VIBRATION DAMPING

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This paper has been written as a chapter to be included in a book designed to describe practical methods of reducing machine noise. Since little has been published on the subject of vibration damping materials and since such materials are useful in some cases in reducing machine noise, this chapter has been prepared for distribution before the completion of other chapters of the book. It is hoped that it will be useful to those who are called upon to design machines for naval vessels or to those who have the problem of reducing the noise radiated from a machine already built.

It is, of course, understood that this chapter covers only one small phase of the general subject and that the use of vibration damping materials, although of great value under certain conditions, is by no means a cure-all for all noise problems.

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VIBRATION DAMPING

Since the vibration of any solid body results, in general, in the radiation of sound, any means of reducing the amplitude of the vibration will result in a decrease in noise. This chapter is concerned with those materials and structures which are capable of reducing vibration in solids. They function because part of the energy associated with the vibration is converted into heat energy and thereby becomes impotent in producing sound. The use of vibration damping materials is not a cure-all, applicable to all noise problems, but is limited to the cases (1) where resonance exists between one of the noise components generated by the machine under study and a natural frequency of a part of the machine, its housing, or some neighboring surface; or (2) where a surface is subjected to transient impulses, such as impact or shock forces.

Damping structures and materials are also occasionally used where the presence of noise is not objectionable but where conditions are such that vibrations may be built up of such excessive amplitude that danger of mechanical failure is incurred.

The use of a suitable damping material may sometimes permit changes in design which result in a distinct savings in weight or cost, for light weight sheet metal parts can often be substituted for castings. In many machines such a substitution without the addition of a damping material would result in an appreciable increase in noise because of the possibility of exciting resonances in the sheet metal part; such resonant conditions not being prominent when a casting is used because of its greater mass and because of the inherent damping of the casting itself. A similar application is the use of damping materials in the construction of light weight metal furniture; a comparatively low cost damping treatment will remove the objectionable "tinny" sound often associated with such furniture. For example, a pressed steel bath tub was made with satisfactory appearance and cost, but its sale was limited because the user got the impression of cheap, flimsy construction due to the noise made by water flowing into it or the user moving in it. The application of a damping treatment gave the user the feeling of solidity associated with a cast iron construction.

Metals and alloys have varying degrees of inherent damping, but such damping is small in comparison with that which can be obtained with a material made solely for its damping properties. It is generally of advantage to design a part to use the material most suitable for the mechanical requirements, without considering the factor of vibration. The damping material can be added afterwards thus avoiding any necessity of compromising the other mechanical requirements. Lead is usually considered as having high inherent damping, but, pound for pound, some of the materials made solely for damping purposes are far better.

Dynamic Vibration Absorbers

From the preceding paragraph it is evident that this chapter is concerned with materials or structures which exhibit the property of mechanical hysteresis. Such materials resist motion in any direction, not acting like a pure mass which, when a force is applied, acquires a velocity and corresponding kinetic energy, or again, like a spring which stores energy when it is deflected by a force and is ready to return this energy on the return stroke.

Unfortunately there is some confusion in the terminology of damping devices. Some so-called vibration dampers exist which do not depend for their operation upon the conversion of vibratory energy to heat energy but depend upon the generation in themselves of a vibratory force which is 180° out of phase with the applied force. Essentially such devices consist of a spring supporting a mass, hence such a device has a definite natural frequency. When applied to a vibrating body, it is only effective in decreasing vibrations of that particular frequency to which it is tuned because, at this single frequency, a vibration of very large amplitude is produced in it. The phase of this vibration is such that it opposes the vibration in the body to which it is attached. The device is useful in the case of constant speed machines but is not applicable to variable speed machines, not only because it is effective at only one speed but also because it actually increases vibration at two other speeds, thereby becoming worse than useless at those speeds. An excellent treatment of tuned absorbers can be found in "Mechanical Vibrations" by J. P. Den Hartog (McGraw-Hill Book Co.)

Conditions Under Which Damping is of Benefit

The presence of resonances in the parts of a rotating machine can be detected by slowly increasing the speed of the machine from a speed below its operating range to a speed somewhat greater than its operating range. If a pronounced resonance occurs at one or more distinct speeds, the condition may perhaps be recognized by a definite increase in loudness at the critical speed or speeds. When the resonances are so prominent that they can be located in this manner, the amplitude of the resonating part will usually be so large that it can be located easily.

More often, the presence of resonating conditions is not so easily determined, but is made evident only by the change in the character of sound as the speed is gradually increased. Due to a resonance, a tone previously not heard will become audible, increase to a maximum, then will decrease in loudness. When either of these conditions exists, the usefulness of a vibration damping treatment is indicated.

If the machine noise does not change in character as the speed is increased, but merely becomes louder, with the various noise components gradually increasing in pitch proportionately with speed, it is doubtful that a damping treatment will be of benefit.

A damping treatment may also be of benefit in the case of shock excitation or impact noises. When thus excited a panel will vibrate at its natural frequencies. Since, in general, there is no musical relationship between these natural frequencies, the resulting sound will be non-musical. If the panel thus excited is well damped or "dead" a blow will result in a dull thud, but if undamped the resulting sound can be described as "tinny". For this reason a damping treatment is sometimes used on metal furniture and fixtures even though the only time the article can be a source of noise is when it is struck or moved.

As is implied above, the most common use of vibration damping materials is for the treatment of sheet metal structures. Indeed, a large percentage of damping materials sold commercially is used by the automobile industry for the treatment of the various surfaces of automobile bodies. The introduction of the metal tops on cars was delayed somewhat by the lack of a suitable damping treatment. A damping treatment is of value in the case of automobiles for several reasons:

1. Elimination of the effects of resonance between vibrations generated in the engine and the various parts of the body. Since

each metal panel of the car body has many natural frequencies and since the engine is a source of vibrations of many frequencies, there is no speed but where some body panel is resonating with some engine vibration.

2. The body is subjected to shock excitation due to passage of the car over a rough road surface, or by pebbles and gravel thrown by the wheels. Rain on the roof of the car would be the source of highly objectionable noise were it not for the damping treatment on the roof. Even the knuckles of a salesman of a competing car can induce unwanted noise when knocked against the door panels. This well known knuckle test is supposed to distinguish between solid and flimsy construction, but it is usually not pointed out that a heavy gauge door, if untreated, will sound "tinnier" than a lighter gauge door.

Area Coverage

The application of a damping device such as an oil dashpot to a single point on a vibrating panel is not of benefit even though the device is in itself a very effective damper. This statment holds true even though the device is applied at the anti-node[1] of the mode of vibration giving the loudest noise component. When applied to the panel the device will so alter the original vibration pattern that the point of application will become a node, thereby resulting in a very small amplitude of vibration of the device and consequently in ineffective damping.

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[1] An anti-node of a vibrating surface is a point of maximum amplitude of vibration. The nodal line is the locus of points where the amplitude of vibration is zero. The vibrations on opposite sides of a nodal line are 180° out of phase. These remarks obviously refer to the case where the surface is excited at only one frequency.

Although complete coverage of a vibrating panel does not lead to the most economical use of a given amount of damping material, it does insure good damping at any frequency. The most economical treatment is obviously obtained by covering comparatively small areas at the anti-nodes. As an example of the use of anti-nodal treatment, a description of a study made on an automobile door may be of interest.

The door under test was excited by means of a small electromagnet connected to an audio-frequency oscillator. A non-polarized electromagnet was used, without direct current superimposed on the alternating exciting current, because, by this means, the frequency of the vibromotive force exerted on the panel is double the frequency of the exciting current. In this way, the effect of any stray magnetic coupling between the magnet and the microphone used for picking up the sound radiated by the door under test can be eliminated by using a wave-analyzer, tuned to double the oscillator frequency, in the microphone amplifier.

As the frequency of the oscillator was gradually swept over the audible range of frequencies, the natural frequencies were easily detected and measured. Since any mode of vibration of the door having a node at the point of application of the exciting magnet would not be expected to be excited, the procedure was repeated with several positions of the magnet. It was later found that the position of the magnet had surprisingly little influence on the vibration pattern under resonating conditions; only a slight distortion of the nodal lines occurred at the point of application of the exciter.

The results of the procedure outlined above are shown in Figure 1. In this figure each vertical line represents a natural frequency of vibration of the door; the height of the line represents the loudness[1] of the sound radiated and the position along the horizontal axis represents the frequency. The vibration

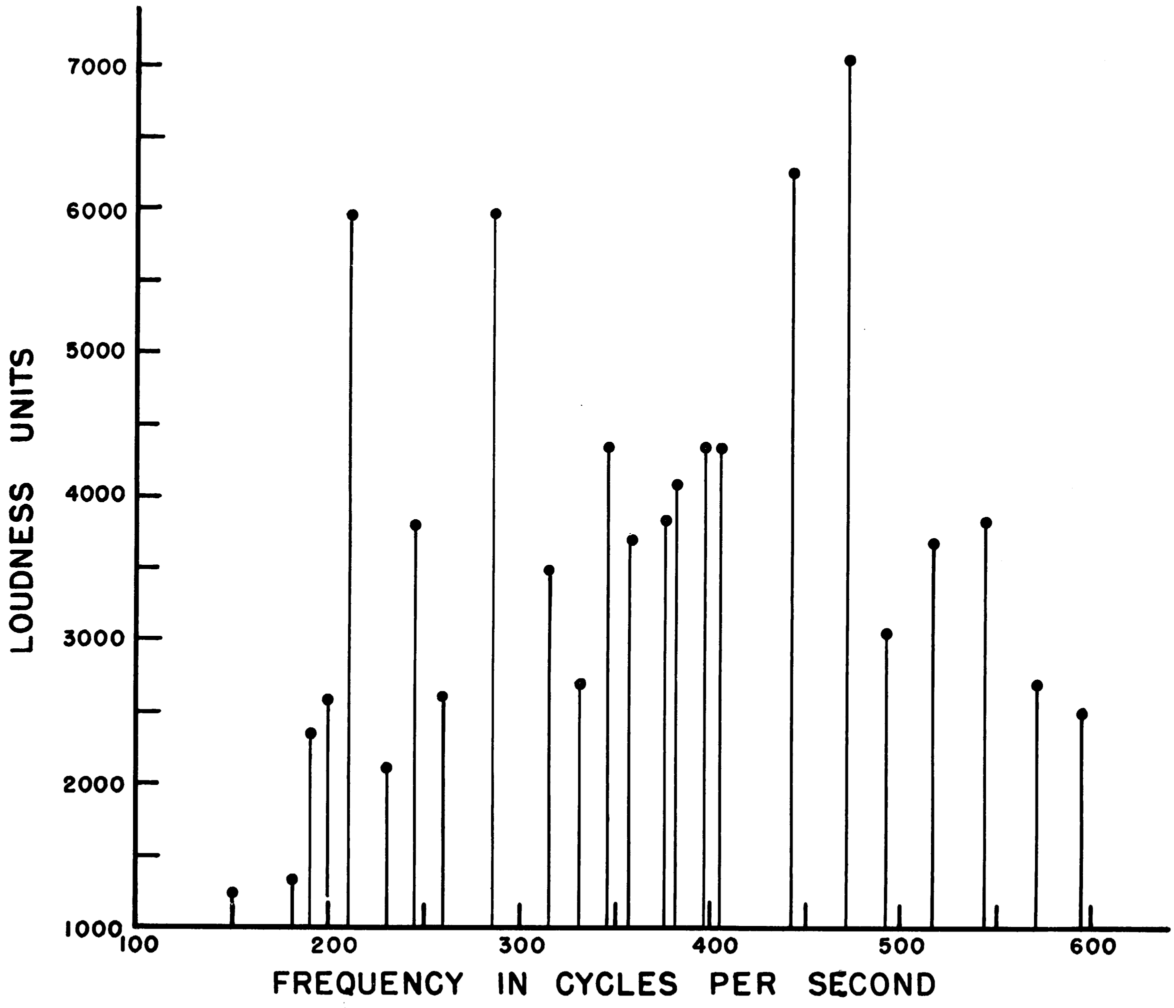

Figure 1 Natural Frequencies of an Automobile Door Panel.

