What's All This About Damping?

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An engineering discussion of the elements entering into the effects of variable damping in an amplifier when the loudspeaker itself cannot be complemented accurately and completely.

IN RECENT MONTHS, much has been written about variable damping, ultimate damping, and various aspects of damping—principally concerning its application to the coupling between an amplifier and a loudspeaker. In an endeavor to clarify the general understanding of this subject, let us consider what damping means in a somewhat broader sense.

Let's start, for example, with damping as applied to musical instruments, where electronics does not enter into the picture at all. When a piano string is struck by the piano hammer, it continues to vibrate for a considerable period, especially if the check action is held off by holding the piano key down. This indicates that the Q of the resonant system is very high. It's true that considerable sound energy is radiated, but in comparison with the energy stored in the vibrating string the radiation is small because this energy is not radiated directly from the piano string.

In illustration of this fact, the writer well remembers listening to a piano which was not provided with the regular sounding board. This piano has been designed for use with electronic pickups, so the quality of sound could be entirely under electronic control. When this piano was played without the amplifier switched on, its music could only be heard by putting the ear close to the instrument. Just sitting in the same room with the piano, one would imagine that the musician was pretending to play it rather than actually depressing the keys. This shows that in the normal type of piano the principal radiation of sound comes from the sounding board, to which it is transmitted from the strings' supports.

Having realized this fact, consider how the vibration of the piano string may be damped. Application of damping to the sounding board has very little effect. It may be possible, applying some damping material to the sounding board, to considerably reduce the radiation of sound, but it will not materially damp the vibration of the string. On the other hand application of the felt provided on the check action of the piano to the string itself, will damp the vibration of the string almost instantly. Touching the string with the finger while it is vibrating will also damp its vibration quite rapidly.

A number of other musical instruments could be similarly discussed. The principal things that we can learn from a consideration of these phenomena are two. First, a large surface is required to radiate sound into the air, because only in this way can satisfactory acoustic matching between the vibrating medium and the air load be achieved; a small vibrating element such as a string does not move the air, it rather cuts through it. Second to produce satisfactory damping, the damping agent must be applied at a suitable point sufficiently close to the vibrating medium itself. Although the vibrating medium is coupled to some extent to the sounding board, damping of the sounding board can only damp the movement of the string to the same extent as it is coupled to it. Because the coupling is what we would term in radio very loose, the damping that can be effected in this manner is extremely small.

Before turning to the discussion of loudspeakers and their damping, let us consider briefly two other analogies that will prove useful in helping to visualize the various components that make up our problem.

The first is a transmission line. A transmission line has a characteristic impedance. If the line is terminated by its correct matching impedance all the transmitted energy is absorbed when it reaches the receiving end, but if the line is not correctly matched some of the energy is reflected and travels back along the line. Correct matching of the transmission line can be considered as correct damping, because it will prevent reflections from occuring.

The other analogy that we can consider is a transformer. The particular properties with which we are concerned are the primary inductance and the leakage inductances of the transformer, together with the secondary winding capacitance. For simplicity we will consider the transformer to be of 1:1 ratio. *Figure* 1 shows the equivalent circuit of a transformer, with the elements in which we are interested shown. The transformer can be a resonant circuit in several ways. The primary inductance can resonate with some capacitance in the primary circuit; similarly the same relative inductance can be resonated in the secondary; or the combined inductance can be resonated with capacitance part of which is in the primary and part in the secondary. All of these resonances are of the same basic type in which the inductance element being resonated is the primary inductance, but it is also possible to resonate the leakage inductance between primary and secondary with a capacitance either in the primary or secondary.

Consider the particular case of leakage inductance resonating with capacitance in the secondary circuit. Although the capacitance is physically connected in parallel with the transformer secondary winding its effect is very different from a similar capacitance connected in parallel with the primary winding. Short circuiting of the primary will result in maximum Q of the tuned circuit, because any resistance in series with the primary appears virtually as resistance in series with the tuned circuit. This is illustrated in *Fig.* 2. This kind of resonant circuit can be damped with either a resistance in shunt with the secondary winding, which provides shunt damping for the tuned circuit, or a resistance in series with the primary winding which provides series damping for the resonant circuit.

