equation (9) with V = 2640 in/sec. (Dropper $K_{D,\text{eff}}$ = 30 lb/in, except adjacent to towers, $K_{D,\text{eff}}$ = 5 lb/in., otherwise as in Fig. 11.)

3.8 Dropper Spacing. In [1] it has been suggested that placing the droppers more closely near midspan than at the towers would be beneficial. In Fig. 25(E) are presented results for the case in Fig. 7, Section 3.1, with the changes of dropper stiffness to 81 lb/in. Under (B), Fig. 24, the droppers are uniformly spaced at 360 in. while under (E), Fig. 25, the spacing at the tower is 520 in., dropping off regularly to 220 in. at midspan. The variable spacing seems to show no significant improvement for the case studied involving soft effective dropper stiffness. Use of additional terms in the sine-series expansion for the mode shapes might alter this conclusion since with 10 waves in 540 ft the shortest wave was 54 ft (634 in.) long, which exceeds the dropper spacing slightly.

4 Conclusions

Though a substantial number of computer runs have been made for this report, the conclusions to follow should be tempered by the fact that many other system combinations would have been possible. Also the runs used a relatively low number of modes, 10, and a moderately long time step, 0.05 sec, in order to keep costs within bounds. Nevertheless, the trends indicated by the results would probably be the same in a more exhaustive study. These trends are as follows:

(a) Sag can be very beneficial, particularly when selected by equation (8).

(b) The pantograph spacing given by equation (9) is somewhat better than twice that spacing.

(c) Substantial softening of the tower supports gives a modest improvement.

(d) Choice of pantograph constants by equations (18), (19), and (22) gives substantial improvement.

(e) Reduced stiffness of the contact spring, equation (23), gives definite performance benefits.

(f) Reduced effective dropper stiffness, equation (26), shows moderate improvement.

(g) Softening the dropper spring rate near the tower gave no significant improvement for the 10 sine waves used in the calculations but use of more terms might alter this conclusion.

(h) Spacing droppers more closely at midspan than at the towers gives no significant improvement for the case studied involving relatively soft dropper effective stiffness.

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4 Beatty, E. H., and Baker, P. H., "Application of the Faively-General Electric Type AM Pantograph to Pennsylvania Railroad Electric Locomotives," Institute of Electrical and Electronics Engineers, Paper No. CP63-188, Nov. 1962.

DISCUSSION

A. H. Kidder[3]

My profound respect for the authors' knowledge of railroad pantograph design leads me to think that their evident failure to corroborate mathematically the consistently favorable reports from European and Japanese experience with so-called "constant tension" railroad catenary systems must be attributable to having inadvertently assumed some artificially frustrating constraints upon the natural ability of a catenary system to disperse, as well as to absorb elastically, whatever mechanical energy it may receive from some external power source.

For example, the authors appear to have made three assumptions which could appreciably exaggerate the effect of their catenary upon their pantograph:

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1 That the displacement caused by the pantograph force illustrated in the curves of Fig. 3 will not affect the tensile strain (or tension) in the elastic, load-supporting wire of the catenary system.

2 That three-dimensionally rigid tower support of the upper wire assures equally rigid support of the contact and auxiliary wires, despite the fact that the relatively long, elastically supported droppers nearest the rigid tower may also swing so as to provide all of the freedom needed to permit transferring appreciable amounts of incident wave energy into adjacent spans.[4]

3 That there is, therefore, essentially no damping effect in the catenary system.

An ideal pantograph system can of course be expected to do no more than accommodate itself to whatever instantaneous variations in displacement velocity dy/dt may be required of it in order to maintain a harmonically stable, if not constant, contact force.

Several years of intimate association with investigations of the analogous and equally diverting problem of controlling wind-induced galloping catenary waves in high voltage overhead electric power transmission lines have led me to suspect that much of the almost baffling complexity of the authors' mathematical model, and the attendant risk of misunderstanding its limitations, probably are attributable to some failure to realize that the gross dynamic response of a railroad catenary system to any external power source, such as that of a moving pantograph contact force, is predominantly determined by the net accumulation of energy in the system and is almost entirely unaffected by harmonic variations in the disturbing force.

In the predominantly flexible, elastic, and undamped catenary span which is illustrated in Fig. 3 of the paper, all of the energy received from the pantograph would be trapped between the assumed rigidly supported ends of the span. Repeated reflections of each of the number of unattenuated traveling waves, respectively introduced by a succession of n passing pantographs, should then be expected to coalesce into a standing wave train of more or less simple harmonic motion.

The simplest method for evaluating the total energy in such a standing wave train in an S-foot catenary span, supporting a distributed mass of m slugs per foot, is to express it in terms of the kinetic energy $\frac{1}{2}mSv^2$ at the instant when the midloop displacement velocity $\omega A \cos \omega t$ is maximum. For simple harmonic motion of catenary-shaped wave loops, it can be shown that the total galloping wave energy must be

$$E = 0.267mS(\omega A)^2, \text{ ft lb per span} \tag{1}$$

This relationship, incidentally, provides convenient means for estimating the total energy in any galloping wave train, in terms of the readily observed maximum height of the waves and their galloping frequency.

