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THE DEGENERATIVE SOUND ANALYZER

BY

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Measurement of Noise

IN countless factories and laboratories the sound-level meter has become well established as an almost indispensable measuring device. With this instrument, engineering and production tests are carried on as easily as measurements of current and voltage, thus allowing the noise-producing characteristics of electrical and mechanical devices to be held within definite limits in much the same manner as other characteristics. Modern sound-level meters are designed to comply with the tentative standards which were formulated by the American Standards Association under the sponsorship of the Acoustical Society. Such meters provide a standardized means of noise measurement, applicable to all general types of sound and allowing engineers, manufacturers and consumers to express their noise specifications in units which are readily understood by all.

In all fields of measurement, as soon as it has become possible to obtain satisfactory data concerning certain characteristics of the phenomena being studied, the demand arises for equipment to make further measurements in order to investigate other phases of the phenomena. The sound-level meter provides a measure of over-all noise, and through the use of weighting networks the readings may be closely correlated with the estimate of an average person regarding the sound level. Such measurements are quite sufficient for many types of work, particularly for acceptance and production tests on finished products. To engineers who are trying to design quieter equipment, however, other types of data are frequently desirable, and, in particular, an analysis of the characteristics of the sound may provide many clues as to the sources of the most undesirable components. The result has been a persistent demand for a suitable sound analyzer, and, with this problem in mind, many types of devices have been tried. However, analyzers originally developed for other purposes have, in general, certain characteristics which limit their use for noise analysis.

Classification of Noises

The noises generated by machinery may be divided roughly into two classes. The first class includes sounds at the fundamental frequency at which the machinery is operating, or at some harmonic of this frequency. Sounds of this class are characterized by the harmonic relationship between the important components and are characteristic of most types of rotating or reciprocating mechanisms, particularly those operating at high speeds.

The second class of noises contains those components which are not definitely related in frequency to the fundamental speed of the machine and includes mainly those components caused by the vibration of various mechanical parts at or near their natural frequencies. Such noises are generally caused by shock excitation and result in a series of damped waves which, although they may recur at regular intervals depending upon the speed of operation of the mechanism, consist essentially of components corresponding with the natural frequency of the vibrating parts or harmonics of that frequency. The actual frequencies involved in such sounds are seldom clearly defined, since the effects of the shock excitation, the natural damping of the mechanical parts, the movement of the parts and the variation of forces impressed upon them cause frequency shifts of an appreciable order of magnitude.

Of course, the total noise made by any one machine generally consists of sounds falling in both classes, but in a large percentage of practical cases it will be found that all of the important components are in one class or the other. For example, the whine of a dynamo consists almost entirely of the fundamental and harmonics of the dynamo speed and thus falls into class one.

The noise made by a typewriter, on the other hand, may be considered as falling into class two since all of the important components are caused by shock excitation of the various parts of the mechanism. Sounds in class one are characterized by being rather sharply pitched, the pitch depending upon the machine speed, and containing mainly harmonics of that speed, and any variation in this speed will result in a corresponding percentage shift in frequency of all of the components of the sound. Noises falling in class two, in comparison, are characterized by being only approximately pitched and including many components which are not harmonically related. The frequency of the components in a class two sound is affected only to a small degree, if at all, by a change in the operating speed in the mechanism.

Analysis of Noise

The idea of analyzing sound by means of an electrical device is not new. Various types of analyzers have been developed for use on electrical wave forms, and, since a sound-level meter provides at its output terminals an electrical wave form corresponding closely with the acoustical wave form picked up by the microphone, it is only logical to attempt to use these analyzers for resolving the noise wave into its component frequencies. The average electrical analyzer, however, is of the heterodyne type, and a characteristic of this sort of analyzer is that the band width expressed in cycles remains constant, regardless of the frequency to which the analyzer is tuned. This response is the natural result of the type of circuit used in the heterodyne analyzer. In a device of this sort the tuned circuits or filters which provide the selectivity remain fixed, and the component being measured is heterodyned with another sinusoidal wave form, providing a beat note which passes through the filters.