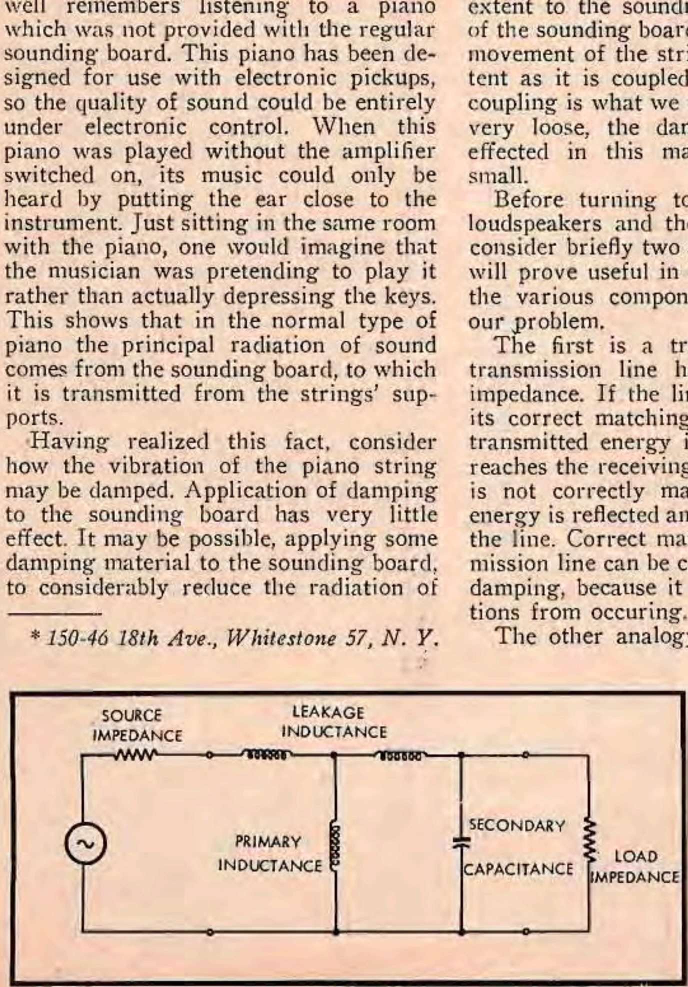

Fig. 1. Equivalent circuit of a transformer, to show possible resonances. For convenience the transformer is assumed to have 1:1 ratio.

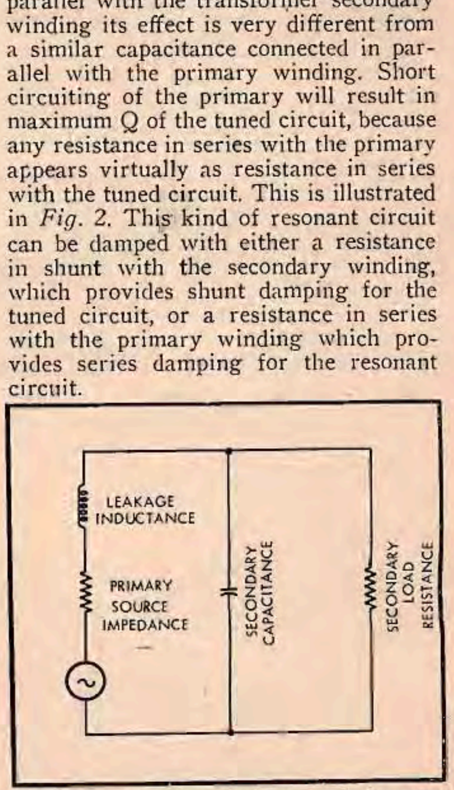

Fig. 2. Rearranged equivalent circuit for resonance between leakage inductance and secondary capacitance.

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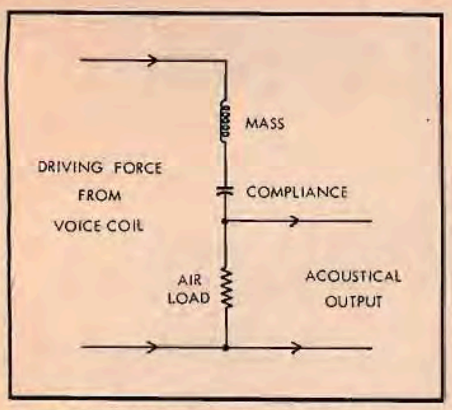

Fig. 3. Simplified equivalent circuit of acoustical action of a loudspeaker.

In this respect a transformer can be considered as somewhat similar to a quarter wavelength of transmission line, when the transmission line to which we referred previously is incorrectly terminated. If the termination value is too high, at a distance back along the line equivalent to a quarter wavelength of the frequency being transmitted the reflected impedance becomes the inverse of the terminating impedance, using the characteristic impedance as a mean.