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[1] The actual measurements were made in a reverberation room with a large rotating sound reflector on which was mounted the microphone. By this means it was possible to avoid the effects of standing wave patterns which would have made the results of the measurements of doubtful value if no means of averaging was adopted. The sound levels measured were actually low, to avoid magnetic saturation in the exciter, so each reading was increased by an equal amount so that the corrected values would correspond to the amplitudes which might actually occur in a car on the road. The values thus corrected were then converted to loudness values, see pages 5 and 6 of report "Technique and Interpretation of Noise Analyses" dated 3 January 1949, ONR Project No. NR 261 020.

pattern of the panel when excited at 472 cps, the loudest component shown on Figure 1, was then determined by the use of a "nodagraph", an instrument which was designed for this purpose and which will be described below. A small area of a vibration damping felt was cemented to the back of the door at the point of maximum amplitude as determined by this procedure. Measurements showed that vibrations of this frequency were damped satisfactorily by this small area of felt. The procedure was again followed and the most prominent remaining frequency damped by a second piece of felt. After the process was repeated a total of five times, the experiment was about to be given up in discouragement because the door still sounded "tinny" even though the nature of the sound was markedly different from what it was originally.

However, on looking over the accumulated data, it was found that each successive "loudest"frequency came at a lower frequency than the previous one. Each patch of material was effective not only for the mode of vibration which it was planned to suppress but also was fairly effective for all higher frequencies. In other words, the high frequencies were much easier to damp out than the lower frequencies. With this in mind a new procedure was adopted. Instead of applying the felt to damp out the loudest frequency for each step in the procedure, it was applied at the area of maximum amplitude of vibration of the lowest natural frequency. This procedure was followed on doors of several sizes and shapes. Each door could be made satisfactorily "dead" by covering three areas, each of about 0.3 to 0.4 square foot. One door gave satisfactory results with only two areas covered. A surprising feature was that, with the proper spots treated, the sound had substantially the same character regardless of where the door was struck, whereas with a uniform damping treatment covering the entire door, an appreciable difference in the quality of the sound is noticeable as the panel is struck at different points, even though satisfactorily damped for all points. To study this effect, lines were laid out on the door dividing it into six-inch squares and the door struck a measured blow at the corner of each square by a pendulum consisting of a golf ball mounted on a steel rod. The resulting sound was measured on a "tinniness" meter[1], an instrument to measure that quality of sound which most individuals designate as "tinniness". It was found that the maximum variation in the readings thus obtained on a spot treated door was only about 25 per cent of the maximum variation obtained on a door with a damping treatment applied completely over its inner surface.

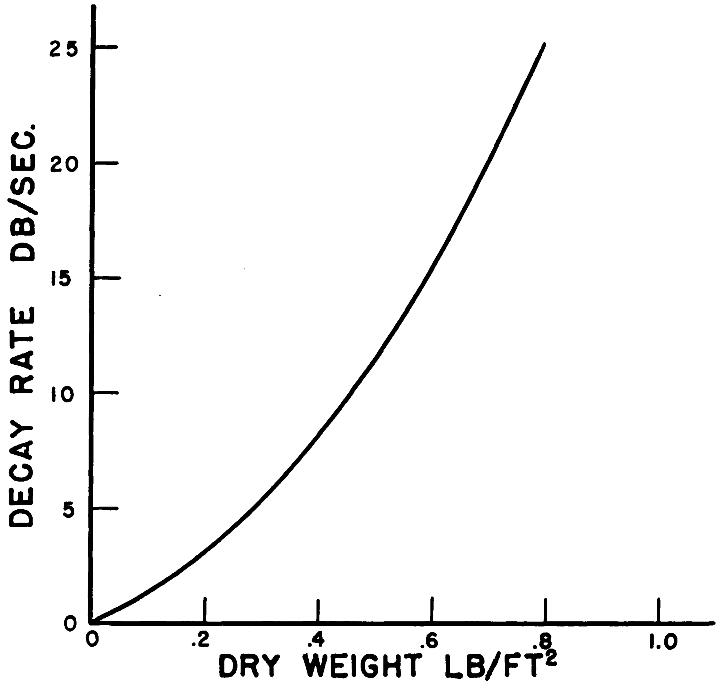

Figure 2 Effectivness of a Mastic Deadener as a Function of its Weight.

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[1] An ordinary sound level meter can be converted to a "tinniness" meter by merely reducing the plate voltage on the power output stage and using a slow-acting output meter (about one second period, critically damped). The plate voltage should be reduced to a value such that the tube will overload on the initial impact noise. Tests made with a jury of observers show very satisfactory agreement between instrument readings and subjective judgments. The attenuator of the sound level meter is to be set at a position to give readings of a convenient size, and not changed during a series of tests.

The spot treatment of a vibrating panel leads to another economy in material and weight other than that obtained by its placement on the most effective areas. As the thickness (or weight per unit area) of a damping material is increased, the effectiveness is usually increased by an amount appreciably greater than proportionately to the thickness or weight. This effect is shown in Figure 2, where the variation in the effectiveness is plotted as a function of the weight of the treatment. The data from which this curve was plotted were obtained on a typical, asphalt base, mastic deadener. An explanation of the meaning of the units used on the vertical axis of this curve will be given in another section of this chapter.

As an example of the savings which can be effected by the use of a carefully designed spot treatment, the figures obtained on the automobile door study mentioned above can be quoted. It was found that a spot treatment on this door panel was fully as effective as an overall treatment at a savings in weight of two thirds.

Although the savings in weight and cost brought about by a spot treatment is attractive, the method has the obvious disadvantage of requiring a rather tedious series of measurements to determine the proper location of the areas of application of the treatment. The cost of the study can,of course, only be justified where a very large number of identical panels are to be treated. The adjective identical is important here for it is meant to imply that the vibration patterns are substantially the same on all units. Since the vibration pattern is influenced to a marked extent by seemingly insignificant differences in the units, the use of a spot treatment on hand made units will be of doubtful merit.

The spot treatment was successful on automobile door panels because these are made as nearly identical as is practicable in the production of such an item. The automobile industry pays a considerable premium in the purchasing of body steel because of the close tolerances specified in composition and in thickness. For this reason the vibration pattern is substantially the same on all units made on a given die. This was demonstrated by treating five additional doors in the same way as the test door mentioned above. The "tinniness" reading on the door on which the detailed study was made was 1.6. The five other doors treated with the same amount of damping material and at the same areas gave the following "tinniness" readings: 2.3, 2.3, 1.6, 2.3, 1.7. A difference of 0.5 in the tinniness reading is barely perceptible by ear, even by an experienced observer working under the conditions most favorable for making the comparison. The tinniness reading on any one of these doors when untreated was about 20.

The Nodagraph

The instrument devised to plot the vibration pattern on an automobile door may be of such general use in vibration studies that a brief description is given here. The instrument offers the advantage of determining the nodal lines (lines of zero amplitude of vibration) by the phase shift which occurs at a nodal line rather than by the determination of the locus of the points of zero amplitude. In a curved surface an anti-node may exist in close proximity to a nodal line, so if the study were to be made by amplitude measurements, there would be a possibility that a nodal line might be missed. Likewise there may exist areas of comparatively low amplitude which can be distinguished from a true node only with difficulty. Since phase relations instead of amplitudes are measured by the nodagraph, a miniature velocity microphone is used as the pick-up device. This permits measurements to be made without making contact with the vibrating body, thereby preventing the distortion of the vibration pattern which would occur if a vibration pick-up were to be used. The mass of any of the commercial vibration