This type of characteristic is, of course, entirely satisfactory for the applications for which these analyzers were originally designed. In measuring the wave form of power-line voltages, or in measuring distortion in amplifiers, etc. the actual wave form being measured is generally steady in frequency and absolutely recurrent. This is also the case with class one sounds of constant pitch, and for sounds of this type the heterodyne analyzer is quite satisfactory. For class one sounds of variable pitch, however, and for the unpitched sounds of class two the extreme selectivity of the heterodyne type of analyzer in the high frequency ranges makes accurate results impossible and in many cases makes it difficult to obtain any sort of measurements whatsoever.

Since few types of machinery operate at a sufficiently constant speed for satisfactory analysis of the high frequency sound components with a conventional type of heterodyne analyzer, various alternatives and modifications have been tried. Heterodyne analyzers have been made available with two or more band widths which are obtained by switching the filter circuits. This is an improvement, but obviously there will be a discontinuity in the readings at that point in the frequency range where the shift is made from one band width to the other, the extent of the discontinuity depending upon the pitch variations in the sound.

Other experimenters have abandoned the heterodyne analyzer entirely in favor of the tuned-circuit type, such as was in common use in electrical laboratories before the development of heterodyne analyzers. Since the band width of tuned circuits widens out as the frequency is increased, such an analyzer is, from this standpoint, inherently better for noise analysis than the heterodyne type, since the band-widening process may be continuous and automatic. The disadvantages of such analyzers are many, however, including undesirably large size and weight, caused mainly by the large coils and condensers required for operation at low audiofrequencies, susceptibility to magnetic interference, the difficulty of obtaining sufficient selectivity at low audiofrequencies and the fact that large inductances and capacitances cannot be made continuously variable. The use of the tuned-circuit type of analyzer has, accordingly, been restricted to only a few applications.

The Ideal Noise Analyzer

Most users of sound-measuring or sound-analyzing equipment are in agreement that, in the ideal noise analyzer, the band width or selectivity curve should be proportional to the frequency to which the device is tuned. Obviously, for class one sounds of variable pitch this will provide the minimum error, since any attenuation caused by frequency modulation of the sound will be equal for all components, which will then remain in their true relative proportions. For the unpitched sounds of class two it is somewhat more difficult to determine an ideal characteristic, but it is apparent that the broader selectivity curve in the high frequency ranges of the constant-percentage-band-width analyzer, as compared with the conventional heterodyne type of analyzer, will provide a considerable improvement in the response to these high, unpitched components. In this connection it may be well to note that sounds falling in class two are generally considered more annoying by the average person than sounds of a similar level falling in class one, since class two sounds are generally what are referred to as rattles or clashes. It is these sounds of the most annoying character which it has not been possible hitherto to analyze satisfactorily.

The Degenerative Sound Analyzer

In an effort to produce an analyzer more suitable for the great majority of industrial noise applications, the Engineering Department of the General Radio Company has developed a device operating on the inverse-feed-back principle,[1] which combines many of the advantages of the heterodyne and tuned-circuit types of analyzer without the disadvantages of either. The degenerative analyzer consists essentially of a high gain amplifier and a feed-back network which is so designed that all frequencies except that to which the analyzer is tuned are fed back to the input of the amplifier with such a phase relationship as to produce degeneration and consequent cancellation of the gain. The maximum gain of the amplifier is obtained, therefore, only at the frequency to which the device is tuned, and the amplification decreases rapidly as the frequency of the impressed signal is varied away from this point. This arrangement is shown in Fig. 1.

[1] H. H. Scott, "A New Type of Selective Circuit and Some Applications," Proc. I. R. E. **26**, 226–235 (1938).

In this analyzer the feed-back network is of the parallel-T type, which balances to a sharp null at a frequency predetermined by the values of the circuit elements, in much the same manner

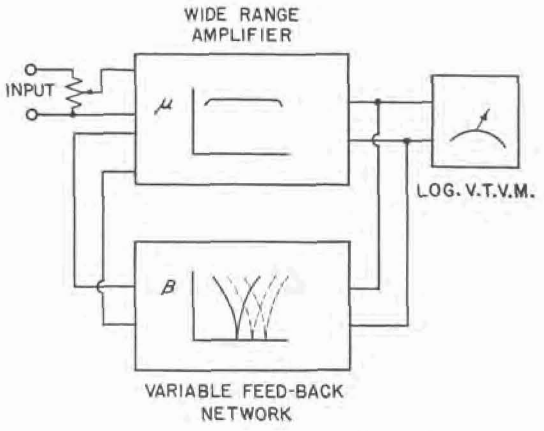

Fig. 1. Functional schematic showing principle of operation of the degenerative sound analyzer.

