A Magneto-Elastic Source of Noise in Steel Telephone Wires

By W. O. PENNELL and H. P. LAWTHER

The appearance of an electromotive force at the terminals of a vibrating rod or wire of magnetic material was investigated. It was concluded from experiments somewhat more simple and direct than those employed by other investigators that the effect was due to changes in the state of circular magnetization accompanying the variations of stress. The results suggested problems for more intensive investigation and applications of possible practical value.

THERE probably are few persons who have not had the experience of standing near some telephone or telegraph line out in the open and hearing the singing of the wires resulting from the wind blowing over them. Perhaps in childhood it was a source of wonderment why these sounds could not be heard at the telephones, and later, upon learning that telephone transmission was accomplished electrically and that these vibrations were mechanical only, tolerant amusement was felt at this earlier ingenuousness. Apparently it has remained until a very recent date for the discovery unmistakably to be made that it is possible under certain conditions for the mechanical vibration of a telephone wire to generate electromotive forces of sufficient magnitude to become objectionably audible in the telephone circuit. It was in April, 1935 that Mr. G. G. Jones of the Long Lines Department of the American Telephone and Telegraph Company mentioned to one of the writers the experience his Company had had a short time before in tracing down a supposed case of inductive noise to the action of the wind upon a 1200-foot steel-wire river-crossing span near Topeka, Kansas. This particular case had been cleared promptly by the application of suitable vibration damping devices generally recommended for situations where vibration might cause trouble. Special investigations then were made of long steel-wire spans at several locations in the Southwestern Bell Telephone Company territory, and it was revealed that some slight noise derived from this source actually was present in every case—and in one particular instance, where the wind velocity and direction happened to become very favorable to the production of wire vibration during the time of the inspection, the noise arose to a serious magnitude. In none of these locations had there been previous evidence that vibration was serious. That so simple and direct a phenomenon had escaped identification at the hands of telephone workers through the years of the art's existence seemed remarkable, and especially so in view of the fact that Bell, the inventor of the telephone, in 1879 made passing note [1] of an experimental finding that probably was due in part to this effect. Accordingly, the writers' interest was aroused to the extent that an investigation was undertaken to learn the basic cause of the observed result.

In the light of subsequent knowledge it was surprising that some keen observer had not predicted and demonstrated the effect as the natural and necessary consequence of the researches of Ewing [2] and his predecessors upon the relation between state of magnetization and state of stress of a ferromagnetic specimen. Apparently it remained for von Hippel and Stierstadt [3] first to remark the phenomenon in 1931. These men were unable to interpret the effect in simple terms, however, and their reports presented a series of premature conclusions. Von Auwers [4] alone recognized the effect as capable of complete and satisfying explanation on the basis of magneto-elasticity, but he chose a method of establishing this, the interpretation of which was quite involved. For their own satisfaction in comprehending the phenomenon the present writers were led to conduct a series of experiments of qualitative character. It was felt that knowledge and clear understanding of the effect should be of immediate interest and value to workers in the general field of electrical communication in the United States.

With the aid of an amplifier having a gain of 110 decibels and terminating in a loud speaker it was practicable to conduct the experimentation with specimens of table-top dimensions. This amplifier had an input impedance very much higher than that of any of the specimens, and the response of the speaker therefore was proportional to the voltages generated by the specimens. A stretched iron wire three feet long would yield a clear sound in the speaker when its ends were connected to the input of the amplifier while it was being mechanically stimulated by plucking or bowing, and the sound from the speaker would be closely of the same quality as that heard by direct air transmission from the vibrating specimen. With this arrangement it was possible to detect any change in the magnitude of the effect as great as two to one simply by observing the loudness of the sound.

It was verified immediately that the effect must be dependent upon the property of ferro-magnetism. Taut wires of soft iron, tempered steel, or nichrome; rods of soft steel or permalloy—all produced strong sounds in the speaker when their ends were connected to the input of the amplifier while they were stimulated to vibration by bowing, plucking, or tapping. With wires of copper or brass, or with a rod of carbon, no sound could be heard. Those small electromotive forces which must have resulted from the motion of any of the specimens in the earth's magnetic field were totally inappreciable with the apparatus employed.