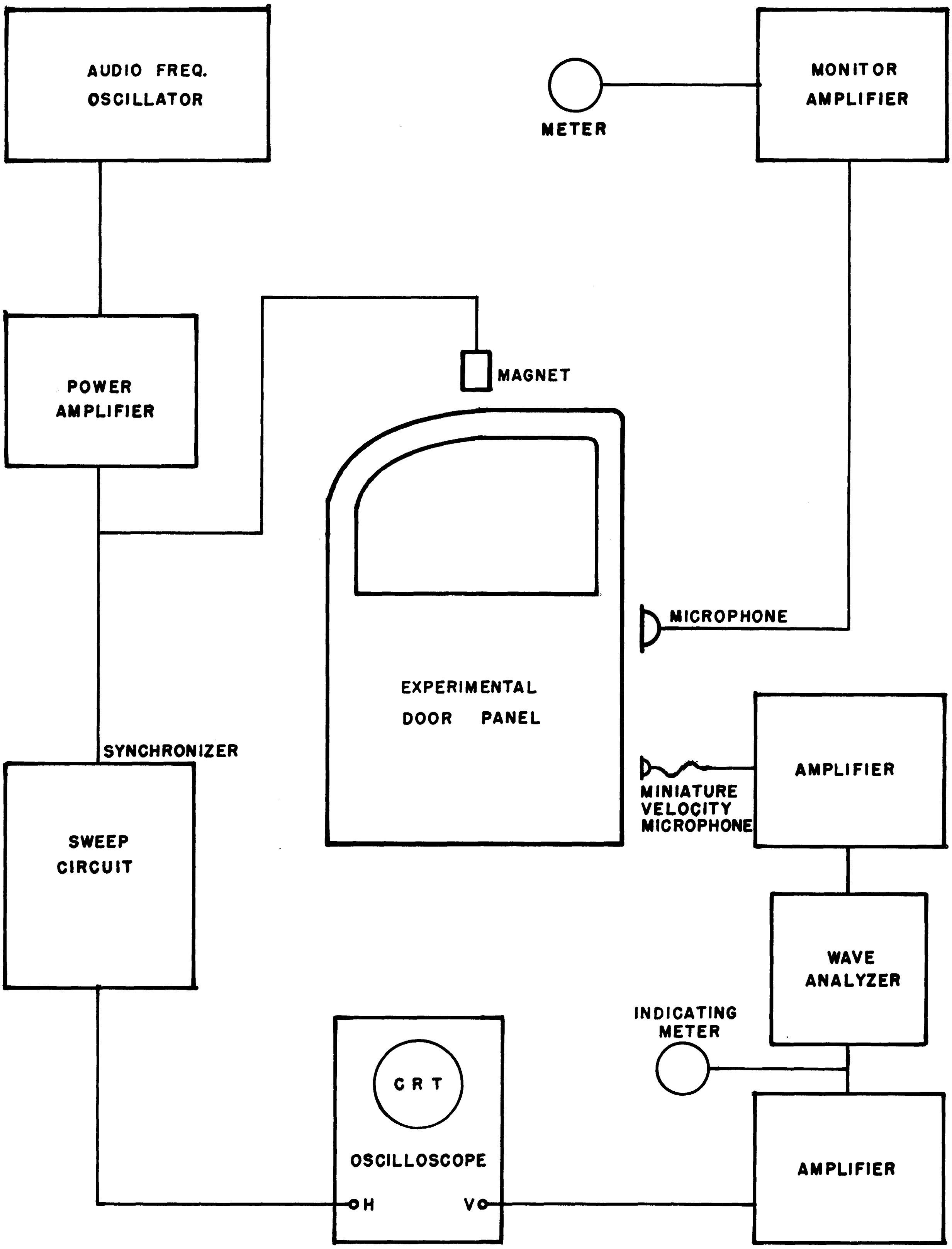

Figure 3 Block Diagram of the Nodagraph.

pick-ups is sufficient to distort the vibration pattern (under resonance conditions) even when a comparatively heavy structure, such as an automobile frame is being studied.

A block diagram of the equipment is shown in Figure 3. Vibrations of the desired frequency are excited by an electromagnet energized by an audio-frequency oscillator working into a power amplifier. The use of a non-polarized electromagnet is advantageous because the frequency of the vibromotive force generated by the non-polarized magnet is double the frequency of the current applied to it. Since the amplifier associated with the measuring equipment is tuned to the frequency of the mechanical vibrations generated, it will not then be affected by stray magnetic fields of the exciting circuit.

The miniature velocity microphone used as a pick-up is connected through suitable amplifiers and a sound analyzer to the vertical plates of a cathode ray oscilloscope. The horizontal plates of the oscilloscope are connected to a sweep circuit which is synchronized with the voltage output of the oscillator used to excite the vibrating body. The image on the oscilloscope screen is to be one cycle of the sine wave, but since the sweep circuit is synchronized with the exciting voltage, the position of the wave on the screen will be determined by the phase relations of the sound striking the microphone.

In operation the microphone is moved across the vibrating surface at a distance from it of about one-quarter inch. This distance is not critical; the microphone can be held in the hand. When the microphone is moved across a nodal line, the phase of the sound striking the microphone shifts 180° and the screen image will therefore reverse suddenly from one side of the horizontal axis to the other. By holding a piece of chalk in one hand and the microphone in the other and by moving the microphone

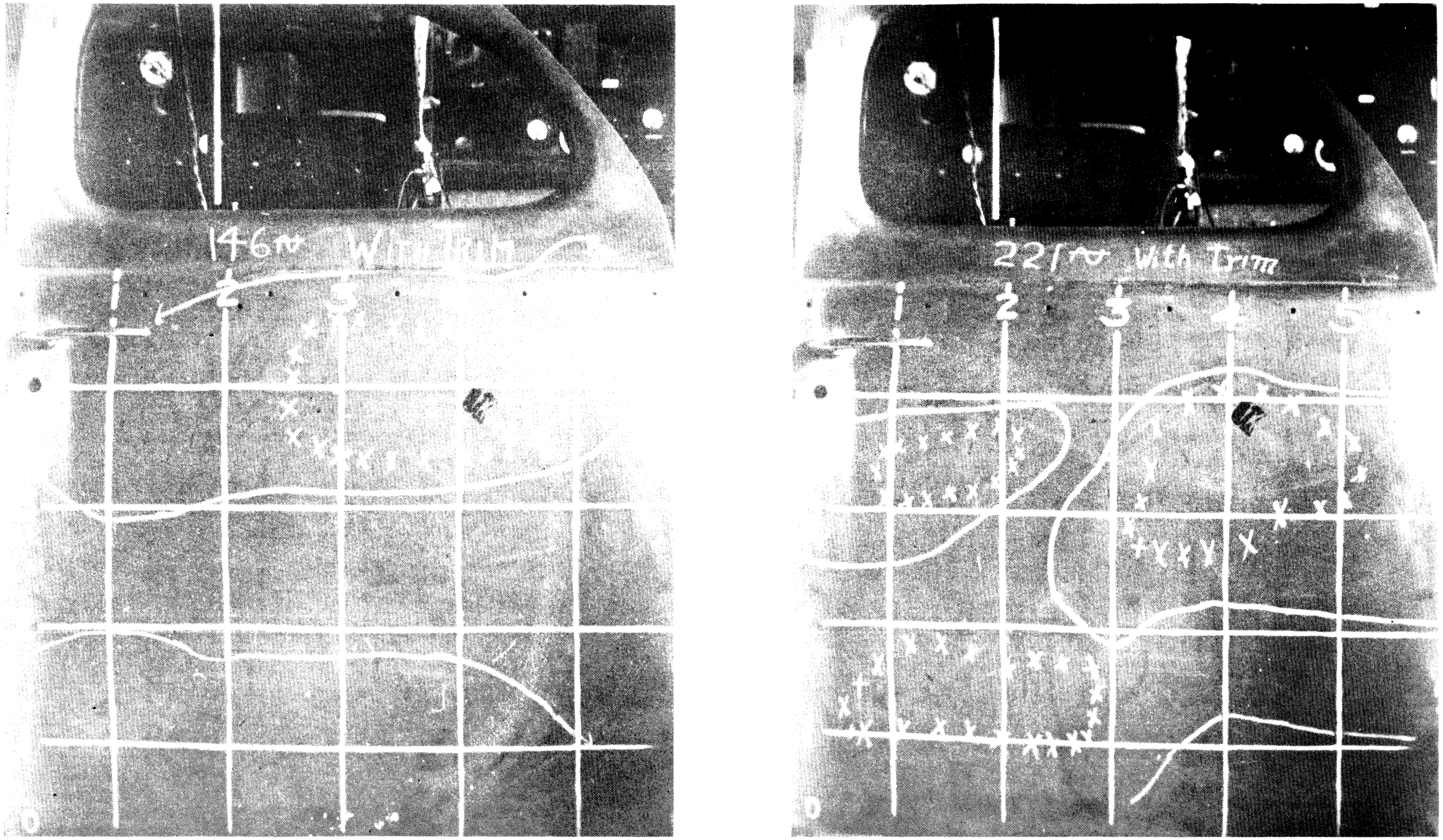

Figure 4 Vibration Patterns in Automobile Door Panels

back and forth a few inches, marking where the reversals take place, the nodal lines can be plotted directly on the panel in a comparatively short time.

The vibration patterns of two natural frequencies of an automobile door panel are shown in the photographs of Figure 4. The nodal lines are the irregular curves shown by the solid lines. The small crosses outline the areas wherein the amplitude of vibration lies between the maximum value for the whole panel, to a value of one-half of this maximum. These areas were also plotted with the nodagraph. For distances within about one-quarter of an inch of the panel, slight movement of the microphone in a direction perpendicular to the surface makes a surprisingly small change in the output, so the areas of maximum amplitude can be determined with sufficient accuracy for all practical purposes.

Amount of Damping Material Necessary

No definite rules can be given for the amount of damping material to be used in any given application. In most practical applications there exists a point of vanishing returns, which comes, obviously, at a point where the particular noise component for which the damping treatment is being used, becomes inaudible against the background of the other noises of the machine. A practical procedure to determine how good a treatment is necessary to insure full benefits is to first make measurements with an extremely effective treatment, even though this treatment is not practical for use for other than experimental purposes. Noise level measurements made with this treatment will show how much noise reduction can be accomplished by the use of damping. The amount of treatment just sufficient to reach the point of vanishing returns can usually be obtained with sufficient accuracy with only two more trials; first with a treatment of only half the effectiveness of that of the initial experiment, then again half or one and one-half of that value according as the second test shows results equal to or less than those obtained with the first treatment. In making the measurements to compare the effectiveness of the various treatments, it is, of course, essential that the conditions of operation be selected which emphasize the particular noise components which it is hoped to suppress by an application of damping material.

The method outlined above may seem rather inelegant to those who wish to do their work with paper and pencil rather than with actual machines. However, in this case, the computation of the desired damping treatment is dependent upon so many complex and interrelated factors that a mathematical study becomes so involved that it is impractical if not impossible. Also, such an analysis would, in general, require certain items of information which in turn would require measurements more difficult than the simple experiments outlined above.

It will be pointed out later that a given damping treatment is more effective for high frequencies than for low. Likewise a massive member will, in general, require a more effective treatment than a light weight structure. It is for these reasons that the stamping of ribs in a sheet metal panel is of advantage, for by this means the lowest natural frequency of the panel is raised without increasing its mass.

Mechanism of Damping

Fundamentally, damping consists in the conversion of vibratory energy to heat. However, we shall never be concerned with the development of high temperatures due to the proper action of a damping material, for the energy associated with sound is very small. Lord Raleigh has estimated that ten million cornets, blowing fortissimo, would be required to generate one acoustic horsepower. This computation will serve to verify the previous statement to anyone who has heard a single cornet, even though blown only forte.