If there is any catenary damping effect α, the incremental rate of increase in wave energy can be expressed directly as follows, in terms of the rate p of energy receipts and the rate αE of energy losses during that instant, that is,

$$dE = (p - \alpha E)\, dt \text{ ft lb} \tag{2}$$

if p represents the effective average rate of energy receipts, the total accumulation in t sec would be,

$$E = \frac{p}{\alpha}(1 - \epsilon^{-\alpha t}) \tag{3}$$

I infer that the effect of instantly varying rates of power input p upon the net total accumulation E probably can be evaluated most readily by use of the authors' mathematical model which also permits accounting for some catenary damping effect α. The resultant effect upon the maximum response velocity ωA to be satisfied by the pantograph system can then be determined directly from equation (1). This and the minimum practical average contact force should serve as the principal if not exclusive criteria for optimum pantograph design.

If, as a last resort, it should be found that some supplementary catenary damping is necessary in order to maintain a satisfactorily stable catenary-pantograph interface, it is entirely possible that this could be provided at minimum cost by inserting some recently proposed friction dampers[5] in series with the tension of the upper catenary wire, i.e., at each of the fixed supports and on intermediate swinging supports at intervals of two or more span lengths. At any rate, this would seem to me to require much less effort and inconvenience than resagging the catenary, respacing droppers, etc., as suggested by the authors' conclusions a, c, f, g, and h.

Conclusions

1 Complete solutions of catenary-pantograph system interface problems require reconciling the singularly different needs and characteristic responses of two essentially sovereign systems.

2 The effects of a pantograph upon a catenary system are almost exclusively determined by average rather than by instantaneous rates of power transfer through the pantograph-catenary interface, and can be reduced if the pantograph can be made sufficiently agile to permit reducing the average contact force.

3 When the combination of a minimum practical contact force and maximum practical pantograph agility will not be sufficient to assure a tolerably stable pantograph-catenary interface, appreciable relief can be provided by inserting additional damping resistance in the catenary system.

Authors' Closure

We wish to thank Mr. Kidder for his interest and for submitting his discussion to our paper. Our reply is prefaced here by a clarification of what may be a misunderstanding of the intent of parts of this paper. The companion paper, 68-RR-2, describes a mathematical model and digital computer program for simulating the dynamics of one or more pantographs traversing an overhead electrical distribution system, commonly called a "catenary." Fig. 2 in that paper illustrates the mathematical model of the catenary that is included in the computer program. This paper, 68-RR-1, reports on the selection of parameters used as input data for the above computer program, and the results of the calculations. Section 2 of this paper (68-RR-1) describes the theoretical approach used to determine the ranges of values of the catenary and pantograph parameters to be investigated with the computer program. Fig. 3 illustrates how taut cable theory is used to estimate the desirable static sag of the overhead wire and the desirable spacing between two or more pantographs. Fig. 3, with only one span of a single cable having fixed ends, should not be misconstrued to be the mathematical model used for the actual catenary.

The model of the actual catenary system, illustrated by Fig. 2 in 68-RR-2, considers the energy at all times, in up to ten consecutive spans of wire, and considers that damping is distributed throughout the catenary system. Any changes in the initial static tensions of both the upper wire and the lower wire caused by the moving pantograph forces are considered to be negligible secondary effects, and both tensions are assumed to remain constant. There are several thousand pounds of initial static tension in each wire, and the maximum deflections, both computed and observed, are usually in the range of 5 in. to 7 in. If there is a slight change in the tensions, it will mean that the

[4] The bronze wires, for instance, are exceedingly effective conductors of mechanical energy, by invisible tensile strain waves which propagate through swinging supports at a velocity of about two miles/sec.

[5] Kidder, A. H., "Proposed Friction Damper for Galloping Conductor Waves," *IEEE Transactions*, Vol. PAS-86, Nov. 1967, pp. 1368–1374.

traveling waves will propagate somewhat faster, but with no significant change in the overall effects. In addition, with cross cable suspensions of the catenary (called "cross-span construction") both wires can move slightly in the direction of their length with some restraint, enough to accommodate most of the elastic strain that would occur if the ends of the cable were otherwise fixed. As for constant tensioned cable catenary system (weights and pulleys) used outside the United States, the assumption of negligible increase in tensions is even more valid.

Mr. Kidder has stated the overall problem very well in his three conclusions, and because of this problem, considerable efforts are underway by many people around the world to develop pantographs and catenaries for high-speed operation. However, it is unfortunate that limiting conditions do not allow the use of a pantograph that is "sufficiently agile to permit reducing the average contact force." The Japanese have approached this on their new Tokaido Line using a small pantograph with dampers that operates at an extended height of about $3^1/_2$ ft. However, with more than one pantograph per train, some current collection difficulties have been observed, even under composed compound catenary with dampers and under constant tension. Pantographs on European railways are extended about 5 ft to 9 ft upward, but in the U. S. pantographs are normally extended from 8 ft to 12 ft upward. Consequently, there is the difficult problem of trying to develop large pantographs that are "agile."

Concerning the installation of dampers in the catenary, this has been done on the Tokaido line and in limited tests on some European railways, but the thinking at this time is that dampers in the catenary system would be too inconvenient and too expensive to install and maintain. With two dampers per span, it would require roughly 9000 dampers for a single track between Washington, D. C. and New York, assuming 270 ft spans throughout the 226 miles. Many of the people working on this problem believe it is more practical at this time to use dampers in the pantographs than in the catenary system. Also, recent practice with constant tensioned catenary systems outside of the U. S. has been to cut dropper lengths to give a prescribed sag to the contact wire that is symmetrical about the midspan, and once installed, there is no maintenance as there probably is with dampers.