Now the appearance of a potential difference between the two ends of a wire consequent to its vibration necessarily must have implied one of two situations—either there was some external influence or some relation to its surroundings which was capable of discriminating between the two ends, or else the wire possessed inherently some property that differentiated between the two directions along its length. Accordingly, exhaustive efforts were made to learn if orientation had any influence on the phenomenon. A stretched soft iron wire about three feet long yielding a clear sound in the speaker upon being plucked was employed. First, the ends of the wire were held stationary, and the wire was plucked time and again so that its plane of vibration covered representatively the various inclinations possible for this. Then there was tried a large number of positions for the axis of the wire, spread uniformly over the complete sphere. No response to orientation could be found. This negative result meant that the phenomenon under investigation must have arisen fundamentally through some condition of polarity resident within the specimen.[5]

With the phenomenon associated so definitely with the ferro-magnetic property of the substance, and attributable so certainly to some quality of polarity of the specimen, it was but natural to recall [2] the considerable changes in their states of magnetization which accompany the applications of stresses with ferro-magnetic materials. In order to have produced an electromotive force along the axis, the state of magnetization of a rod or wire would have had to change in that same sense in which magnetization would have been acquired when an electromotive force was applied, and current allowed to flow, between its two ends; i.e., magnetization in closed circular paths centered upon the axis and at right angles thereto. Having formed this reasonable hypothesis of the fundamental process, experiment then was carried along the lines of testing its validity.

Any circular magnetization of the wires and rods, since its circuit would have been along paths of low reluctance wholly within the material, should have been comparatively stable and free from disturbance by external magnetic fields of moderate intensity. The observed fact that the phenomenon was quite independent of the orientation of the specimen in the earth's magnetic field was consistent with this view. The further fact that the imposition of a strong magnetic field along the axis substantially weakened the effect was additional confirmation, for it is well known [6] of ferro-magnetic materials that strong magnetization in a given direction reduces their susceptibility in other directions.

Of course it was inferred at once that the same stresses that brought about changes in the intensities of circular magnetization of the specimens also were causing changes in the intensities of longitudinal magnetization. A coil of insulated wire was connected to the input of the amplifier. When one of the ferro-magnetic specimens was placed along the axis of this coil so that the coil winding was approximately midway between its ends, and then was stimulated to vibration, similar sounds were heard from the speaker as with the previous arrangement. As an interesting comparison it was found with a soft steel rod specimen six feet long and one half inch in diameter that a few more than fifty turns of wire on the coil were necessary to produce a sound in the speaker of the same loudness as that obtained when the amplifier input was simply connected to the two ends of the rod. Taking account of the cross-sectional areas available to the circular and to the longitudinal magnetizations, it thus was shown that the two classes of effect were not of different orders of magnitude.

There now was prepared a specimen planned especially to emphasize the effect of circular magnetization. A soft steel tube six feet long and having an external diameter of three eighths inch and a bore diameter of one eighth inch was obtained, and midway between the two ends a small opening was cut between the outer surface and the bore. Two similar windings of insulated wire were placed, each encircling closely with four turns the longitudinal wall cross-section of the tube between one end and the mid-point. Switching arrangement was provided for connecting these two windings in series either so as to encircle the total wall cross-section in one sense, or so as to encircle the two halves in opposite senses. The tube then was placed at the axis of a six-foot long solenoid, and the entire assembly was mounted with its axis horizontal and lying in the magnetic East-West direction. Sources of direct current and of sixty cycle alternating current were available.

Demagnetization of the specimen was accomplished by passing initially strong alternating current through the solenoid and the bore windings, either successively or simultaneously, and then tapering this current off uniformly to zero value. The effectiveness of the treatment could be inferred from the following observations. The specimen was made to acquire strong residual magnetism in the longitudinal direction by passing direct current momentarily through the solenoid winding, and its magnetized condition was verified by exploration with a magnetic compass. Then upon applying the demagnetizing cycle either to the solenoid or to the bore winding this evidence of the magnetized state would disappear.