as a Wien bridge. This type of network requires only resistances and capacitances, and hence no coils whatsoever are required. This results in several advantageous features. Continuous tuning is accomplished by ganged variable resistors wound on tapered cards to give an approximately logarithmic frequency characteristic, and switching from one frequency range to the next is accomplished by means of a push-button switch. Since the main tuning dial may be rotated continuously in one direction, it is possible to scan the entire frequency range quickly and easily, while the push-button range control allows quick transfer between two widely separated frequencies. The elimination of all inductances from the circuit results in an appreciable reduction in weight and makes the instrument unsusceptible to magnetic pick-up.

In regard to stability of tuning, an analyzer operating on these principles is, of course, far superior to the conventional heterodyne type. In the latter the tuning depends on the high frequency oscillator, and a relatively small percentage shift in its frequency will result in a large percentage shift in the analyzer tuning. In the case of the degenerative circuit the selectivity is determined by the constants of the feed-back network, and, since these consist of high quality mica condensers and wire-wound resistors, the analyzer possesses an inherently high degree of frequency stability. This is an important advantage since it eliminates the need of any adjustments for resetting the frequency calibration, which in the case of heterodyne instruments generally have to be reset each time measurements are made.

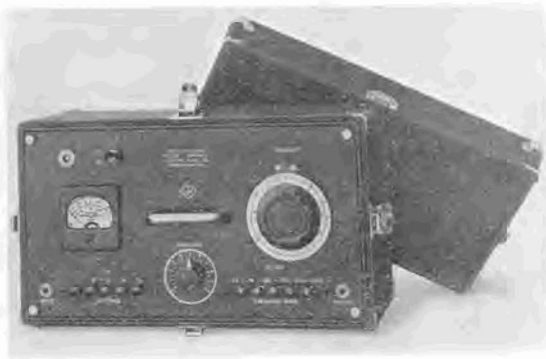

FIG. 2. The Type 760-A Sound Analyzer, which operates on the degenerative principle.

The complete instrument, which is known as the Type 760-A Sound Analyzer, has been designed as a companion instrument for the Type 759-A Sound-Level Meter and, accordingly, is housed in a similar case of airplane-luggage construction. As a result of the circuit and mechanical design, the instrument is small and relatively light in weight when compared with other types of analyzers. The appearance of the new analyzer is shown in Fig. 2.

Another noteworthy feature of the new analyzer, which is entirely distinct from the selective circuit, is the vacuum-tube voltmeter used as an intensity indicator. The circuit for operating this meter was developed in order to provide as simple operation of the analyzer as possible. The output from the vacuum-tube voltmeter amplifier tube is rectified, and a part of the resulting direct voltage is fed into the grid circuit, providing an automatic volume-control action. Thus the complete intensity range over which the analyzer is usable may be read on the single meter scale without the aid of any multipliers. This feature speeds up noticeably the process of analyzing noises.

ACCURACY IN NOISE ANALYSIS

The accuracy of the results obtained in analyzing any particular sound do not, unfortunately, depend only upon the conventional accuracy ratings of the analyzer. The usual accuracy ratings for an electrical analyzer give the limit of error on frequency and voltage calibrations, but apply only so long as the measured component is of a constant frequency. This condition is seldom encountered in noise measurements. As has been pointed out, the selectivity characteristics of a conventional heterodyne type of analyzer are such as to produce serious errors, although the analyzer for many other applications might be entirely satisfactory. Disregard of the true seriousness of these errors has been the reason for the failure of many attempts to analyze noise and is probably one of the main reasons why the subject of noise analysis is avoided by many engineers who have the impression that it is generally unsatisfactory and, at best, involves complicated and expensive equipment.

Figures 3 and 4 are presented to show comparative performance characteristics of the degenerative type of analyzer as contrasted with the heterodyne type of wave analyzer, in order to show the relative magnitude of errors possible with the two types when used for noise analysis.