Although the addition of stiffness or of mass to a vibrating body will change the natural frequencies at which the body tends to vibrate, neither will, per se, provide damping, for the compression of a spring results only in the storage of the energy pending its release on the return stroke, and the motion of a mass results in the conversion into kinetic energy which is not lost to the system but which merely tends to prolong the motion once it is started. In the case of a machine running at constant speed it is sometimes advantageous to change the spring constant or the mass, so that the natural frequency of the vibrating part is brought to a value either higher or lower than any of the vibromotive exciting forces in the machine. Such changes are obviously of no advantage in the case of a variable speed machine where an exciting force will at some speed or other coincide with the natural frequency of the part, unless the natural frequency is either decreased to a value below or above audibility, that is, below about 30 cps or above about 15000 cps. Only seldom is it found practical to adopt such a design. The natural frequency of a body is proportional to the square root of the ratio of the stiffness factor to the effective mass. In increasing the stiffness to raise a natural frequency sufficiently, it is usually necessary to increase the mass, thereby demanding a further increase in stiffness. Then, considering that the stiffness to mass ratio must be quadrupled to merely double the natural frequency, the difficulty of raising the natural frequency to a sufficiently high value is evident. Trouble in lowering the natural frequency is incurred because of the loss of mechanical strength and even if this is overcome, other natural modes of vibration are likely to occur which will have a higher natural frequency, thereby defeating the purpose. We glibly talk of a natural frequency of a structure as if there were only one. Actually there are many, almost always with no simple mathematical relation between them.

In practice, damping is obtained by making use of the property of a material which may be called internal friction, viscosity, or mechanical hysteresis or it may be obtained by making use of friction between surfaces or between fibers. Occasionally mention is made of air damping but the amount of damping which can be obtained in this way is very small indeed. This is fortunate, for the energy which is damped out in this way is likely to be converted to sound, thus achieving the exact opposite of the desired result.

Some materials have in themselves more damping than others. For example, any vibration in a lead structure is damped out quickly. Cast iron shows appreciably greater mechanical hysteresis effects than cold rolled steel. Likewise some methods of fabrication tend to introduce more damping than others. For example, fastening metal parts together with bolts gives appreciably greater damping than is obtained with welding. When one automobile manufacturer used welding in place of bolting in fastening two cross members into the frame, body rumble was very greatly increased. The damping furnished by the four surfaces bolted together was appreciable even though the members were tightly bolted with one-half inch bolts.

Even though some materials and some methods of fabrication are intrinsically more quiet than others, it is not necessarily good engineering practice to adopt certain materials or constructions solely because of their damping characteristics; it is usually of advantage to choose the materials and methods of assembly to comply with other engineering factors such as strength, weight, durability, cost, than to obtain the necessary damping by means of materials specifically designed for that acoustical purpose.

In order to supply the need for a good damping treatment, a considerable amount of research and development has been done. A number of materials have been formulated which show a pronounced mechanical hysteresis and structures have been devised which give damping either by mechanical hysteresis or by friction or by both. Descriptions of some of these damping materials and structures will be given below, but first a method of measurement of damping properties will be discussed so that quantitative comparisons can be made.

Method of Measurement

Since damping materials are used more extensively by the automobile industry than by any other, the test method was originally planned to be most suitable for materials used by that industry. Since the loudest noises, and those hardest to eliminate from an automobile, lie in the frequency range from 100 to 200 cps, the decision was made to make the test at 160 cps. It is essential that the damping material be applied for the test in the same manner that it is applied in actual use, so the use of a metal test panel was obviously called for. Other requirements for the test panel and associated equipment are:

1. The damping of the bare test panel when mounted ready for use must be negligible in comparison with the damping given by any sample under test.

2. The panel should be heavy enough so that it will not be overdamped or critically damped by any sample.

3. The natural frequency of the test panel should not be appreciably changed by the application of any sample.

4. The test panel must be rugged to withstand rough handling and shipment.

5. The panel when mounted for test should vibrate at only one frequency. If two modes of vibration of approximately the same frequency exist, the decay of vibrations will not be logarithmic.

It was found that a cold rolled steel panel twenty-inches square and one-fourth inch thick could be made to fulfill all the requirements. Each test panel is carefully prepared by grinding the edges so that the panel will have the desired vibration pattern. Since some pieces of steel have to be rejected due to non-uniformity of elastic constants and since the preparation of the panels is a sufficiently difficult matter without imposing further restrictions, no attempt is made to adjust the natural frequency of each panel to exactly 160 cps. However, in making the final computations the results are corrected to 160 cps by assuming that the rate of decay is directly proportional to the frequency. Although this can not be rigorously justified, careful measurements of identical samples on panels having natural frequencies from 131 to 166 cps show that this correction is applicable within experimental error.

Although the test method measures the damping at, or near, a frequency of 160 cps, additional measurements have been made at 30 cps and 430 cps on many types of damping materials. The order of ranking of materials commercially available was found to be the same at each of these frequencies. A damping structure has been devised recently, however, which can be broadly tuned so as to present maximum effectiveness at any desired frequency. This structure will be described later in this chapter.

Three methods of supporting the test panel during test are in use: one supports the panel in a vertical position, the second supports it in a horizontal position with the sample facing upwards, the third also uses the horizontal position but with the material facing downward. In each case the supports touch the panel only on the nodal line of the mode of vibration being used. For most materials, any of these three positions of test will give exactly the same results. However, in the case of a few rather unusual structures such as those using a soft fibrous blanket in conjunction with a septum, the results depend to some extent upon the position. The second position (horizontal, material upwards) is used for most tests.

The panel can be excited by any of a number of means; it can be hit with a rubber or leather mallet, a ball can be dropped or thrown against it, or it can be hit with the knuckles or even kicked with the foot. The same decay rate will be obtained in any case provided that the measurements are started after the decay becomes purely logarithmic. This condition occurs very shortly after the impact, for the high frequency vibrations are damped out very quickly due to the location of the panel supporting members and due to the fact that the panel is prepared so that the tones other than the 160

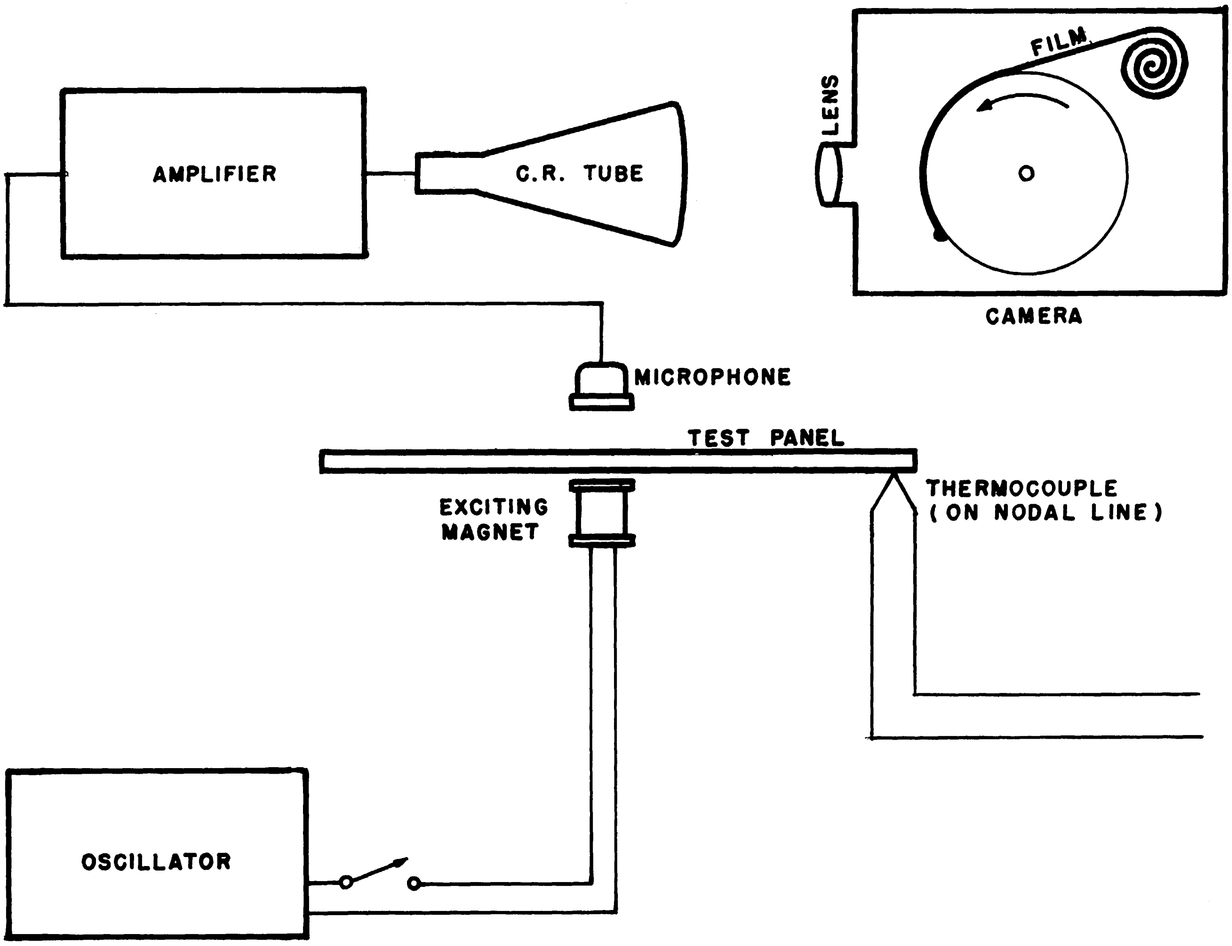

Figure 5 Schematic Diagram of Deadener Test Equipment.

cps tone have a much higher frequency than 160 cps. Usually the excitation for the test is provided by a polarized electromagnet supplied by an oscillator and power amplifier. The oscillator is tuned to resonance with the test panel for each measurement. With this form of excitation, the measurements can start immediately after the exciting current is switched off, for the test panel is vibrating at only one frequency and logarithmic decay starts immediately after the excitation is cut off.

The effectiveness of the damping material under test is given by the rate of decay of vibrations, expressed in decibels per second. The decay rate can, of course, be measured in any of several ways, but since the decay rate obtained with a good sample is large and the corresponding time intervals are small, it is convenient to use an oscillographic method.

