IMPROVEMENT OF LOUDSPEAKER PERFORMANCE THROUGH THE USE OF FEEDBACK

by

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ABSTRACT

This paper compares two methods of measuring the motion of a loudspeaker cone. An accelerometer device was built by designing and attaching a preamplifier to the piezoelectric crystal transducer assembly. This crystal has a voltage output proportional to the acceleration of the loudspeaker cone. The other technique consisted of measuring the back emf across the voice coil by using a bridge network. The voltage obtained is proportional to the velocity of the loudspeaker cone. Measurements indicate that for a sinusoidal input the velocity and acceleration voltages have a 90° phase shift. Thus, both methods of measurement are in agreement with theory. Feedback will also reduce the harmonic distortion caused by a nonlinear suspension system. Also, a mathematical analysis is made to determine the effects of acceleration, velocity, and displacement feedback on the frequency of the system.

ACKNOWLEDEMENTS

I would like to thank Texas A&M University for its support of the University Undergraduate Fellows Program. This program will have my support in the future. The author is especially indebted to Dr. D.L. Parker for his patience, time, and willingness to work with undergraduates.

DEDICATION

I dedicate this paper to my mother and father, Jean M. and George C. Machos.

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In the audio industry, the loudspeaker is still the least understood component in the reproduction chain. This component is interesting to study because scientific measurements do not always correlate with exactly what a person hears. Researchers have tried unsuccessfully for years now to determine why there is a difference between these two types of measurements and why the results are not fully predictable. Despite these unsuccessful studies, recently engineers have begun to examine the characteristics of loudspeakers in the time domain. This time domain analysis is usually performed by measuring the sound pressure level as a function of time and frequency. Another method of correlation is to study the amplitude response versus time. This displacement of the loudspeaker cone versus time appears to be the most accurate method of measurement at low frequencies assuming the cone moves as a piston, i.e., there is no cone break-up. The main area of interest for this project is the low frequency region below about 400 Hertz. The low frequency region usually has more distortion caused by the large cone excursions. If one could observe the actual motion of the cone then a type of measurement might possibly evolve which could correlate scientific measurements with subjective listening

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The format of this paper follows the style and format of the *Journal of the Audio Engineering Society*.

tests. The primary objectives in the research area to observe the motion of the cone as a function of time and to ultimately control this motion through the use of feedback.

A review of the literature shows that the idea of feedback is not new; it has in fact been around since about 1925 [1]. A recent survey shows one manufacturing facility presently manufacturing a motional feedback system which use a piezoelectric crystal mounted on the loudspeaker cone along with an integrated amplifier incorporated into the system [2]. Another system proposed [1] more recently in an Australian journal uses an operational amplifier bridge network to obtain the back emf across the voice coil. This back emf is proportional to the velocity of the voice coil. This system is advantageous in that it uses less circuitry than the crystal method and requires no platform for a crystal. On the other hand, the back emf is proportional to the velocity only when the coil is in the linear portion of the magnetic flux field. Nowhere, however, ahs research been cone to determine if both of these methods are in accordance with each other in practice.

OBJECTIVES

The objectives of this research are to 1) compare the voltage singal from the piezoelectric crystal with that of the back emf to determine if both measuring techniques are consistent with each other, and 2) to analyze mathematically the effects of three different types of feedback, i.e., acceleration, velocity, and displacement.

RESEARCH PROCEDURE

The first problem encountered was to securely mount the crystal on the loudspeaker cone such that a voltage could be obtained from it. See Figure 1. After removing the dust cover from an 8" driver, a styrofoam platform was securely fastened at the apex of the cone with silicone rubber cement. Styrofoam was used because it is extremely rigid and lightweight. Weight is of paramount importance in this design because the efficiency of the loudspeaker is inversely proportional to its moving mass. After mounting the platform in place, the crystal (PXE 5) was mounted onto a brass ring or washer by soldering into place. PXE 5 is one of several different grades of ceramic material which is polarized by a high intensity electric field. When mechanically stressed, it will produce a voltage. This grade of material provides good sensitivity along with an excellent time stability characteristic. This method of mounting allows for the crystal to flex in response to cone movements thus producing a voltage signal proportional to the acceleration of the cone. Finally, this brass ring was glued to the platform with epoxy.