The selectivity curve of two analyzers is shown in Fig. 3. The solid line is for the new Type 760-A Sound Analyzer, and the most noticeable feature is that the constant-percentage

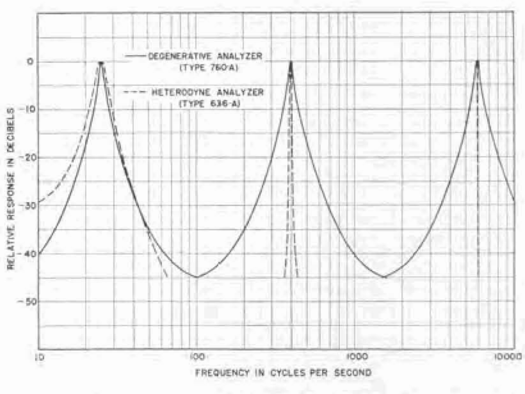

FIG. 3. Comparison of the selectivity characteristics of the degenerative analyzer and a typical heterodyne type of analyzer.

selectivity feature results in a selectivity curve which, when plotted to the conventional logarithmic frequency scale, remains the same throughout the entire range of frequencies.

The broken line represents the corresponding curve for an analyzer of the heterodyne type. This particular model uses a crystal filter and has proved very successful in many applications in the electrical and radio industries. The selectivity curves for the device, however, show readily why it is difficult to obtain satisfactory noise analyses with any device of this type. At 25 cycles the heterodyne analyzer is noticeably broader tuning than the degenerative type, making it more difficult to measure frequencies closely. At about 50 cycles the peaks of the two selectivity curves will be quite similar, but above that frequency the heterodyne analyzer becomes increasingly selective in terms of percentage of the frequency to which it is tuned, so that by the time 400 cycles is reached this device is quite unusable for many purposes unless the frequency is extremely stable. At higher frequencies the percentage selectivity curve becomes so narrow as to appear as a single straight line on the logarithmic chart. At 6000 cycles, for instance, a frequency shift of only 0.03 percent will throw the component being measured entirely outside of the band of the analyzer.

This figure shows quite clearly how difficult it is to tune an analyzer of the heterodyne type when measuring high harmonics which are varying in frequency. The inconvenience of this extreme selectivity is, however, considerably less important than the seriousness of any possible error if measurements are made with an analyzer of this type. In general, the most important characteristic of the noise which can be learned from the analysis is the relative amplitude of the various components. The problem of the response of an analyzer to sounds of varying frequency is extremely complicated, and no single set of conditions can be set forth which will clearly show the many possible variations in the results. The curves in Fig. 4 have been plotted, however, as being typical of a large number of such cases.

For purposes of simplification, it was assumed in plotting these curves that, after the analyzer had been tuned to the desired component, the frequency shifted by one percent, thus causing an amount of attenuation depending upon the selectivity curve of the analyzer. In actual practice, of course, the frequency would be shifting continuously back and forth, and the error would depend not only upon the extent of the shift, but on the frequency *versus* time characteristic. It is believed that Fig. 4, however, gives a rather good idea of the type of error caused by the variation in frequency and serves to point out that the error may be extremely serious. Since it is unpredictable with the equipment ordinarily at hand, the actual extent of the error is seldom known. This, of course, renders most measurements made under these conditions quite worthless.

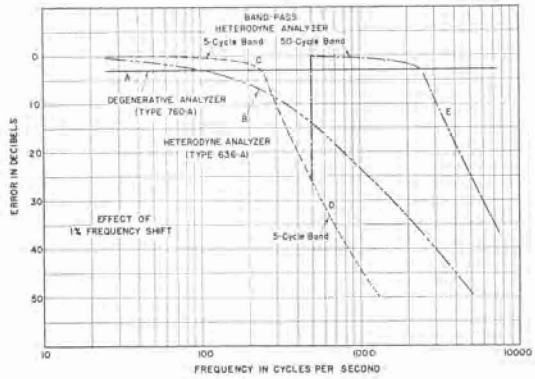

FIG. 4. The effect of one percent frequency shift on the accuracy of various types of analyzers.

Curve *A* shows the characteristics of the Type 760-A Sound Analyzer. For any given percentage frequency shift throughout its range it will be noted that the attenuation on all components is exactly the same. Accordingly, in the analysis the relative amplitudes of the components are not disturbed, and the absolute amplitudes are only slightly reduced. An analysis made with this instrument will, therefore, show actually what class one components are the most important from the standpoint of the amount which they contribute to the total noise.