A block diagram of the electrical equipment is shown in Figure 5. The sound radiated by the test panel is picked up by a microphone held a few inches from, and directly in front of the center of the test panel. The microphone output is amplified by a broad band amplifier working into the horizontal deflecting plates of a cathode ray tube. A timing signal is placed on the vertical deflecting plates, when desired. The trace on the cathode ray screen is photographed on a film moving at a constant, known speed. A reproduction of a record thus obtained is shown in Figure 6. The white horizontal lines in Figure 6 are produced by opaque lines placed on the oscilloscope screen. These calibrating lines are carefully located on the screen so that the sound pressure at the microphone which corresponds to a deflection between the two outer lines is accurately e (the base of natural logarithms) times the sound pressure which will produce a deflection between the two inner lines. The ratio e is used because measurements on a logarithmic curve can be made with the greatest accuracy for this particular value. The central horizontal line on Figure 6 corresponds to zero sound pressure. The vertical white lines are produced by a timing device; the distance between two adjacent lines corresponds to 0.05 second. With these values known, the rate of decay of the sound radiated from the test panel can be computed from the oscillogram. The deadener sample used for making the oscillogram of Figure 6 has a decay rate of 38 db per second. The corresponding oscillogram taken with a bare panel would be about eighteen feet long.

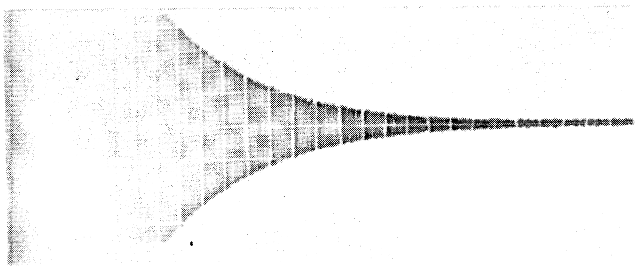

Figure 6 Decay Curve

Verification of Test Method

Although at the present time the test method described above seems perfectly obvious, when it was first devised in 1933, someindividuals raised the question as to its general applicability, reasoning that the action of a damping material on a one quarter-inch thick test panel might be different than the action on the sheet metal used in the construction of an automobile body. For this reason some careful measurements were made to justify the use of the test.

The first series of tests were concerned with the validity of the test when applied to damping treatments intended primarily for the suppression of certain running noises in automobiles. Measurements were made of the noise inside an automobile when running over various kinds of roads over a speed range from 20 to 70 miles per hour both at constant speed conditions and also under open throttle. These measurements confirmed the validity of the test, for the laboratory tests on the various treatments were consistent with the road tests on the automobile treated with these same damping materials. The only exception was the case when extremely effective damping treatments were used. It was found that the automobile noise did not measurably decrease when the decay rate of the damping treatment used was increased beyond a certain value. The reason for this is obvious; no further noise reduction can be expected when the treatment is improved beyond that which reduces the noise produced by the treated panels below the point where it is completely masked by the other noises of the automobile.

This "point of vanishing returns" is not a fixed value for all cars, or for different panels on a given car. On one make of car the point of vanishing returns for the door treatment was obtained by a damping treatment having a decay rate of 12 db per second; for another make of car it was found unnecessary, for suppressing running noises, to use a treatment better than one having a decay rate of 5 db per second. This point of vanishing returns is of course dependent on many factors, for example, the size and contours of the panels, the method of mounting the body to the frame, the streamlining of the body to suppress windage noises. It might be mentioned here that no point of vanishing returns was found for the floor treatment of the particular car used for the experiments, even though a damping treatment having a decay rate of 400 db per second was applied.

A second series of tests to establish the validity of the test method was made on seven identical automobile doors. Six of these doors were given various damping treatments, the seventh was left untreated. A jury of observers was asked to rate these seven doors in order of their "tinniness" when struck with the knuckle. Each individual judgment was made on pairs of doors. The rank ordering of the doors by the jury was identical with that given to the various damping treatments used, by the test method described above. The experiments to establish the usefulness of the "tinniness" meter mentioned previously were made at the same time and on the same door panels.

Although the experiments described in the preceding paragraph showed that the damping test ranked the various treatments in the same order as they were ranked by the jury, nevertheless a possibility exists that the ranking would not always be the same in the case of certain materials. For example, if two treatments with the same decay rate but with greatly differing weights are compared by the "knuckle" test, the heavier sample will give less "tinniness" than will the lighter. The explanation for this difference due to mass alone is that, when struck, the initial deflection is less with the heavier treatment than with the lighter treatment, therefore the vibration and the resulting sound will take less time to decay to inaudibility even though the rate of decay is the same in both cases. Thus for impact noises, such as pebbles, raindrops, or other particles striking a panel, the test method is not perfect. However, even with this rather special type of excitation, the test is practical for usually the difference in mass between two suitable treatments is small when compared with the total weight of the panel being excited. For shock excitation, where the deflection of the panel is caused by a shock applied to the whole panel (for example, that due to the slamming of an automobile door) only the decay rate of the treatment needs to be considered, for although the force tending to deflect the panel is proportional to the weight, the inertia is also proportional to the weight.

Although the above experiments to validate the test method were devised to apply to automotive vibration problems, they obviously also serve to demonstrate its applicability to the testing of materials for other applications. One possible limitation may be pointed out, however. In case deadeners should be developed in the future which are appreciably more effective than any known at present, the present test method might not distinguish between them, for if the test panel is critically damped or over-damped, the test method fails. If such deadeners are devised, it will be necessary to use thicker and larger test panels. The other portions of the test equipment and the testing procedure will, in this case, remain the same as before, but the results obtained with the thicker panel will of course, not be directly comparable with the results obtained with the present standard test panel.

Damping Materials and Structures

Several forms of damping materials are on the market. The characteristics of these will be described below and their suitability for various application will be discussed. The use of materials not manufactured primarily for damping purposes will also be considered. A few examples will be given of structures where damping is accomplished by adopting types of construction which make the assembly inherently dead.

Mastic Deadeners: The most extensively used of all materials designed solely for its damping ability is the mastic deadener. The material is supplied in a semi-fluid form which can be applied with a spray gun and which, after baking or air drying, becomes hard. Since the automobile industry is by far the most extensive user of mastic deadeners, most of those on the market have been formulated with the particular requirements of that industry in mind.

The most essential requirements for automobile use are (1) low cost, (2) ability to adhere to a metal panel under rather severe shock (for example, the slamming of a door) over a wide range of temperatures, and (3) the capacity to withstand a baking temperature of about 300°F soon after spraying, without flowing, even when the application is made on a vertical panel. In order to comply with these specifications, the damping effectiveness must be sacrificed to some extent. Due to the requirement of low cost, asphalt is used as the base for all of the mastic deadeners sold extensively at the present time. Various fillers and fibers are used by the different manufacturers. Some of the early experiments showed that the use of the proper amount of a high density granular material in the mixture gave extraordinarily good results. Metal filings were found to be very effective but due to the limited supply of low cost metal particles, screened sand is used for the purpose. The optimum size of granule appears to be dependent upon the kind of asphalt and other fillers used, as well as the method used for mixing the final product.

Both emulsion and cut-back asphalt compositions are used, the majority being of the latter type in spite of the fire hazard occasioned. Solid content varies from about 65 per cent to 85 per cent in the products of various manufacturers.

Although the appearance of all of the asphalt base deadeners is very similar, their damping efficiencies cover a remarkably wide range. Samples have been measured with a decay rate as low as two db per second and as high as 32 db per second.[1] One manufacturer may make a number of deadeners, each sold under the same trade name, yet with widely different mechanical and acoustical properties. Automotive underbody coatings are made primarily for their corrosion and abrasion resistance characteristics and have decay rates that are comparatively poor. For the above reasons, it is advisable to obtain from the manufacturer, or by test, the decay rate of the particular material which is to be used, either for experimentation or for production. Some experiments made to determine the feasibility of using a damping material in a given application have failed for the reason that the alleged damping material was so poor that its decay rate could not be measured on a laboratory test setup without special precautions. One early experimenter came to the conclusion that a damping treatment was worthless on an automobile floor. The reason for the seeming failure was that the actual amount of damping secured with the treatment used was less than that given by the carpet alone, for the carpet when laid on the steel floor was an efficient deadener, but when laid over the surface of the treatment used for the experiment, much less damping was obtained. Since the experimental treatment was very inefficient by itself, the combination with the rug gave less deadening than did the rug alone when laid on the steel floor.

All of the asphalt base damping materials have a pronounced temperature coefficient. The decay rates at various temperatures of two typical deadeners are shown in Figure 7. The manufacturer can, to a certain extent, vary the composition to make the maximum decay rate occur at any desired temperature. However, as yet, no highly effective material has been developed with the maximum at a temperature higher than 80°F. Although the curves of Figure 7 are typical of a majority of asphalt base deadeners, other shapes of curves are occasionally found. For example, a

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[1] For applications having a dry weight of 0.5 pound per square foot.

few deadeners show two maxima between 20° and 70°F. In making damping measurements it is essential that the sample be held at the desired temperature for a time sufficiently long to permit temperature equilibrium, otherwise a considerable error will be incurred.

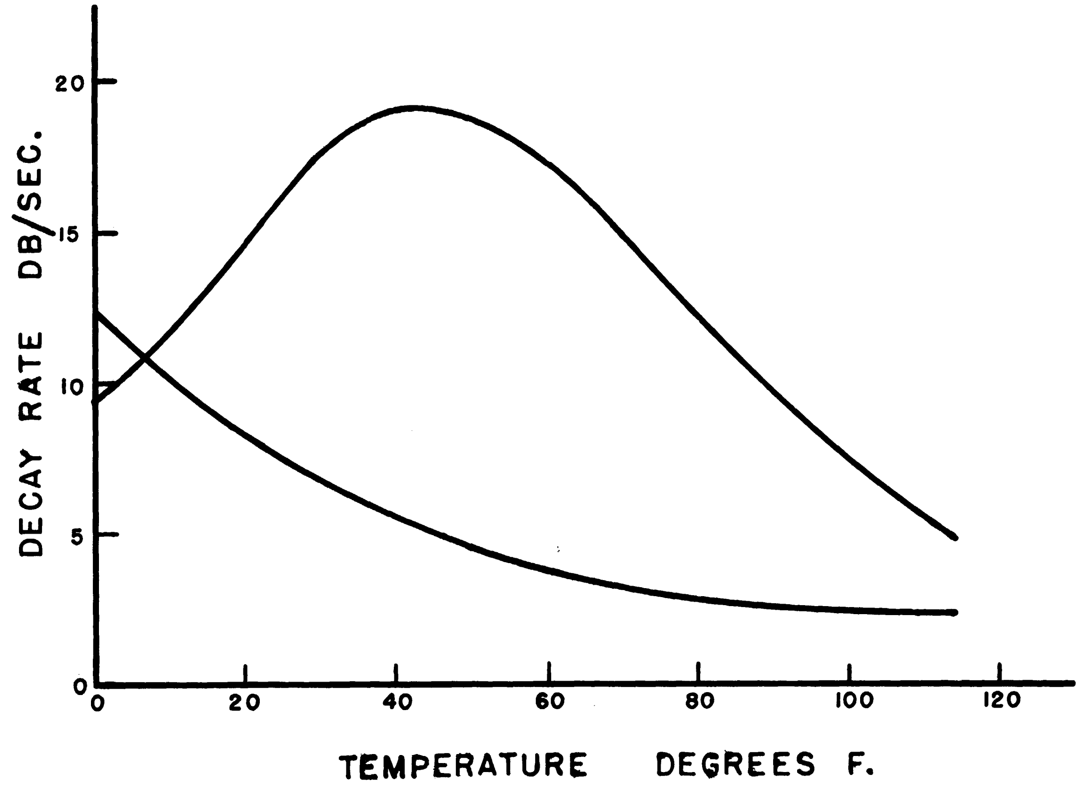

Figure 7 Decay Rates of Two Typical Asphalt Base Mastic Deadeners. (Dry weight of each = 0.5 lb/ft^2)

The full effectiveness of an asphalt base deadener is not obtained until all the volatile matter is driven out. For this reason measurements on a deadener should be made only on a sample which has been given the same baking treatment as will be given in production. In the automotive industry the baking to which the deadener is to be subjected is determined by the requirements of the paint, not those of the deadener. Since different manufacturers use different kinds of paints and therefore different baking times and temperatures, a deadener which will satisfy the requirements of one manufacturer may not be satisfactory for another. Very probably the decay rate of a deadener will ultimately arrive at its final value merely by air drying, but this would require a long period for most deadeners, especially the cutbacks. One deadener subjected only to air drying at about 70°F reached 90 per cent of its final value in five months. Another sample reached only about 50 per cent of its final value after one year of air drying.