Back along the line at consecutive quarter wavelength intervals, the impedance will change alternately between one that is high and one that is low compared with the characteristic impedance. Similarly, if the termination instead of being incorrect in resistive value is incorrect by being a reactance instead of a resistance, the apparent impedance measured at quarter-wavelength intervals back along the line will alternate between inductive and capacitive reactance.

If the line is loss-free, which corresponds with high Q conditions in a mechanical arrangement, then this transfer of impedance will go on indefinitely at quarter-wavelength intervals, without changing the relative magnitude of impedance at each half-wavelength interval. But practical lines introduce a certain amount of electrical loss, and for this reason each alternation away from the characteristic impedance of the line deviates by a decreasing amount from this value, and after a sufficiently long length of line, the measured impedance will become sensibly equal to the characteristic impedance. However, in such a line the loss becomes considerable and a relatively small amount of the transmitted energy will reach the receiving end.

The Loudspeaker

Having briefly discussed some of the analogies we can apply, now let's turn to the consideration of a loudspeaker. Basically, what we are concerned with in a loudspeaker is driving a column of air which communicates with the room so as to recreate a desired sound field.

Let us first consider the acoustical arrangement that achieves this. It consists of a loudspeaker diaphragm in contact with the air in front of it (which communicates with the room) and also with the air behind it which is contained in the loudspeaker enclosure.

This can constitute a resonant system which can be analyzed by using the same mechanical terms for the elements of a resonant system as would be applicable to a vibrating piano string. The mass of this resonant system consists of the mass of the moving diaphragm and the voice coil attached to it, together with the mass of the small quantity of air adjacent to it, which can be regarded as having to move with it. The compliance consists of the compliance of the diaphragm surround and also the compliance of the centering spider, if one is used, together with the compliance of the air inside the enclosure behind the diaphragm. This latter will act basically as a compliance rather like the air inside a Helmholtz resonator. These are the reactive elements of the resonant system. The resistance elements provide damping and prevent it from having a natural vibration of its own in a well designed system. These are the viscosity of the air in the enclosure, the viscosity in the compliance of the surround and centering spider, and the radiation resistance coupled to the diaphragm by means of the air load which it drives to radiate energy into the room.

So far we have just considered an acoustical resonant system. Now we come back a stage further, to consider a mechanical-acoustical relationship. This rather corresponds—but in different proportions—with relationship between the vibrating piano string and the sounding board. The piano string is the basic driving force, but the sounding board is the element that radiates sound energy into the air. Similarly in a loudspeaker, the voice coil is the basic driving force but the diaphragm is the element that radiates the sound into the air. So the coupling between the voice coil and the diaphragm has to be considered as part of a loudspeaker system.

In the preceding discussion we considered the voice coil as if it were rigidly coupled with the diaphragm, but this idea ignores the fact that the diaphragm has to be constructed of some material which cannot be absolutely rigid. The diaphragm material itself has mass and compliance distributed over its entire surface area, and hence all parts of the diaphragm do not have to vibrate in an exactly similar manner.

This means that the diaphragm can behave somewhat after the fashion of a transmission line. A driving force is applied at the voice coil end of the diaphragm and is transmitted outwards toward the periphery where the surround is located. It's true that at the lower frequencies the time taken for the wave to be transmitted this distance corresponds with a small fraction of a wave period. But at higher frequencies an appreciable fraction of a wavelength is involved and various cancellation effects can arise which interfere with the frequency response of the loudspeaker.

For this reason a loudspeaker of good design has the surround viscously damped, either by choice of suitable configuration for the surround, or by application of some impregnation which will have the desired effect. This will prevent such cancellation effects due to transmission of sound waves to and fro radially in the diaphragm itself before they get transmitted to the air in contact with it.

There is another fashion in which the diaphragm can set up resonances of its own—by setting up local vibration patterns similar to Chladni figures in a vibrating plate. At higher frequencies the coupling of the air load to the diaphragm improves, and for this reason it is easier for the diaphragm to vibrate in a complex manner than to follow the driving force as a single element. In this case the diaphragm does not have to move as much air, because parts of it will be traveling inwards while the other parts are traveling outwards; this enables the air to oscillate sideways across the surface of the diaphragm instead of having to drive in and out as a single large mass.