With the halves of the bore winding in series aiding and connected to the amplifier input, tapping on the end of the demagnetized tube produced a low but distinct sound in the speaker. Upon reversing one half of the bore winding the loudness of this sound usually was slightly reduced, but occasionally was slightly increased. Following the momentary passage of direct current through the bore winding with its halves connected in either sense, the loudness of the sound from the speaker was tremendously and permanently increased. Now upon reversing one half of the bore winding the loudness of this sound always was reduced markedly—although never to so low a level as that produced by the demagnetized specimen. Also, it was noted that with the bore windings in series aiding and connected to the amplifier input and starting with the tube demagnetized, the momentary passage of direct current through the solenoid winding (thereby imposing a state of residual longitudinal magnetization upon the specimen) was followed always by a moderate but marked increase in the response to tapping.

The foregoing results established quite firmly that the effect under investigation was due largely if not wholly to variations in the intensity of circular magnetization accompanying the applications of stresses. The presence of the effect to a slight degree with a specimen which presumably was in a demagnetized state remained unexplained, since testing equipment was not available for extending the inquiry further. Several plausible explanations suggested themselves. Perhaps a specimen of ferro-magnetic material could not be demagnetized completely, or—what amounted to the same thing—perhaps the state of complete demagnetization was unstable, and was followed immediately and spontaneously by the appearance of some magnetization. Again, it might have been that the state of complete demagnetization was reasonably stable of itself, but was readily disturbed by the initial application of the mechanical stresses. It seemed reasonable to expect that any such self-magnetization would have arisen most pronouncedly along the paths of least reluctance. For the time being, it was necessary to leave this point to conjecture. Certain of the results described in the paragraph immediately preceding clearly were attributable to lack of homogeneity of the specimen.

That a simple length of iron rod should be capable of functioning as a complete alternating current generator appealed to the writers as being novel and curious. So direct a means of converting mechanical into electrical energy should find some useful applications. As the sensitive element in a telephone transmitter it should be added to the considerable list of other devices which have been used for this and allied purposes. The following arrangement was constructed. A fine iron wire was laced back and forth between pegs located along the opposite edges of a five-inch square opening in a wooden frame so as to screen the aperture with one hundred spans of the wire all in series, evenly spaced, and parallel. A sheet of paper then was cemented to the screen and the two ends of the wire were connected to the amplifier input. This device performed as a crude telephone transmitter. It was recognized, of course, that with this simple arrangement the iron wire would undergo two complete cycles of stress for each complete cycle of the air pressure upon the diaphragm, and that mechanical bias or some equally effective means would have been necessary to eliminate this distortion. Where the vibrating element itself was of magnetic material, there was the possibility of the sound source constituting its own transmitter. For example, when the amplifier input was connected between the bridge and key-head of a steel-stringed guitar the music of this instrument was reproduced quite faithfully from the speaker. This was suggestive of the possible use of the effect in studying the vibrations and strains occurring in steel structures such as bridges.

References

1. "The Bell Telephone," American Bell Telephone Company, Boston, 1908, p. 54. The following quotation from Bell's testimony was called to the writers' attention by Mr. R. I. Caughey. *Yes. I tried such an experiment, I think in the year 1879. A continuous current from a voltaic battery was passed through a stretched wire—I think a thin steel wire—which was placed in the same circuit with an ordinary commercial hand telephone. When the wire was plucked by hand, it vibrated, producing a musical tone. The hand telephone was in another room, and I listened at the telephone while a young man was plucking the wire. I heard a musical tone from the telephone at each pluck, and could recognize, also, that the character or "timbre" of the sound produced by the vibrating wire was reproduced by the telephone at my ear.*
2. Ewing, "Magnetic Induction in Iron and Other Metals," 3d ed., 1900, Chap. IX.
3. Von Hippel and Stierstadt, *Zeitschrift fur Physik*, 69, 52 (1931).
   Von Hippel, Stierstadt, and von Auwers, *Zeitschrift fur Physik*, 72, 266 (1931).
4. Von Auwers, *Zeitschrift fur Physik*, 78, 230 (1932).
5. From the results at this preliminary stage the present writers were convinced that the electromotive forces appearing at the terminals of the vibrating wire were determined by the cycles of strain, and not by the cycles of displacement, of the specimen. It seemed to them that this fact, and this fact alone, was demonstrated by von Auwers' elaborate study of the frequency and phase relationships between the mechanical vibration and the terminal electromotive forces.
6. Ewing, Chap. IX, p. 234.