A few of the mastic deadeners are soft enough so that a thumb nail can be pushed in them, but most of the effective compositions are hard at room temperature.

Table 1 gives typical acoustic requirements of several automobile manufacturers for mastic deadeners. Other specifications cover cold adhesion, sag on entering the oven, spray rate, abrasion and chemical resistance, settling, and consistency.

Table 1. Typical Automotive Specifications for Decay Rate of Mastic Deadeners.

Minimum Decay Rate at 70°F.	Minimum Decay Rate over Temperature Range Shown.		Air Dry hrs.	Bake hrs.	At Temp. °F.
	Decay Rate	Temp. Range			
15 db/sec	4 db/sec	0 - 100°F	12	0.5	325
9	4	0 - 100	12	0.5	325
15	4	0 - 110	-	3	275
11	5	0 - 100	24	7	225
6*	4	0 - 110	-	3	160

All the above values apply to a sample weighing 0.5 lb/ft^2 dry.
* Underbody Coating

Many asphalt base deadeners on the market do not comply with any of the above specifications, even though they are similar in appearance and are sold by dealers for automobile use. Only a comparatively few companies make deadeners which give a 15 db per second decay rate at 70 °F.

Water Soluble Mastic Deadener: There is one non-asphalt base mastic deadener on the market at present. It also is furnished in a semi-liquid form ready for application by spraygun or trowel. It will adhere to any clean metal surface and will dry within a few minutes, although several days of air drying are needed before its final damping characteristics are reached. This material will withstand fairly high temperatures and will not burn. An application of the material can be removed, even when completely "set", by soaking a few hours in hot water.

The characteristics of the material can be adjusted by the manufacturer over a considerable range. The decay rates on several typical compounds are shown in Table 2. The effect of temperature on another sample is shown by Figure 8.

Table 2. Decay Rates on Typical
Water-Soluble Deadeners.

Dry wt. lb/ft^2	Decay Rate, db/second	
	70°F	150°F
.41	21	5.7
.51	37	9.9
.50	5.7	6.9

Asphalted Felt: In quantity of sales, asphalted felts are second only to asphalt base mastic deadeners. These felts are paper felts impregnated with asphalt, and are made in various forms and thicknesses as well as

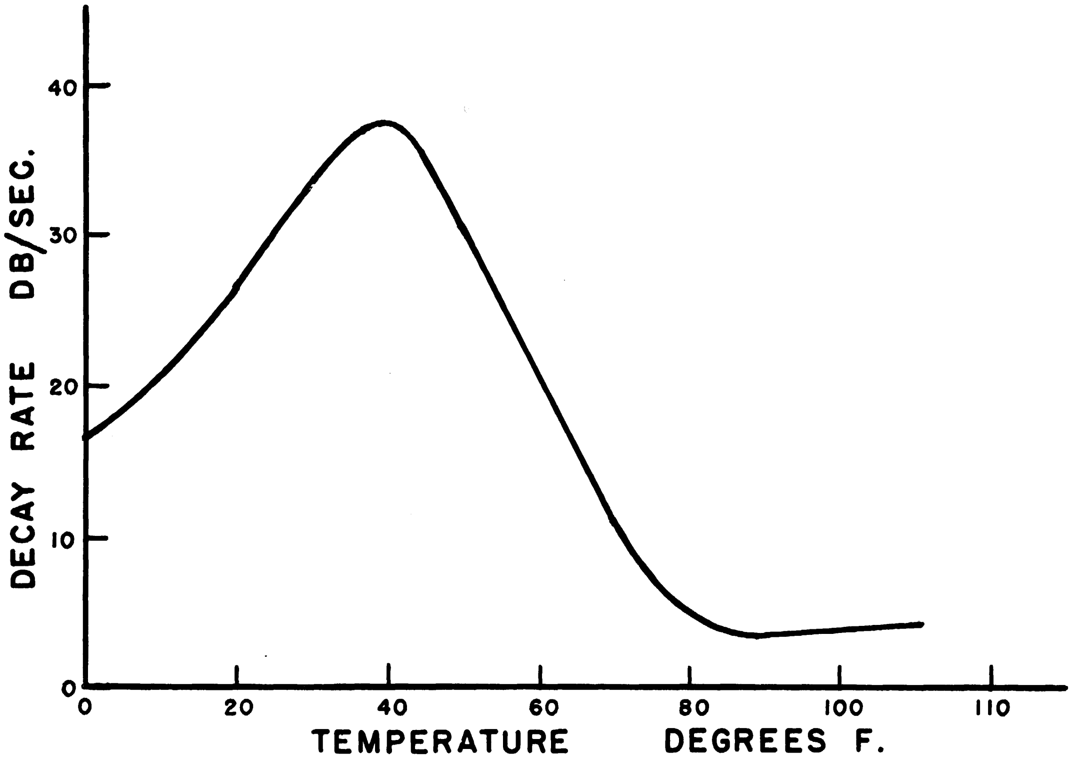

Figure 8 Variation of Decay Rate with Temperature. Water Soluble Mastic Deadener.

different degrees of saturation. They are usually cemented, with an asphalt base or rubber base adhesive, to the surface to be damped. The simplest form is similar to the common "tar paper" used for building purposes. In order to make the material more flexible it is often "needled" by passing it through rolls made with many fine needle points. The material is also furnished in an "indented" or "waffled" form. This form is also made by passing the material through rolls which form dimples about one-quarter to one-half inch in size thus giving an appearance which may be described as being similar to that of a waffle. A photograph of an indented felt is shown in Figure 9a. The materials described in this paragraph commonly weigh between 0.17 and 0.3 pound per square foot.

In order to obtain more damping than is given by any of the felts described above, the manufacturers cement two or more thicknesses together.

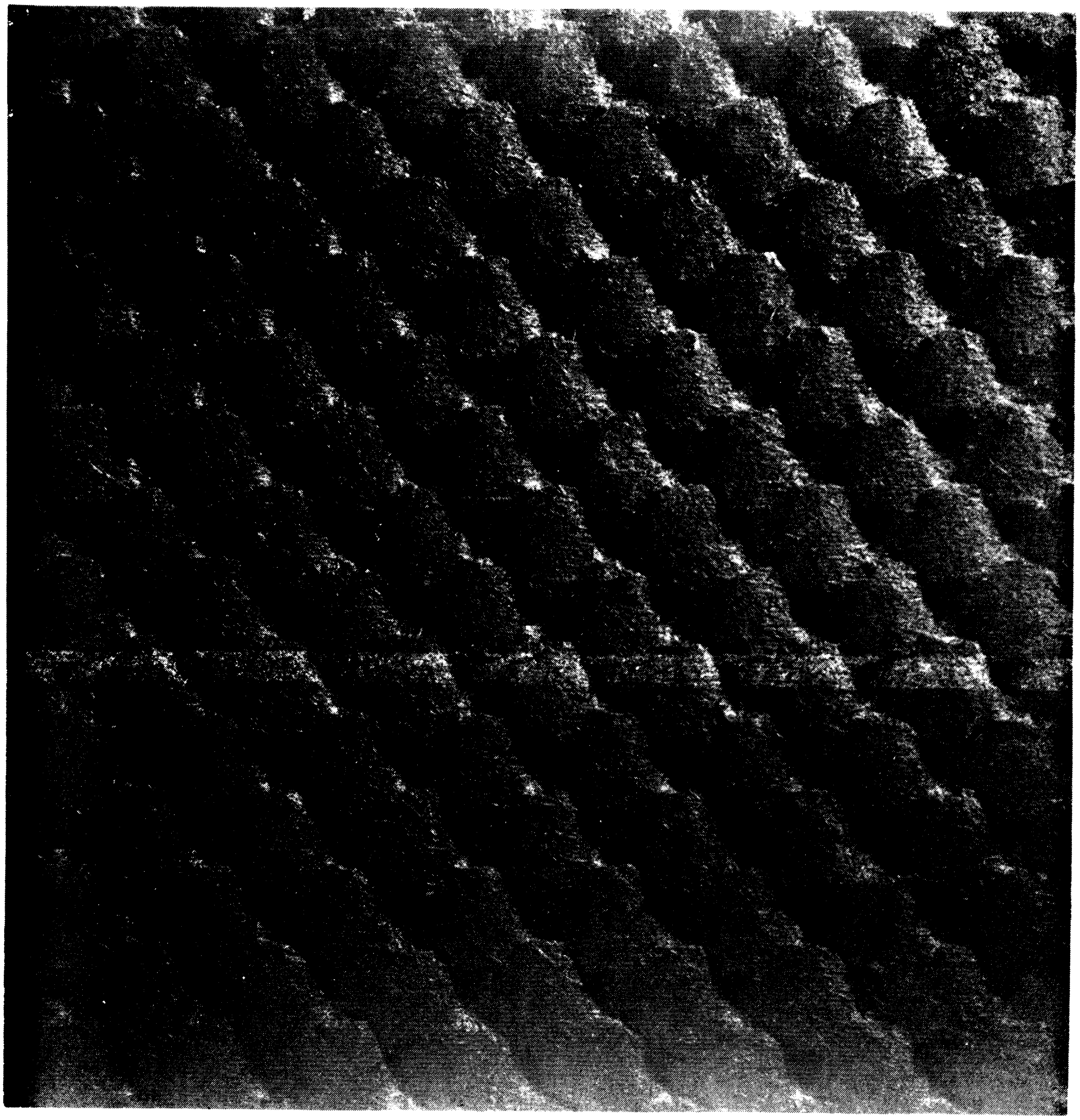

Figure 9a Indented, Asphalted Felt

Figure 9b 2 Ply and 4 Ply Asphalted Felts

(Figure 9b) Almost invariably sheets of indented felt are alternated with plain felt in the multiple-ply materials. In use, the indented side of the structure is always cemented to the panel to be damped because the damping thus obtained is very considerably greater than that obtained with the plain side cemented to the vibrating surface.

