PERFORMANCE OF A LOUDSPEAKER AS DETERMINED BY INPUT MEASUREMENTS

A thesis submitted to the faculties of
the School of Engineering and Architecture
and the Graduate School of
The University of Kansas

For

THE DEGREE OF ELECTRICAL ENGINEER

By

HAROLD WILLIAM ANDERSON

1929

PREFACE

The writer worked in 1922 in the Development and Research Department of the American Telephone and Telegraph Company on a problem concerning the telephone receiver diaphragm. The solution attempted was based upon an electrical analogy at frequencies near that of resonance of the mechanical oscillatory system consisting of the diaphragm. Work at that time was based upon a series circuit of resistance, inductance, and capacity.

Since this experience, the writer has hoped to do similar work upon a loudspeaker, and the subject was accordingly chosen for this thesis. During the work, an electrical analogy of a parallel circuit appeared to offer a more complete explanation of the phenomenon of resonance than the series circuit. The merits of the parallel system are presented in this report.

CONTENTS

PERFORMANCE OF A LOUDSPEAKER AS DETERMINED BY INPUT MEASUREMENTS

INTRODUCTION

Methods are in common use for the determination of the performance of electric motors entirely from measurements of power input. Typical conditions under which such measurements of input may be made are: with the motor running without load, with its moving parts blocked to constitute a resistance or impedance determination, and with the motor running at a particular load of which the magnitude may be determined by the test. In 1912, Kennelly and Pierce reported upon a somewhat comparable test* of telephone receivers. Impedance measurements at various frequencies were made upon receivers of which the diaphragms were at first free to vibrate and later mechanically damped. The present report concerns the testing of a loudspeaking telephone receiver in this manner. For reasons which will appear later, a Radiola model 100 loudspeaker was chosen for this test.

Since the loudspeaker is a special form of electric motor, a discussion of the testing of it will be preceded, for comparison, with some remarks concerning the ordinary motor. The purpose of the ordinary motor is to convert a reasonably large part of an electric power input into a mechanical output in the form of a torque at some desired speed. A motor is usually operated on a system of constant voltage and, in the case of alternating current, constant frequency. Economic considerations observed in the design of a motor will prescribe that the maximum flux

* Bibliography 1.

density of its magnetic circuit reach well toward the point of saturation. Since the flux density, in some of the common types of motors for systems of constant potential and frequency, will not change greatly throughout the entire range of performance, it follows that high densities may be encountered in regular operation. Motor performance sometimes actually depends upon an approach to saturation of the magnetic circuit. The ordinary motor is thus a device specifically designed for operation at a particular voltage. Accordingly, an investigation of its performance through measurements of electrical input would include important tests made at its definite rated voltage. It may be observed, however, that input data at this voltage could be completely recorded as complex impedances.

The purpose of a loudspeaker is to convert electric power of telephone frequencies into acoustic power, with reasonable efficiency and in accordance with the peculiar requirements of the loudspeaker's service. To the extent practicable, the loudspeaker should perform uniformly over a wide range of frequency, say 50 to 7,000 cycles.* Likewise, reasonable proportionality between output and input, i.e., constant efficiency, should be maintained between minimum and maximum extremes of power. Finally, it should radiate only those frequencies present in its input. Since the loudspeaker is being considered as a special form of motor, it should at the outset be noted that the loudspeaker, while operating among any particular surroundings, has upon itself an unchanging absorbent load. Though its output is in the form of vibrations transmitted from a sound radiating surface, it may to some extent be likened to a fan motor, of

* Throughout this report frequency will be stated merely as a number of cycles; the usual time period of one second is to be understood.

of which the load for any particular surroundings depends upon the power input to the motor.

Of the ideal requirements listed above, that of uniformity of response over a wide band of frequencies is the one from which practical loudspeakers deviate furthest. The criterion for the quality of a loudspeaker depends, therefore, to a large extent upon its relative response at various frequencies. Practical testing thus becomes mostly a determination of relative performance at different frequencies. That the loudspeaker should respond as nearly as practicable in proportion to the magnitude of its input requires that parts carrying alternating magnetic flux be of sufficient size to prevent saturation during normal operation. The condition of greatest flux density is produced with loud signals at low frequency. Since density approaching saturation should occur only in extreme cases, average operation will take place far below the point of saturation. Testing may thus be done with any applied voltage in a considerable range. At any such voltage, input measurements may consist of determinations of current and power factor, or their equivalent. Therefore, according to this postulate of proportionality at various values of power, input measurements may become merely complex impedance determinations. For consistency, however, a series of impedance tests at different frequencies should be made with some definite condition of input. To represent typical operation, an input value that will produce a signal of average strength should be chosen.

LOUDSPEAKER TESTED

The loudspeaker chosen for this test was of the balanced-armature type, equipped with a conical radiating surface flexibly supported at its edge. Such a loudspeaker seemed especially desirable for the test contemplated because of representing a type of mechanism conducive to the phenomenon of lightly-damped resonance. Since this test was to be based upon a fundamental type of loudspeaker rathern than a combination of the device and an auxiliary, the filter was at the outset disconnected. This was later found to have been an almost unnecessary precaution because of the low frequency range in which the most prominant resonant effects were found.