Curve *B* in Fig. 4 illustrates what happens when a conventional type of heterodyne analyzer is used under the same conditions as outlined above for the feed-back analyzer. The error reaches 10 decibels at a frequency only a little above 300 cycles, and in the range from 1000 cycles to 2000 cycles, where the ear is most sensitive, the response of the analyzer is down by approximately 30 decibels. Obviously, these conditions will result in highly erroneous readings.

To minimize this difficulty, analyzers have been developed which use several band widths, usually related by factors of 10. Curve *C* shows the response of a typical analyzer having a 5-cycle band-pass characteristic with a sharp cut-off beyond that point. Curve *D* is a continuation of curve *C* into the higher frequency range and shows the extreme attenuation which would be obtained if only this single band-pass characteristic were employed. Curve *E* represents the response of the same analyzer with a 50-cycle band width. Under normal operating conditions, the error obtained with this analyzer would, therefore, be indicated by curves *C* and *E*. The large discrepancy falling at the cross-over frequency, in this case 500 cycles, should not be overlooked. An error of 25 decibels occurs at this point, which falls within the range of a large part of the energy of the average noise. If the 50-cycle band were used at lower frequencies in order to minimize this error, the selectivity would generally be insufficient to give satisfactory results because, even at the cross-over frequency of 500 cycles, the band width is ten percent of the frequency to which the device is tuned.

As previously mentioned, the actual results obtained with any given sound with the heterodyne types of analyzers may be better or worse than that shown in the diagram, depending upon the extent and other characteristics of the frequency shift. The unpredictability of the results and the possibility of such serious errors are probably the main reasons why the heterodyne type of analyzer has been generally abandoned for most purposes of sound analysis except in those few cases where the machinery speeds can be held within very close limits and where clashing and rattling sounds are not present.

This discussion of frequency shifts and the resulting errors is obviously more readily applicable to class one sounds than it is to class two sounds. The rattles and clashes falling in this latter class do not necessarily shift in frequency by the same percentage as the fundamental speed of the machine, and, accordingly, it is far more difficult to evaluate the performance of any analyzer for sounds of this character. In general, however, two characteristics may be said to be desirable. The first of these is a relatively wide band width compared to conventional heterodyne analyzers, so that the normal frequency range covered by any average component in these sounds will be included satisfactorily. The second is that the selectivity curve should have a rounded top, so that the analyzer may be tuned definitely to the component. In this connection band-pass filters are, of course, useful for locating these noises in certain parts of the frequency spectrum, but an analyzer having continuously variable tuning and a rounded-top selectivity curve is essential to locate the components with any particular degree of exactness.

It has been shown by actual experience that the type of selectivity curve present in the degenerative analyzer is well adapted for measuring these relatively unpitched sounds of class two. The curve is wide enough to provide satisfactory indications on all important components, and the shape is such as to allow definite tuning, thus giving an indication of the

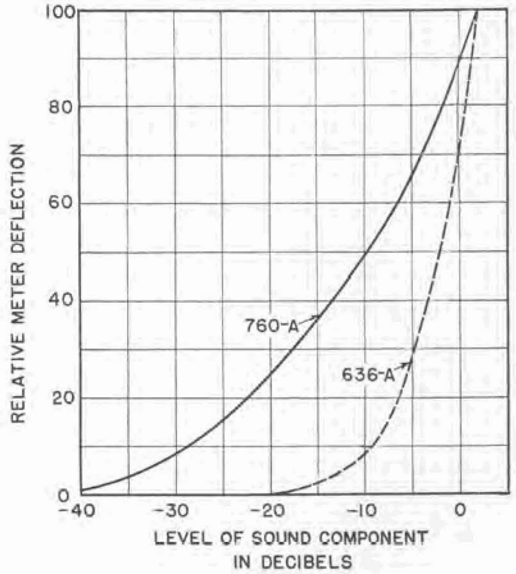

FIG. 5. Response of the approximately logarithmic vacuum-tube voltmeter of the Type 760-A Sound Analyzer, as compared to a conventional type of vacuum-tube voltmeter.

mean frequency of each component. An inspection of the curves in Fig. 3 will show readily why this type of analyzer is so much more satisfactory than the heterodyne type, while plotting additional curves similar to Fig. 4, but for various degrees of frequency shift, will make readily apparent the fact that any error generally encountered with the degenerative type of analyzer will be far less in magnitude than that encountered with the sharper-tuning heterodyne type.