Although the asphalted felts on the market are quite similar in appearance, their damping effectiveness varies over a large range due to differences in the paper base, kind of asphalt used, amount of saturation of paper with asphalt, and other differences in the manufacturing processes. For this reason, the decay rate for a given material should be obtained from the manufacturer or by having a sample tested.

Although the adhesive used in cementing an asphalted felt to a panel contributes only a negligible amount of damping unless an excessive amount is used, nevertheless the manner in which the cementing is done has a profound effect. Surprisingly, the poorer the adhesive is, from a mechanical standpoint, the greater will be the damping. Indeed, if the surface being treated is horizontal and flat so that the felt will make contact over substantially its entire surface, the best results are obtained if no adhesive is used. In such a case, much of the damping is due to the rubbing friction between the panel and the felt. Advantage can be taken of this property by cementing the felt only in spots, leaving most of the area in contact with the vibrating panel but without being adhered to it. The size of the cemented spots should be as small as possible and the spacing between them as large as possible consistent with the necessary mechanical strength of the fastening.

Approximate decay rates obtained with some typical asphalted felts are given in Table 3. For the measurement made with the sample without adhesive, the test panel used for the test was painted with an automobile floor paint. All values given in the table are for a temperature of 70°F. The damping effectiveness of asphalted felts is influenced to a much lesser extent by changes in temperature than are the asphalt base mastic deadeners.

Table 3.

Decay Rates of Typical Asphalted Felts.

Description	Decay Rate db/sec.	Cemented	Weight lb/ft^2
1 ply, plain	1 - 12	100%	.2 - .4
1 ply, needled	1 - 6	100%	.2 - .4
1 ply, indented	1 - 11	100%	.2 - .4
1 ply, indented	21	No	.3
Above covered with carpet	85	No	.7
2 ply, indented plus plain	6 - 20	100%	.4 - .6
4 ply, alternate ind. and plain	20- 40	100%	.7 -1.0

Fibrous Blankets: Soft, fibrous blankets are seldom by themselves extremely effective for damping vibrations, especially if cemented to the vibrating surface. However, if they are covered with a septum having an appreciable mass, substantial decay rates are obtained. The reason for this increase in damping effectiveness is obvious. When a blanket is used without a septum it will vibrate with the panel to which it is applied. Since the blanket is light in weight there will be but little bending or rubbing of the fibers. However, when a septum of appreciable mass is placed over the blanket, the internal motion in the blanket will be greatly increased. The septum, because of its mass, will tend to remain still, so as the panel vibrates the blanket will be alternately compressed and expanded. This rapid stressing and releasing of the blanket dissipates the vibratory energy in the panel by changing it to heat energy.

As an example of the increase in damping which can be obtained by the addition of a heavy septum to a light blanket, data obtained on a piece of Fiberglas are given. The sample which weighed 0.028 pound per square foot when used alone gave a decay rate of 6 db per second but with a septum weighing 0.315 pound per square foot a decay rate of 95 db per second was obtained. As a rough approximation on many light weight blankets, the decay rate may be taken as proportional to the total weight of the combination.

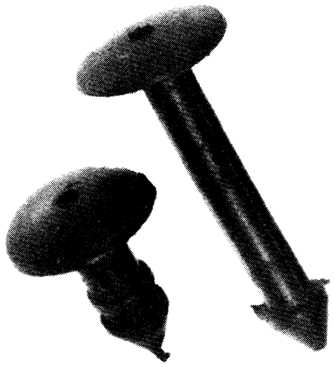

Figure 10 Rubber Dashpad Fasteners

A damping structure consisting of a fibrous blanket and a septum is useful when thermal insulation is needed as well as vibration damping characteristics. When absorption of airborne sound is required in addition to vibration damping, the septum should be perforated. The holes in the septum, even though their area is only a few per cent of the total area, will render the septum transparent to sound so that the ability of the blanket to absorb airborne sound will not be lost.

The blanket-septum construction can also be used advantageously on a sheet metal housing where it is necessary to remove the damping treatment occasionally in order to make openings available for repair or adjustment. the treatment can be fastened to the housing with metal fasteners or with rubber fasteners such as those shown in Figure 10. The latter offer the advantage of sealing the holes through which they are inserted and so are recommended in cases where a housing is used to prevent airborne sound radiated from the enclosed machine from being transmitted into the room.

Since the sole function of the septum is to act as a mass, any material can be used for the purpose. Sheet metal obviously has the advantage of being fireproof and easy to keep clean.

Although the kind of fiber and the method of bonding used in the blanket have some effect on the damping, these differences are not pronounced so the blanket can be selected for properties other than the acoustic properties. Among other materials, suitable blankets are on the market making use of fibers of cotton, flax, glass, jute, kapok, wood, mineral wool, and reclaimed wool. All of these blankets are available in various densities and thicknesses.

The blanket-septum combination is used in the construction of automobile dashpads. The septum is usually a heavy (approximately 0.3 pound per square foot) panelboard although sometimes a heavily loaded rubber sheet is used. Besides damping vibrations in the automobile firewall, against which the dashpad is placed, the assembly is required to act as a thermal insulator to prevent the flow of engine heat into the body of the car. Since the car controls have to pass through the firewall, one of the desirable characteristics of a soft blanket material is its ability to seal openings against both noise and heat. The curve of Figure 11 has been prepared to show the approximate relation between thickness of blanket and decay rate of a combination consisting of a jute blanket and a panelboard weighing 0.3 pound per square foot. The approximation is rough not only because of differences in fiber content of the blankets but also because of differences in the surfaces of the blankets. With a given thickness of blanket, individual tests may show a variation between half and double the value given by the curve. However, if the curve were plotted with the weight of the blanket used as the abscissa the approximation would be even less accurate, for in the case of a heavy septum, the thickness of the blanket has a greater influence than does its weight.

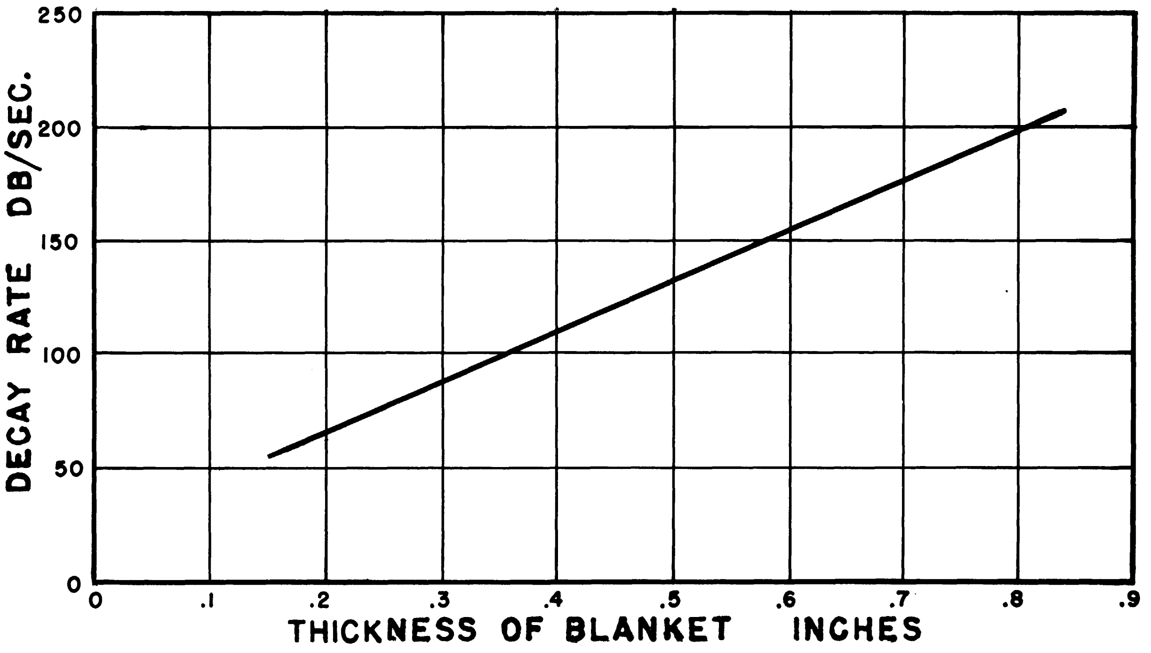

Figure 11 Damping by Jute Blanket plus 0.3 lb/ft^2 Panelboard.

Miscellaneous Deadeners: A number of other damping structures has been made of various materials and fabricated in various ways. Brief descriptions of some of these are given below:

1. A number of thicknesses of waterproofed crepe paper are sewed or spot cemented together. This structure offers some sound absorption in addition to damping. The material is made with from five to twenty thicknesses of the crepe paper. Decay rates of from 5 to 60 db per second have been obtained on this structure. The latter figure was for a sample weighing 0.6 pound per square foot.

2. Waterproofed paper is pleated so that a rubbing action is obtained between the pleats.

3. Small thin pieces of sheet mica are cemented together to a thickness of about .03 inch. A slow drying cement is used. This material is effective when fresh but dries out and loses most of its effectiveness. One sample weighing 0.22 pound per square foot showed a decay rate of 43 db per second when first received but this value decreased to about three db per second after standing in the laboratory for four months. This material has been used by one aircraft manufacturer.

4. Thin sheets of a hard, asbestos base paper are cemented together. This structure gives decay rates from 1.2 to 6 db per second. This material was developed primarily for aircraft use.

5. A mixture of reclaimed fibers, mostly cotton and wool are loosely felted together and sewed between sheets of crepe and pleated paper. This form of covering is used because it is very pliable and will conform to curved surfaces.

6. A heavy layer of an asphalt composition is applied to thick paper. The asphalt surface is covered with sufficient talc to prevent the sheets from sticking together during handling and shipment. When applied to a heated metal surface, the asphalt will soften and the assembly will firmly adhere to the metal surface.