The arrangement of essential parts of the loudspeaker tested is shown in Fig. I. The field of the U-shaped permanent manget A divides between the projecting ends of soft iron pole pieces BB. The soft iron armature C is supported at its center by a flat spring which extends to a non-magnetic housing at the front and back of the unit. By twisting this transverse supporting spring, the armature may oscillate in the plane of the magnetic field. Coil D is wound axially about the armature. If the armature stands at its midposition between the poles and the winding carries no current, main flux should divide equally among the four projecting ends of the pole pieces. Forces acting upon the armature would, therefore, be balanced, and the armature would stand in equilibrium. From this balanced condition of rest, this loudspeaker has received its name. It will be noticed that during this condition the armature is

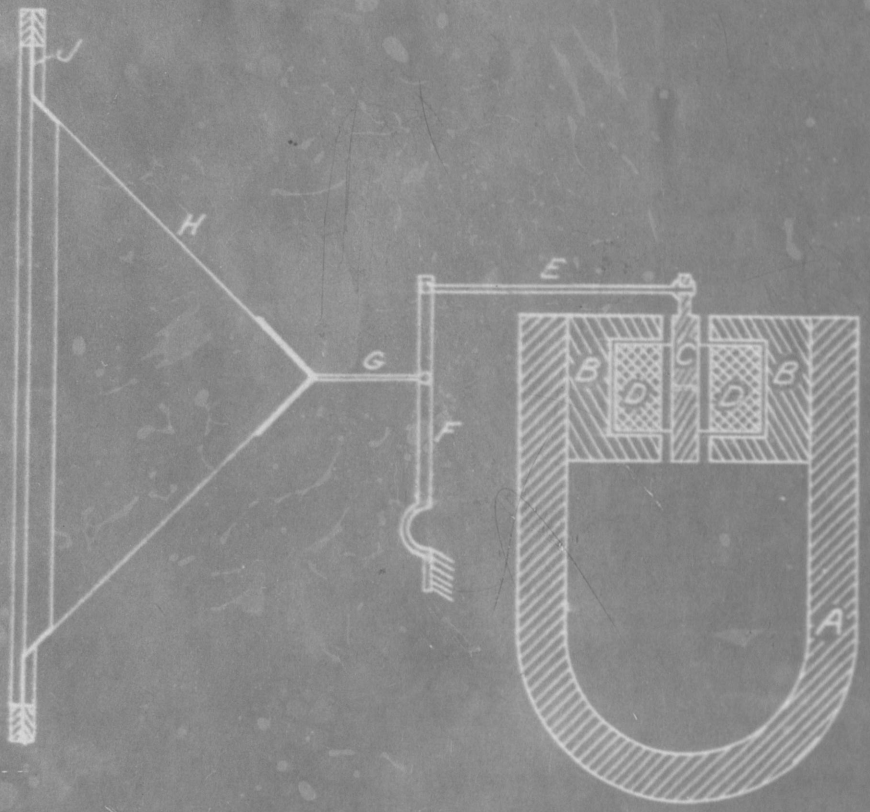

Fig. I. Essential Parts of Loudspeaker.

free from flux beyond the transverse main field at its ends. The presence of a current in the winding will cause, according to its direction, a lengthwise flux through the armature, and a shifting of field at its ends. The field between the armature and a diagonal pair of the projecting ends of the pole pieces will be strengthened, while that at the projecting ends lying on the other diagonal will be weakened. A current through the armature winding, therefore, will produce a torque upon the armature. If the current is alternating, an alternating torque will result. Oscillations of the armature are transmitted from its upper end throgh link E to spring lever F, which bends at its lower end. Link G, which is flexibly attached at an intermediate point on this lever, connects to the apex of cone H. Oscillations of the armature are thus transmitted to the cone from which they may be radiated as sound waves. The base of the cone is supported by a soft leather ring J.which is cemented to the cone and clamped at its outer edge. This system for the reproduction of sound is somewhat compliated. Moving parts consist of the armature, parts of two springs, two connecting links, the cone, and part of the ring of leather at its base. This combination of mass, springs, and radiating surface will have its own periods of resonance, and will cause variations with frequency of the loudspeaker's performance.

LOUDSPEAKER TESTS

It has been previously stated that the loudspeaker test for this report would be based entirely upon measurements of input impedance. During such measurements, applied frequency and voltage may be varied, and the surroundings into which sound is radiated may be changed. Measurements may be made with the armature of the loudspeaker blocked so that none of its parts could move. The opposite extreme to this condition might be obtained by a removal of the sound radiating part and the substitution of an equivalent mass. Doubtless a much better method of obtaining the no-load condition would be operation of the loudspeaker in vacuum. Inasmuch as the medium into which a loudspeaker works is the atmosphere, load tests might be made at different air pressures. Thus a comprehensive series of tests upon a loudspeaker would be of great length. The present report is concerned with the results of but two runs over a range of frequency; one run with the loudspeaker radiating sound from a particular position in the University broadcasting studio, the other with its armature blocked. During all tests the voltage applied to the impedance bridge was maintained at a constant value of 1.4 volts. This was measured with a thermo-couple galvanometer connected through a step-down transformer.