These break-up resonances again depend upon the characteristic mass and compliance of the material of which the diaphragm is made. They can, however, be minimized by attention to the construction of the diaphragm, by the introduction of circular reinforcing indentations into the material, and by other means. However, as regards our damping feature, the important thing to notice is this: these resonances occur in the diaphragm material itself and cannot logically be damped out either by acoustical damping in the enclosure or by some form of damping in the voice-coil circuit, because they take place between the driving force provided by the voice coil and the loading force provided by the air. Nothing beyond these limits can affect the behavior of the break-ups.

Resonances

We have now considered the behavior of a loudspeaker, from the air column that it has to drive into the room back to the voice coil, which so far we have considered merely as a driving force. The basic resonance at this point consists of the mass of the diaphragm with all its appurtenances and some of the air which moves with it, together with the compliance of the surround and of the air in the enclosure, acting as a single resonant arrangement.

The natural frequency of this resonance is usually somewhere between 35 and 125 cps, varying according to the particular design of loudspeaker and the size and type of enclosure used. This is the resonance about which designers are concerned when they talk about damping applied in amplifiers. It should be noted that this is not necessarily the only resonance in a loudspeaker, but it is the principal one.

We now come to the point where the transformer analogy is useful. The voice coil and the loudspeaker magnet system constitute an electro-mechanical coupling unit, the purpose of which is to transfer electrical energy from the amplifier into energy in the voice coil.

This part of a loudspeaker is essentially similar in basic principles to an fibers connecting to the brain (*Fig.* 3).

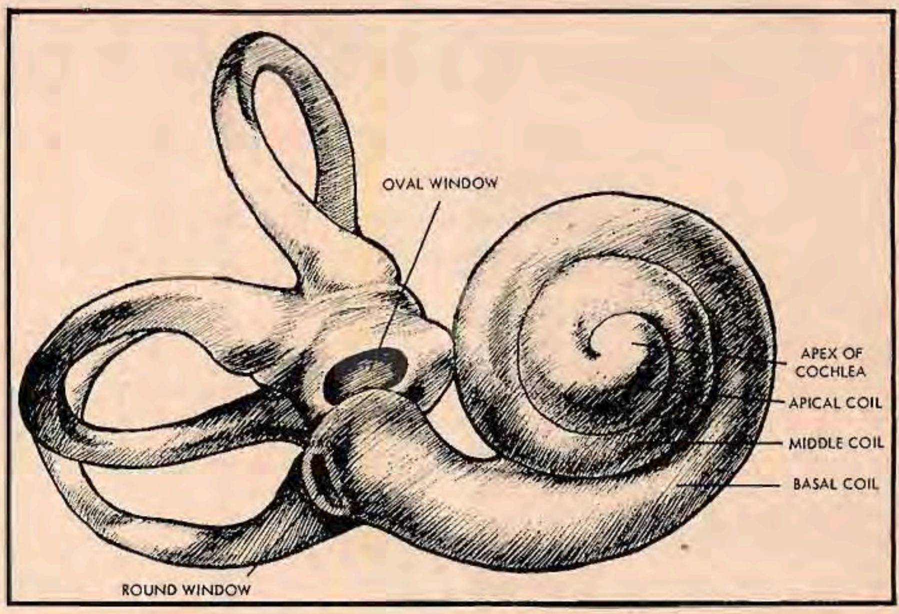

Fig. 2. A front view of the bony labyrinth.

Recent Work

Fortified by this background of research, Helmholtz in 1857 presented for the first time his theory on resonance hearing. As Professor of Physiology at the University of Bonn, he was presenting lectures on the scientific foundations of music. From these lectures, during a period of six years, he built up the foundation of his world-famous theory as expressed in his work "Sensations of Tone" ("Die Lehre von den Tonempfindungen"). Very briefly, Helmholtz's theory was as follows: he conceived a series of progressively tuned resonators in the ear, with the high pitched tones at the apex. This action was compared to the action of piano strings with the dampers raised, singing a note into the opened frame will cause strings to vibrate in accordance with the frequencies contained within the sound emitted. In his conception of the resonance theory Helmholtz felt that the pillars of Corti were the resonators of the hearing system, serving as the intermediate agents between the auditory nerve endings and the resonant fibers of the basilar membrane. A basic concept herein contained is that the frequency discriminability of the ear is directly concerned with the number of active elements (resonators).