Figure 5 has been included to show the relatively wide range available on the vacuum-tube voltmeter of the new analyzer, as contrasted with a vacuum-tube voltmeter of more conventional design. The inclusion of the complete operating range on a single-meter scale is a distinct advantage in regard to both accuracy and convenience. If the low level end of the scale is crowded so that multipliers must be used, the lower intensity components in the sound are frequently passed over without being noticed when an analysis is made. The type of meter used on the new analyzer provides a readily noticeable response for all components having an amplitude high enough to be of any importance in making up the total noise.

As a typical example of the type of analysis which may be obtained with the degenerative analyzer Fig. 6 is presented. This represents the actual noise made by a typical household refrigerator of standard make. The analysis was made with a Type 759-A Sound-Level meter and a Type 760-A Sound Analyzer. The 40-decibel weighting network was used on the sound-level meter, so the level of the components corresponds to their effect upon the average ear under normal listening conditions, where the noise from the refrigerator is noticeable but not loud.

It will be noted that there are strong components at the fundamental speed of rotation and various harmonics. There is also an appreciable hum from the motor field. Of all of the components shown, only this field hum and the lower frequencies can be measured satisfactorily with the conventional type of heterodyne analyzer. The strongest components are actually in the region between 1000 and 2000 cycles, and it is in this very range that the largest errors frequently occur with heterodyne analyzers. In this particular analysis there are several strong components in this region which represent roughly pitched whistling noises due to valves, etc. in the discharge line. The other components represent rattling or clashing sounds. When the analysis is made with a conventional heterodyne

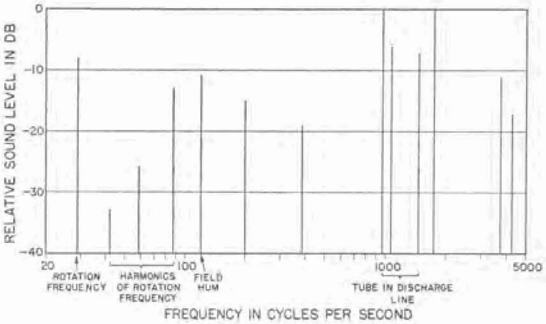

FIG. 6. Noise analysis of a domestic refrigerator as determined with the degenerative sound analyzer.

type of analyzer, all of the components above the 120-cycle field hum are greatly attenuated or do not show up at all.

A large number of field tests on many types of mechanical equipment, including typewriters, watt-hour meters, airplane propellors, office machinery and automobiles, have proved that analyses of this type as made with the degenerative analyzer do show up in their relative amplitudes the important components in a noise as heard by the ear. The accuracy of the instrument on sounds falling in both classes seems to be entirely satisfactory, and results have been obtained in many instances where all previous attempts at analysis had failed. In a surprising number of cases hitherto unsuspected components due to shock excitation were shown up by analyses made with the degenerative unit. Naturally, such data are invaluable to manufacturers, since it is only by knowing the source of a noise that they can take effective steps to eliminate it.

Additional Uses of the Degenerative Analyzer

Because of its important features, such as continuous tuning at low frequencies, freedom from magnetic pick-up, and stability, the Type 760-A sound analyzer is being used in many fields other than that for which it was originally designed. Of most importance, probably, is its use as a null detector in making bridge balances. The device may also be modified to function as a selective filter.

To meet the special requirements of certain other applications a null indicator and a low distortion oscillator[2] functioning on the same degenerative principle have been developed.

[2] The Type 707-A cathode-ray null detector and the Type 608-A oscillator are described in the April, 1939, issue of the General Radio *Experimenter*.

Conclusion

Of the many possible uses of the degenerative type of selective circuit, it is believed that its function as a noise analyzer is one of the most important, since it provides a much needed and hitherto unavailable type of selectivity characteristic. The ready acceptance of the new analyzer by engineers in many branches of industry and research indicates that it is filling a large demand for simple and effective noise-analyzing equipment. It is hoped that this new instrument will enable engineers to carry further their already noteworthy work of making this world a quieter place in which to live.

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