MEASUREMENTS

The impedance of the loudspeaker was found to lie beyond the range of the impedance bridge of the laboratory. Because of the large impedance angles encountered at low frequencies, the inductance rather than the resistance of the bridge proved to be its limiting factor. Its inductance was thought to be approximately one-eighth of the maximum to be offered by the loudspeaker. Accordingly, a transformer to be placed between the bridge and loudspeaker was chosen. Its winding on the side of the bridge had 0.35 of the number of turns of the winding to which the loudspeaker was connected. Thus, neglecting the losses and leakage reactance of the transformer, the actual impedance of the loudspeaker would be obtained by multiplying the measurements by a constant of 8.16, the square of the reciprocal of the above ratio. Inasmuch as the present report is concerned entirely with relative values of impedance at various frequencies, the above constant has not been used. As tests upon the loudspeaker progressed, it was found to have at certain frequencies more inductance than had been anticipated. Rather than change the transformer between the bridge and loudspeaker, the inductance of the bridge was supplemented when necessary with an air-core inductance of 0.108 henry. This was placed several feet from the bridge in a position which would insure freedom from coupling with the windings of the variometer, and was connected with a twisted pair of wires. Whenever this extra inductance was used as a part of the bridge, correction was made for the resistance of its winding.

It was at first planned to make a survey of impedance measurements with the loudspeaker in operation over a considerable range of frequency, in order that regions of the frequency band where exploration would be most fruitful, might be determined. Impedance values when plotted against frequency were expected to form a smooth prominent peak somewhere below the frequency of middle C where a previous frequency-response curve had indicated large output. A second smooth but less prominent peak was expected at double the frequency of the first peak. For the approximate determination if important frequencies and the range of measurements, the calibration chart of the oscillator seemed entirely adequate. On this chart, coil and condenser settings were given at intervals of 20 cycles, for the first several hundred cycles. According to plan, a preliminary frequency run was made, extending from 100 to 500 cycles. The results of this run were discouraging. It was not apparent how a curve could be plotted through them. The reader may be interested at this point in referring to curves 1 of Figs. II and III, in which final curves of resistance and reactance are shown. It is readily apparent that mere points on ordinates separated by 20 cycles would, because of the number of small peaks present, appear quite unintelligible. Adjacent points at 20-cycle intervals could occur near the top and bottom of one of the many small peaks present in the curves.

The conclusion based upon the first test at 20 cycle frequency intervals was that the prominent peak expected lay at approximately

200 cycles, and that the measurements at the higher frequencies were badly in error. The latter seemed substantiated when attempts were made to check some of the higher frequency measurements. Attempts to reproduce the first measurements failed badly. Because of this inability to check measurements, a run was made at two-cycle intervals. This revealed that the free impedance of this loudspeaker, when plotted against frequency, would not produce the smooth prominent peaks which had been expected. Thus, at the outset, considerable time was lost because work was planned on the basis of a premise obtained from reading of such tests on ordinary telephone receivers.* The impedance-frequency characteristic of this loudspeaker consisted, as is evident in Figs. 2 and 3, of prominent peaks of resonance with subsidiary peaks superimposed at nearby higher frequencies. An explanation was now forthcoming for the fact that measurements made at different times with the same oscillator adjustments produced widely different results. A slight shift in the frequency of the oscillator, caused by variation of temperature or operating voltage, might cause the loudspeaker to change from say the crest to the base of one of the numerous peaks found in its characteristic.

The loudspeaker had thus far been placed in the same room as the oscillator and impedance bridge. It had been covered with a layer of material known to have a low coefficient of sound reflection. This, it was thought, placed a definite and reasonable load upon the loudspeaker,

---

* Bibliography 1, 2, and 3.

and reduced the difficulty of the operator of the bridge to distinguish between sounds from the head receivers of the bridge and those from the loudspeaker. It was decided at this point to determine whether the covering over the loudspeaker caused an entirely definite and constant condition of loading. The covering used was in the shape of a horizontal half cylinder having its axis at right angles to that of the cone of the loudspeaker. At the frequency of highest resistance, a slight rotation of the loudspeaker under its cover produced a considerable change in its impedance. To secure more definite results, the loudspeaker was moved to the highly damped broadcasting studio of the University, where it was placed on the sound-treated floor at an oblique position with respect to the walls so that no large surface would reflect back toward it. Its position in the room was noted so that it might be accurately replaced for succeeding tests. In this room, the placing of a board between it and the rug on which it rested would cause an appreciable change in performance. A small object placed in fonrt of the loudspeaker would also change it. Thus, a load test upon a loudspeaker manifestly depends upon and includes the acoustic characteristics of its surroundings. This is a fact which was not sufficiently recognized during the earlier attempts at quantitative tests uon the loudspeaker.