Received at first with great enthusiasm, Helmholtz's theory has fallen in favor through the years and now must contend with several alternative theories for consideration. The most radical departure in theory stems from consideration of pitch perception and discrimination in a manner differing from that of Helmholtz whose method, classified as the Place Theory, demands a spatial distribution of response in the cochlea, i.e., for every tone in a sound, there is a particular location and of course, a particular group of nerve fibers. Contrasted to this theory is that of the Frequency Theory which states that the auditory nerve receives a signal from *all* hair cells and transmits the signal in the form of electrical signals to the brain. An early exponent of this theory was Rutherford who first presented his ideas in 1886. His name and theory still claim the attention of investigators.

Frequency Theory

Outstanding in the Frequency Theory grouping are the theories advanced by Meyer (1898) and Wrightson (1876). It is not possible to present either theory fully because of space limitations, consequently only a brief synopsis follows:

In preparing the foundations for his theory, Meyer points out that exponents of the "Place Theories" admit[1] . . . "that any 'tuning' by resonance or otherwise could only be very 'broad' so that the ear for discrimination must have a neural ability to tell *which* of *many* cochlea points responding to the same frequency responds with greater amplitude than any other. Wever has calculated[2] that, without a further hypothesis covering this matter, ". . . in the middle pitch-region two frequencies heard in succession should then be just discriminable if the interval is a quarter of an octave. All music would be impossible . . ." Wever concisely describes[3] Meyer's theory as follows: ". . . When the stapes moves inward and exerts a positive pressure on the cochlear fluid, the response of the basilar membrane is at first restricted to its most basal portion. This part of the membrane is bulged downward, and the bulging continues until the limit of free motion is reached, and then it begins to spread to the more remote portions. The bulge extends in the apical direction only as far as necessary to give room to the fluid displaced by the stapes.

"When the stapes reaches its most inward position and starts backward it causes a second displacement of fluid, but in a direction contrary to the first. Consequently, the membrane is drawn upward. This reversed motion of the membrane, like the other, begins at the basal end of the cochlea and spreads toward the apex. If the backward movement of the stapes has the same amplitude and velocity as the preceding forward movement, this second movement of the membrane extends the same distance as the first and exactly erases the original bulge; the membrane then is in its initial position. If the reverse stapedial movement is somewhat less in amplitude, the second displacement of the membrane will erase the first only in the basal region and the most apical part of the original bulge will remain undisturbed.

"The distance of spread of a displacement depends not only on the amplitude of the stapedial movement but also, to a degree, on its velocity . . . .

"Excitation of the hair cells probably ocurs on the upward phase of every up-and-down cycle displacement . . .

"The loudness of the sound is determined by the extent of the spreading

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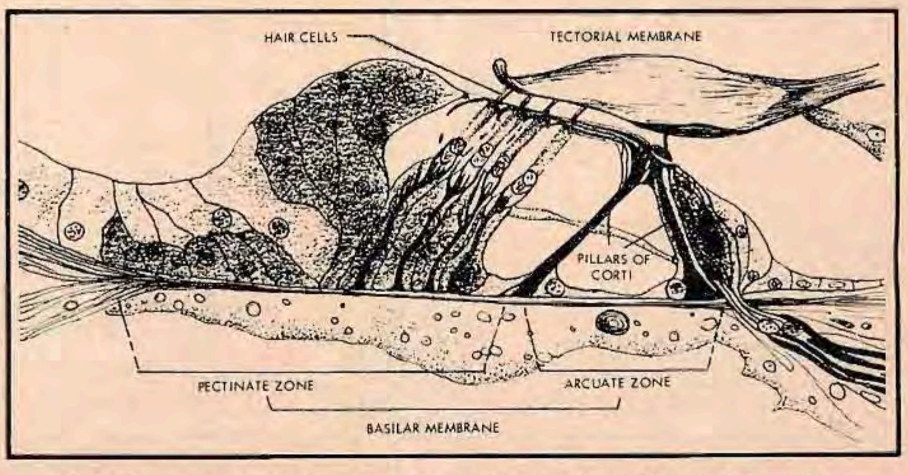

Fig. 3. Cross-sectional view through the Organ of Corti at the middle coil of the cochlea.

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[1] Meyer, The hydraulic theory of the cochlea and comparative anatomy. *Am. J. Psychol.*—April 1952—65—No. 2, p. 289.

[2] Wever, Status of auditory theory. *J. Acous. Soc. Am.*—May 1951—23—No. 3, p. 288.

[3] Wever, Theory of Hearing. Wiley, 1949—pp. 83–84. Permission to quote gratefully acknowledged.

HOW DO WE HEAR?

(from page 21)

over the membrane and hence the number of hair cells involved.