7. Fiber boards made for building purposes, such as sheathing or plaster base, have been used for vibration damping purposes in some instances. These are not as effective for vibration damping as are other materials which are less expensive and easier to apply.

8. Some attempts have been made to use sponge rubber as a damping material but with little success. Those characteristics which make rubber an excellent isolating material prevent its acting as a damping material.

Indented Felt plus Sheet Metal: During early experimentation to find a suitable material for damping out vibrations in automobile frames and floors, the writer found that extremely effective damping could be secured by the combination of an asphalted indented felt (single ply) with sheet metal. The indented felt is cemented to the surface to be treated and a layer of sheet metal is cemented over it. An excess of adhesive should be avoided; the indentations in the felt should not be filled. The best results are obtained with a felt which has rather large indentations (approximately fifteen to one foot). Using No. 26 U.S.S. gauge sheet steel (0.75 pound per square foot), a decay rate of 400 db per second can be obtained. The weight of the sheet metal used is not critical, the decay rate is slightly less than proportional to its weight over an appreciable range of weight. When a standard test panel, treated with this damping structure, is struck, it sounds even more "dead" than a white pine board.

Frequency Selective Deadener: A new type of vibration damping structure is under development[1] which is capable of being constructed to have maximum effectiveness at any desired frequency. The structure offers effective damping at all frequencies and is extremely effective at the selected frequency. Since low frequency vibrations are usually more difficult to damp out than high frequencies, this structure can be designed to offer maximum damping at the frequency where damping is most needed and will still be sufficiently effective at the higher frequencies. One of the most valuable features is that a given amount of damping can be obtained with a surprisingly small weight.

The principle of operation is very simple as will be shown by a description of one of the many possible forms. Small circular portions are embossed in a sheet material possessing damping properties. Asphalted paper felt is one of several suitable materials. A mass is placed at the center of each circle. One unit of the structure is shown in Figure 12. The structure is then cemented to the panel to be damped. When vibrations

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[1] U. S. Patent Application, Serial No. 642,599.

occur in the panel, the center of each embossed circle will tend to remain stationary due to the inertia of mass M, but the portions of the structure which are cemented to the panel will, of course, follow the vibrations of the panel. Obviously considerable bending will occur in the embossed portion of the structure, thus causing generation of heat at the expense of the vibratory energy. This energy conversion, and the resulting damping, would obviously be much less if the masses were not present, for the embossed portions would then tend to follow the vibrations of the panel much more closely.

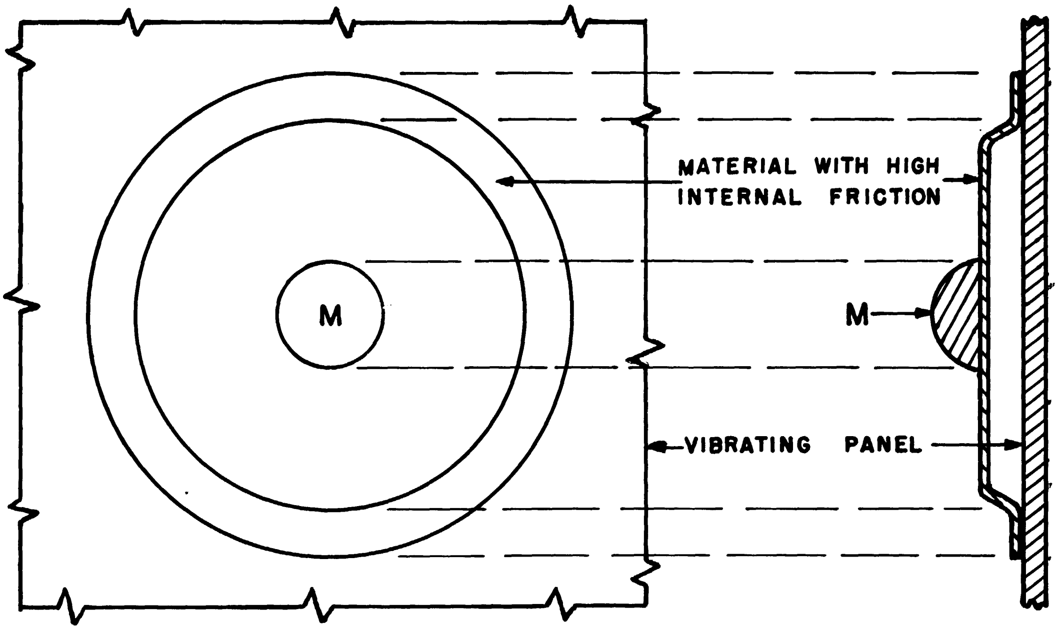

Figure 12 Tuned Deadener Unit.

Damping structures using the above principle have been constructed successfully using many forms of sheet material such as felts, waterproofed papers, plastics, and semi-rigid Fiberglas boards. The floating sections can be made in any of a large number of shapes and they do not need to be embossed from the base material, but can be supported on spacers.

Most of the work on this damping structure done up to the time of writing this chapter has been on the development of a deadener suitable for automotive use. For this reason the development was done with the objective of obtaining the maximum amount of damping at the least cost. Several practical forms have been devised using low cost asphalted paper or felt. For the mass used on each element, sand was mixed with an asphalt binder in order to avoid the cost of metal weights, even though the latter would give better results. Using these low cost materials, a structure has been made which gives a decay rate of 136 db per second with a total weight of 0.4 pound per square foot. The cost per pound of such a structure is, of course, somewhat greater than the cost per pound of a mastic deadener, but the cost for an amount which gives the same amount of damping is very considerably less.

In designing a structure to have its maximum damping occur at a given frequency, computations based upon the stiffness of the diaphragm portion of the unit, as determined by static measurements, have been found to lead to incorrect results when a material is used which possesses considerable mechanical hysteresis. Evidently the apparent stiffness is a function both of frequency and of amplitude of vibration. However, the determination of the proper mass for a given purpose can be determined by experimentation as easily as it can by computation, so the lack of the possibility of computation is not a hindrance.

Figure 13 shows the effect of varying the mass concentrated at the center. A single unit made from one-quarter inch thick Fiberglas board was used for the measurements. The weight of the unit, exclusive of the concentrated mass, was 0.35 ounce. Measurements were made with the unit placed at the center of a standard test panel. A decay rate as high as 160 db per second was obtained with the single unit having a total weight of approximately one ounce. In comparing this result with the decay rates of the usual deadeners, the fact that the unit was placed at the center of the panel (an anti-node) where it acts the most effectively, should be taken into consideration. If a number of units were uniformly spaced on the test panel, the decay rate would be considerably less than the product of the number of units times the decay rate of a single unit.

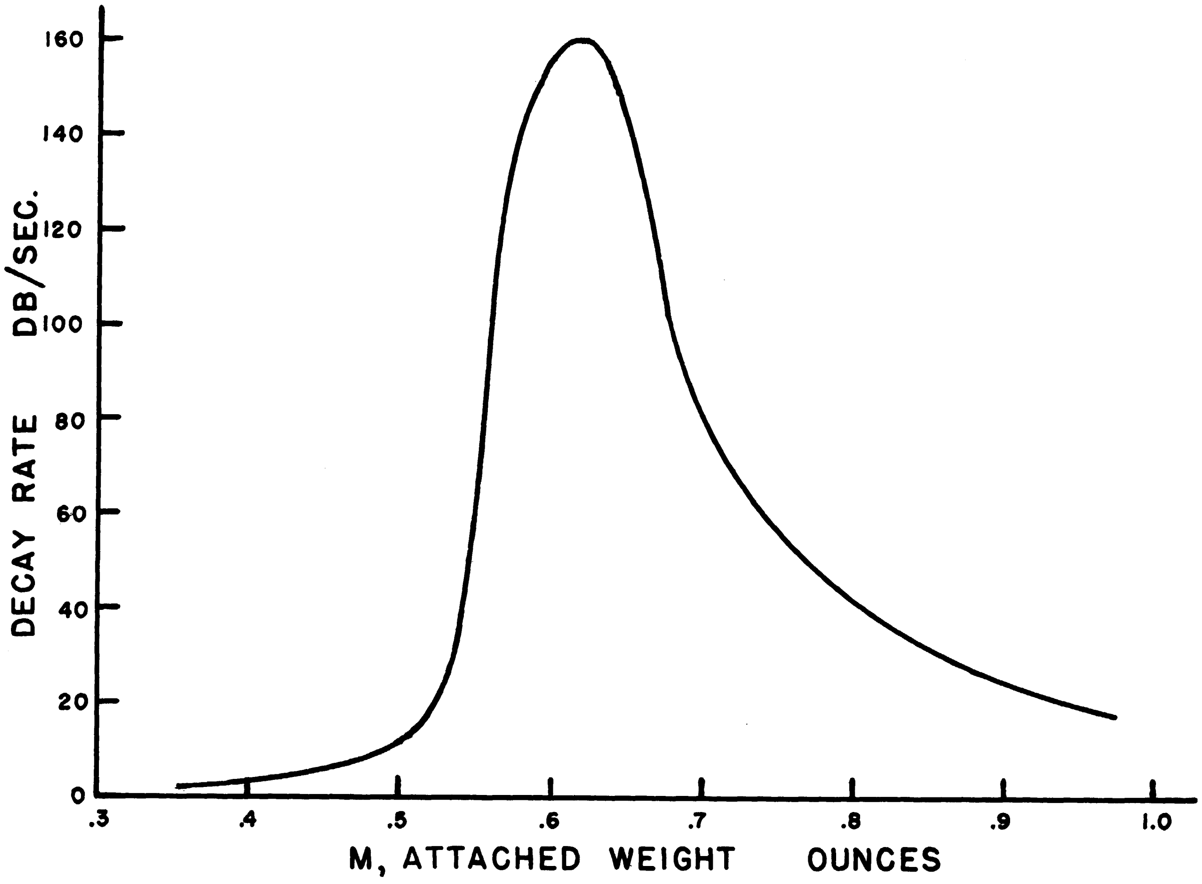

Figure 13 Damping Obtained with a Single Tuned Unit

It has been mentioned previously that the damping effectiveness of any of the damping materials or structures other than the one now under consideration can be specified by giving the decay rate as determined by the described test method, for measurements at other frequencies would give the same rank order. Obviously, due to the frequency selective action of the new structure, a single number will not properly specify its properties. A curve giving decay rate as a function of frequency would, or course, be desirable but the specification of the frequency where maximum damping occurs, the ~~day~~ decay rate at that frequency, and the decay rate at some specified frequency far removed from the first mentioned frequency, should give sufficient information for most purposes.