Having thus made preliminary tests upon the loudspeaker, a run was planned from which more useful results might be obtained. It was to cover the frequency band from 100 to 300 cycles. Previous runs had shown at which part of this band impedance was likely to fluctuate most rapidly;

and over this part of the range frequency was changed in steps of one cycle. Moreover, progress in the frequency band was made in one direction, so that gradual changes in the calibration of the oscillator would be spread over the test. Points which were to be adjacent on the plotted curve were, by virtue of sequency of test, made adjacent in time. They would have between them, therefore, the smallest possible change in the calibration of the oscillator. Curves 1 of Figs. II and III are plotted from the results of this test.

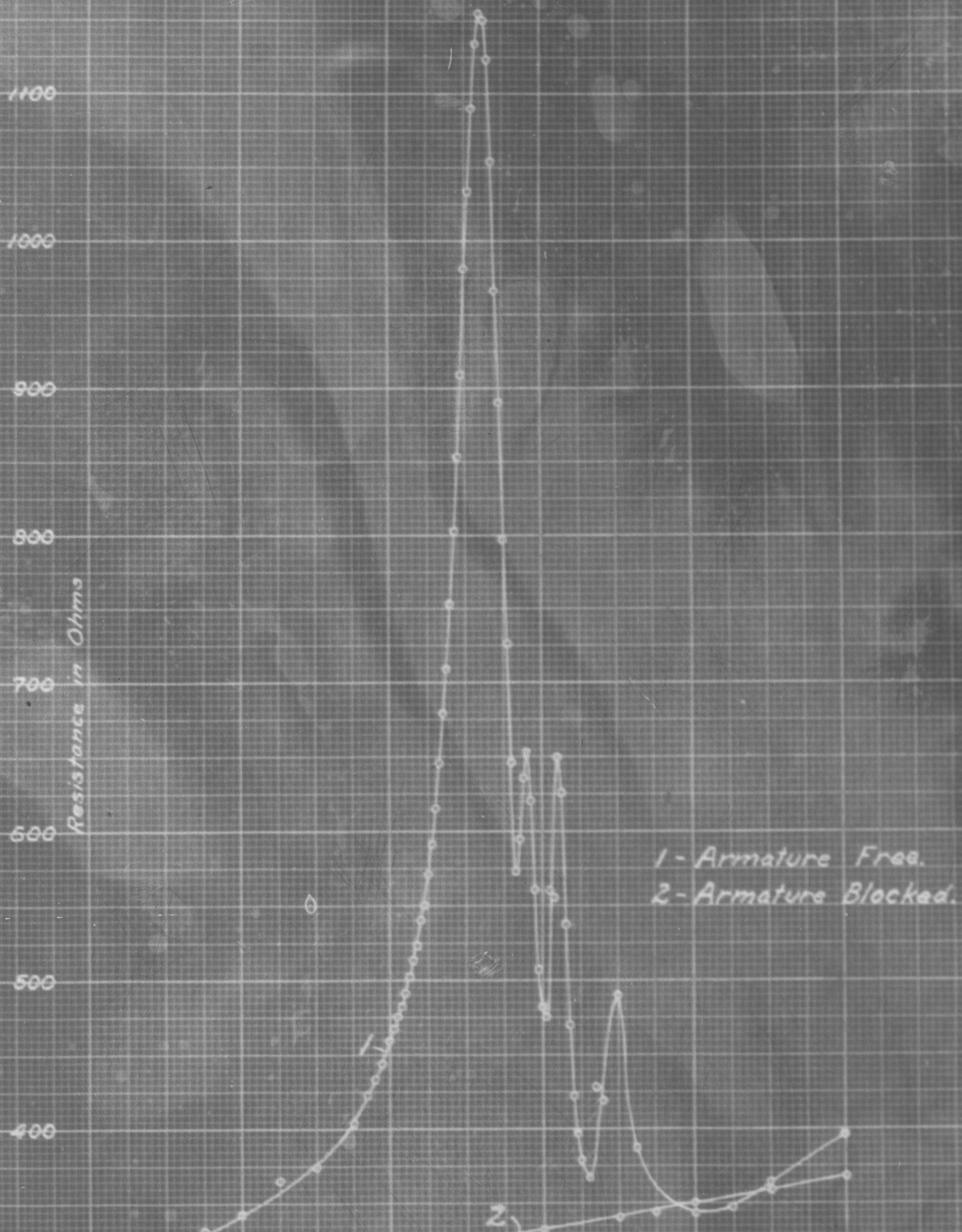

FIG. 2. RESISTANCE CURVES OF LOUDSPEAKER.