"The analysis of a compound wave follows the principles already laid down. However complex the form of the stapedial movement, a bulge always starts at the basal end of the cochlea and continues to be extended until there is a change in the direction of the stapedial movement. The number of bulges formed, therefore, corresponds to the number of maximum and minimum points in the compound wave; and the length of each bulge depends upon the amplitude as measured from one of these points to the next. Since the amplitudes between successive maximum and minimum points always vary in a compound wave, the different bulges will spread for different distances."

This description is clearly illustrated in *Fig*. 4 wherein is presented an initial displacement (position 1) of the first 30 units of the basilar membrane, as induced by the sound pressure amplitude at time *a*. The change in pressure as evidenced by the progress of the amplitude curve from time *a* to time *b* causes the formation of a bulge on the membrane which progresses a distance of 30 units of length, effectively erasing the initial bulge and resulting in a final membrane displacement to the right as shown in position 2. Further changes in the amplitude of the sound pressure wave as given at times *c* through *g* will cause corresponding displacements of the basilar membrane as shown in positions 3 through 7 respectively. The lengths of the membrane will be affected in accordance with the differential amplitudes of the sound pressure wave at the times of observation.

Meyer's theory is unique and his manner of presentation is abrupt, consequently it has not been too well received by the scientific world. This does not alter the fact, however, that it has merit which is recognized, for according to Wever, "Meyer's theory has had far less consideration than it deserves. It is a difficult theory; difficult in conception and perhaps more so in its presentation; and herein may lie part of the reason for its continued neglect."

Wrightson believed that the cochlear fluid was incompressible, consequently any movement of the stapes would set up a pressure wave which was instantly communicated to all parts of the cochlea. Since no time was lost in this transmission process, there could be no space effect, i.e., *all* nerve fibers were stimulated by sounds. Stimulation of the nerve fibers, occurring with every flexing of a hair cell, was said to occur four times for every full cycle of flexing motion of the basilar membrane; triggering of the nerve fibers occurs for every maximum, minimum, and axis-crossing point of the wave. Wrightson's thoughts on loudness of a sound were contained in his belief

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that the nerve fibers were affected more violently as sound intensity increased above near-threshold values. This belief has been subjected to a great deal of criticism in later days because of the "all-or-nothing" principle of nerve fiber firing which was developed.

Somewhere in this accumulation of knowledge an answer lies waiting to be born. From the laboratories and the experiments involving thresholds of hearing, pitch discrimination, spatial discrimination, cochlear microphonics, effects of various compounds upon the nerve electrical potentials, etc., will proceed one day the final link which will unite these findings into the truth sought over many long centuries. Until then, the reader may form opinions of his own, guided by the works of leading scientists partially summarized in the texts contained in the short bibliography below.

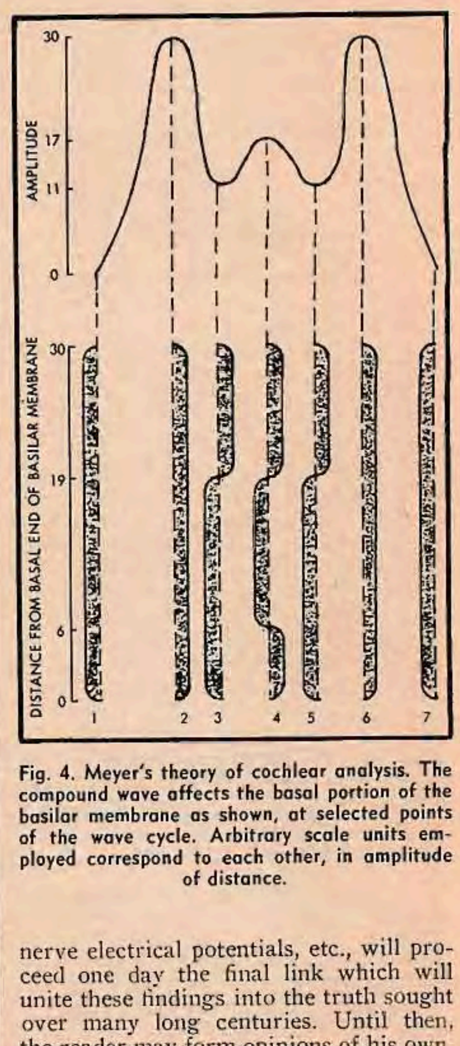

Fig. 4. Meyer's theory of cochlear analysis. The compound wave affects the basal portion of the basilar membrane as shown, at selected points of the wave cycle. Arbitrary scale units employed correspond to each other, in amplitude of distance.

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