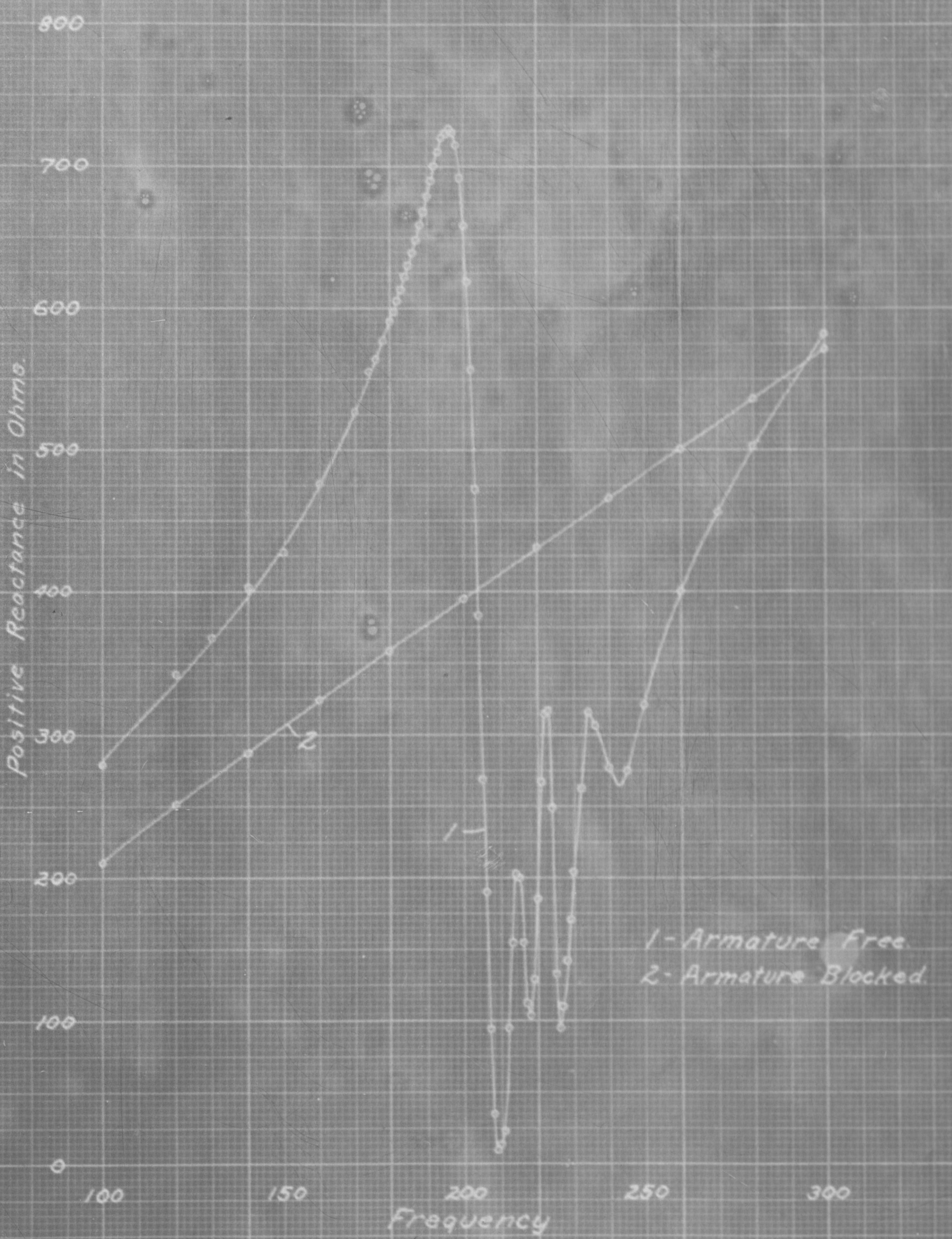

FIG. 3. REACTANCE CURVES OF LOUDSPEAKER.

DISCUSSION OF RESULTS

Results of impedance measurements made upon the loudspeaker with its armature blocked are shown by curves 2 of Figs. II and III. These represent for the various frequencies merely the inherent impedance of the winding on its steel core structure.0 Of this impedance, the resistance represents the power component which consists, in this case of no output, entirely of the losses in the winding and core. When the armature of the loudspeaker has been placed in operating condition, impedance will have been changed as indicated by curves 1. The voltage to produce a particular current in the winding will now be opposed vectorially not only by the inherent impedance drop corresponding to its frequency, but also by the counter electromotive force due to the motion of the loudspeaker armature. The difference between curves 1 and 2 is thus an apparent impedance which is really the manifestation of the loudspeaker's counter electromotive force accompanying the conversion of a part of its input into mechanical power. This difference is designated as motional impedance.* The work of this report is based upon the postulate that the magnitude and phase of this motional impedance are criteria for the determination of the performance of the loudspeaker.

* Bibliography 1.

If for the frequency region above 210 cycles, curves 1 of Figs. II and III were drawn as smooth average curves similar to those in the lower part of the frequency range, it may be observed that a parallel resonant circuit in series with the blocked impedance would simulate the motional impedance. On this basis, the phenomenon of resonance will be discussed. The circuit to simulate motional impedance will consist of two branches, one inductive and the other capacitive, both with losses which will appear as resistance. The current of the inductive branch will lag behind the impressed voltage by an angle whose deviation from 90° depends upon the extent of the loss. The current in the capacitive branch would in the absence of loss lead the voltage by 90°. At low frequencies the current of the inductive branch will be large, but as frequency is increased it will reduce, the variation with frequency being hyperbolic for a pure inductance. At low frequencies the current of the capacitive branch will be small, but for a pure capacity it will increase directly with frequency. At the frequency at which inductive and capacitive currents are equal, resonance will occur. Though the inductance and capacity are each taking normal current, line current will be small because of the equality and phase opposition of its components.

During operation of the loudspeaker, the movement of its armature depends upon the force developed by current in its winding, and upon the forces resulting from its motion. Its movement will, of course, be opposed by the counter forces acting by virtue of power output and losses. Besides these resistive forces, the movement of the loudspeaker armature is influenced by other factors. In the case of the loudspeaker with which the present paper is concerned, the latter factors are for at least certain frequencies far more effective in influencing the motion of the armature than are the former. These latter factors exist by virtue of the mass of the moving parts and the elastic restoring forces of the springs which are bent during movements of the armature.

For analysis of the influence of the mass of the moving parts, movement of the armature which is due to a single frequency of steady voltage will be considered. Let the time interval considered start when the armature is at one extremity of the distance through which it oscillates. At this instant it will be at the point of changing its direction of movement, and will, therefore, be at rest. During the succeeding quarter cycle, the mass will be accelerated, and will have stored within it increasing amounts of kinetic energy. Thus, during this quarter cycle, power will be taken to place the mass in motion. During the next quarter cycle, the mass which has been placed in motion will be decelerated to zero velocity, and its kinetic energy will be entirely spent.

During this constant-frequency oscillation, any displacement of the armature from its midposition will result in bending of springs. At the beginning of the time interval considered in the above analysis, the armature was at one extremity of the distance through which it oscillates. At this instantaneous position, energy storage in the springs will be maximum, and further movement will cause a reduction of this energy. At the end of a quarter cycle this energy will be reduced to zero. During the second quarter cycle, storage in the springs will again occur as the armature is deflected from its midposition in the opposite direction. It may be noted that during the first quarter cycle of the time period, unbending of the spring accompanied acceleration of the mass. During the second quarter cycle, deceleration of the mass accompanied bending of the spring. Thus, these two processes are so related in phase that the discharge of the energy of one may contribute to the charge of the other.

Considering again merely the acceleration and deceleration of the mass, a particular driving force will produce less displacement as its frequency is increased and the time of continuous action in one direction is correspondingly decreased. As indicated by the formula for the distance traveled by a body during acceleration, displacement will vary as the square of time, or inversely as the square of frequency. Since the number of displacements per second are increasing directly with frequency, the net result of an increase of frequency is an inverse reduction in the distance traveled per second, or the velocity of the armature. Consider next the hypothetical cause of a spring structure entirely free from mass and friction. A particular driving force would now produce a definite deflection; and this process would be wholly independent of time. The effect of an increase in frequency would be merely to increase the number of delfections per second. The result, therefore, of a change of frequency would be a direction variation in the distance traveled per second, or the velocity of the armature.

The preceding paragraph concerned the effect of variation of the frequency of an laternating driving force of constant maximum value upon the motion of two hypothetical types of structures. In the case of pure mass, velocity varied inversely as frequency. In the case of a pure spring, velocity varied directly as frequency. Driving force and velocity may be respectively compared to the applied voltage and current of an electric circuit. From the viewpoint of variation of frequency, mass becomes analogous to inductance, and a spring becomes analogous to capacity. In the case of the loudspeaker of this report, an alternating driving force produced by a current in the winding acts upon a mechanism with springs. In an electric circuit where a common voltage is applied to an inductance and capacity, a parallel arrangement must exist. In such a circuit, at some frequency inductive current will equal capacitive current, and the circuit as a whole will appear nonreactive. Similarly, at some frequency the velocity which would be taken by the mass alone is equal to that which would be taken by the spring alone. In has been previously indicated that mass and spring delfections are so related in phase that one receives energy during the discharge of the other. Therefore, at the frequency of equal velocity, a condition of resonance will exist. Energy will be interchanged between the mass and spring, and the driving force will supply merely losses and power for output. Though this condition of mechanical resonance is easily explained by electrical analogy, explanation at other than resonant frequency is more difficult. In the electrical case the inductance and capacity may each take their proper current; but in the mechanical case the mass and spring must have a common velocity. As a first approximation it might seem that this velocity would be the average of the hypothetically separate mass and spring. It has been shown above that the velocity of the mass, as the current of the inductance, would vary inversely with frequency. Likewise, the velocity of the spring, as the current of the capacity, would vary directly with frequency. If these velocities are arbitrarily considered 10 at the resonant frequency of 204 cycles, at 100 cycles their average will be 12.6, and at 300 cycles it will be 11.2. Thus, within this frequency range, average velocity does not vary widely. The first realization of this fact came as a surprise to the writer; and, because of the apparently great deviation from the results of actual tests of telephone receivers, seemed to invalidate completely the analogy just given. However, the difference, between the above conclusions of nearly constant average velocity and the widely-varying velocities of familiar tests, may be attributed to unlike conditions. Discussion of parallel inductance and capacity has been on the basis of constant applied voltage. Though constant voltage may be applied during a test of a loudspeaker such as the one upon which this report is based, the variation in the ratio of its total to motional impedance will result in a large fluctuation in the component of voltage which would exist across the motional impedance. For checking purposes, measurements of the amplitude of vibration of the loudspeaker of this report were made with constant applied voltage of different frequencies. These values were multiplied by their respective frequencies to obtain velocities. To place them on the above basis, they were further multiplied by another factor consisting of the ratio of the total to the motional impedance. These data and the results of the computations are given in table I. It may be observed that with exception of the lowest frequency the modified velocity does not vary widely within the frequency range. This would seem to substantiate the analogy which has been outlined.

TABLE I

AVERAGE VELOCITIES WITH CONSTANT MOTIONAL-IMPEDANCE DROP

Frequency, cycles per second.	Measured deflections in mills.	Avg. velocity in mills per second.	Impedance with armature free.	Motional impedance.	Ratio of preceding impedances.	Corrected avg. velocity mills / sec.
100	2.0	200	407	70	5.8	1160
120	1.7	204	467	95	5.2	885
140	1.6	224	529	125	4.2	950
160	1.9	304	604	167	3.6	1100
180	2.2	396	749	270	2.8	1100
191	2.8	535	909	408	2.2	1190
200	3.4	680	1180	706	1.7	1140
204	3.4	684	1218	830	1.5	1000
210	2.5	525	797	614	1.3	685
220	2.5	550	692	420	1.6	900
227	2.3	522	483	360	1.3	700
234	2.0	468	531	165	3.2	1500
240	1.5	360	562	240	2.4	860
260	.5	130	527	100	5.3	685
300	.3	90	623	27	2.3	2100

APPENDIX

LOCUS OF MOTIONAL IMPEDANCE VECTORS

Motional impedance vectors of a common steel-diaphragm telephone receive for frequencies above and below that of mechanical resonance will, if plotted from a single point, form a circular locus.* For the loudspeaker of this report, the motional impedance vectors of the run represented in Figs. II and III are plotted in Fig.IV. The upper half of this curve, i.e., that part for the frequency range between 100 and 203 cycles, conforms fairly closely to the circular locus which has been obtained in the case of the common telephone receiver. Beyond this, however, the locus leaves the circular arc to form a series of three convolutions. These have been explained by Dr. Kennelly as representing oscillations of coupled mechanical systems.** These secondary oscillations are also indicated by the small superimposed peaks in the high-frequency part of the free resistance and reactance curves of Figs. II and III. The center of the circular arc below 203 cycles lies to the right of the origin and 13° below the horizontal axis. Such a circule, if completed, would have approximate limits on the resistance scale of -20 and 850 ohms, and on the reactance scale of -530 and 340 ohms.

* Bibliography 1.

** Bibliography 4.

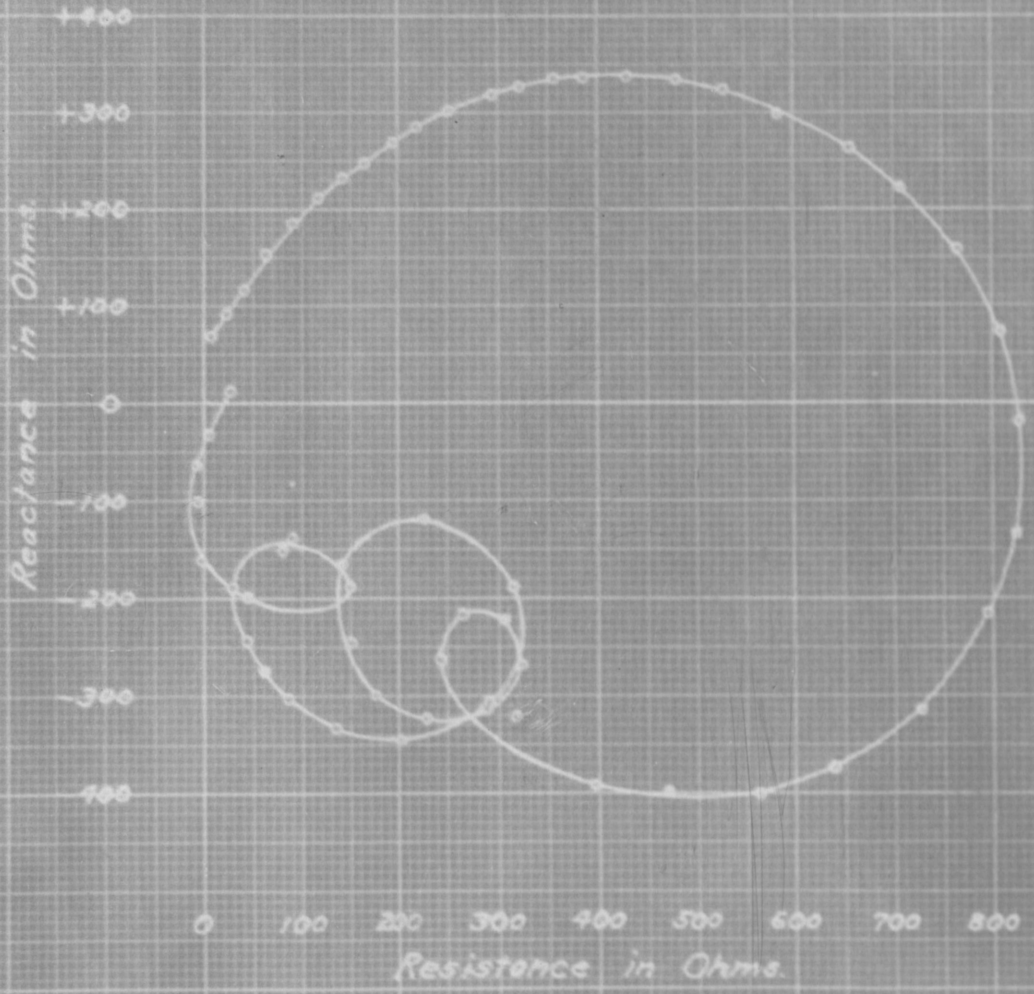

FIG. 4. LOCUS OF MOTIONAL IMPEDANCE VECTORS.

TABLE II

IMPEDANCE DATA

Frequency	Armature free		Armature blocked		Motional impedance	
	R	X	R	X	R	X
100	300	279	292	211	8	68
120	318	342	296	251	22	91
130	331	368	299	268	32	100
140	343	403	302	287	41	116
150	365	427	306	306	59	121
160	374	476	311	324	63	152
170	403	527	313	342	90	185
174	422	555	314	349	108	206
176	433	564	315	353	118	211
178	444	577	316	356	128	221
180	459	591	317	359	142	232
181	467	598	317	362	150	236
182	475	605	317	363	158	242
183	482	613	318	365	164	248
184	491	622	318	367	173	255
185	502	630	319	369	183	261
186	513	639	319	370	194	269
187	523	648	319	372	204	276
188	540	659	320	374	220	285
189	550	668	320	376	230	292
190	571	679	320	378	251	301
191	592	690	321	379	271	311
192	615	700	321	381	294	319
193	645	710	322	383	323	327
194	679	720	322	384	357	336
195	709	723	322	386	387	337
196	753	726	323	388	430	338
197	803	724	323	390	480	334
198	853	715	324	392	529	323
199	909	692	324	393	585	299
200	981	658	324	395	657	263
201	1033	619	325	397	708	222
202	1090	557	325	399	765	158
203	1134	472	325	400	809	72
204	1155	383	326	402	829	-19
205	1150	269	326	404	824	-135
206	1123	190	327	406	796	-216
207	1054	94	327	408	727	-314
208	966	35	327	409	639	-374
209	890	10	328	411	562	-401
210	797	14	328	413	469	-399

TABLE II (concluded)

Frequency	Armature free		Armature blocked		Motional impedance	
	R	X	R	X	R	X
211	726	23	329	415	397	-392
212	646	95	329	417	317	-322
213	573	155	330	418	243	-263
214	594	202	330	420	264	-218
215	636	200	330	422	306	-222
216	653	155	331	424	322	-269
217	620	112	331	425	289	-313
218	561	104	332	427	229	-323
219	507	129	332	429	175	-300
220	648	185	332	431	150	-246
221	475	267	333	432	142	-165
222	560	315	333	434	227	-119
223	555	317	334	436	221	-119
224	649	249	334	438	315	-189
225	625	133	335	440	290	-307
226	537	95	335	441	202	-346
227	470	110	335	443	135	-333
228	422	142	336	445	86	-303
229	397	171	336	446	61	-275
230	379	204	337	448	42	-244
232	367	262	338	452	29	-190
234	428	316	338	455	90	-139
236	419	307	339	459	80	-152
240	490	277	340	466	150	-189
245	387	275	343	475	44	-200
250	344	321	346	483	-2	-162
260	343	400	350	501	-7	-101
270	347	456	355	519	-8	-63
280	364	503	359	536	5	-33
300	396	582	368	571	28	11

BIBLIOGRAPHY

1. A. E. Kennelly and G. W. Pierce, Sept. 14, 1912, "The Impedance of Telephone Receivers as affected by the Motion of Their Diaphragms," Electrical World.

2. A. E. Kennelly and H. A. Affel, Nov. 1915, "The Mechanics of Telephone-Receiver Diaphragms, as Derived from their Motional-Impedance Circles," Proc. Am. Ac. Arts and Sc., No. 8.

3. A. E. Kennelly and H. Nukiyama, March 1919, "Electromagnetic Theory of the Telephone Receiver," Proc. A.I.E.E., pp. 491-539.

4. A. E. Kennelly, 1923, "Electrical Vibration Instruments," Macmillan, New York, Chapter XII.