After having mounted the crystal device, the next problem consisted of matching the output impedance of the crystal (40 Megohms) to a low output impedance device such as a JFET. It is desirable to convert this high impedance signal into a low impedance signal as quickly as possible to avoid unwanted noise. A JFET preamplifier was used because of its ability to achieve a high input impedance. The circuit designed for this purpose is shown in Figure 2. The relevant

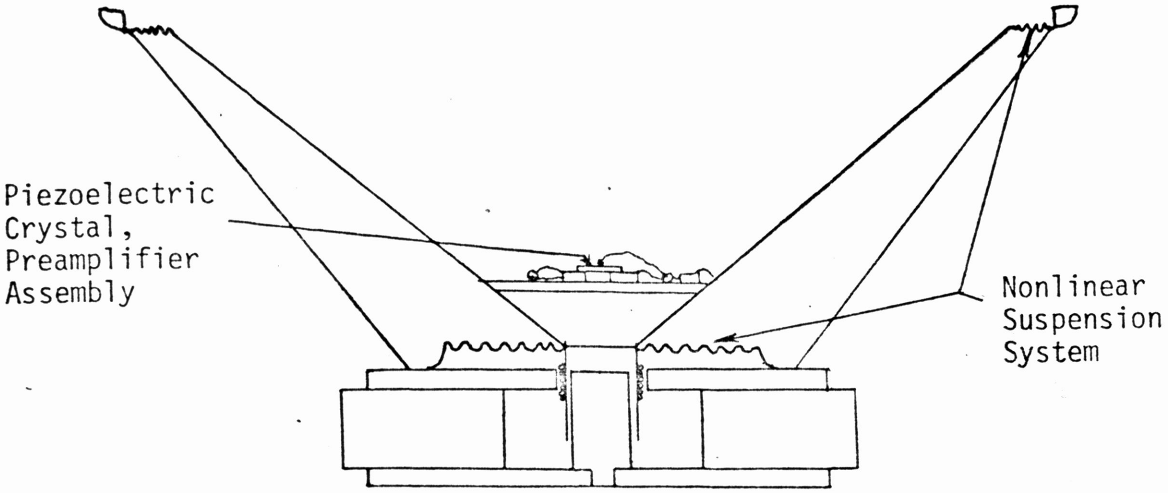


Fig. 1. Diagram depicting experimental crystal/preamplifier.

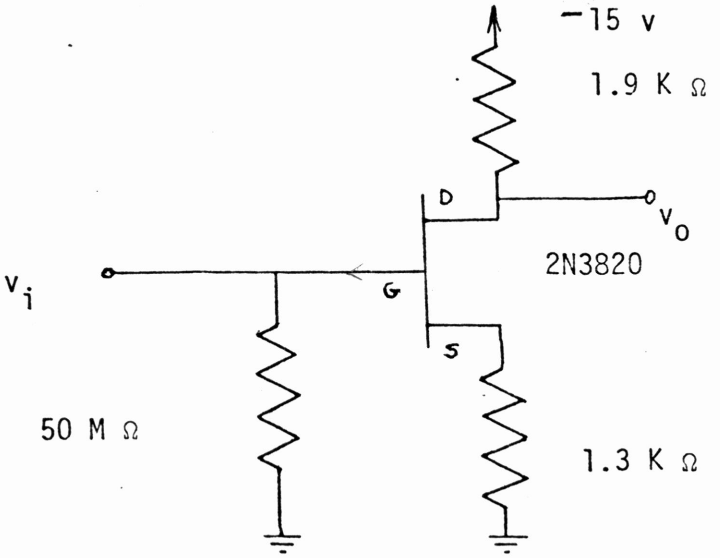


Fig. 2. Design of JFET preamplifier for crystal.

calculations are shown in the appendix. The circuit was optimized for maximum voltage swing by allowing the circuit to clip equally on both the top and bottom of the signal. The output voltage is taken from the drain side of the JFET to limit the number of wires attached to the loudspeaker. The JFET preamplifier was also attached to the platform. Then the output of the crystal was fed directly into this preamplifier to reduce the possibility of noise entering the system usually caused by utilizing high-impedance lines over relatively long distances. Thus it is desirable to convert the high impedance signal into a low impedance signal as quickly as feasible to avoid unwanted noise. The complete crystal/preamplifier structure is shown mounted at the apex of the cone in Figure 3.

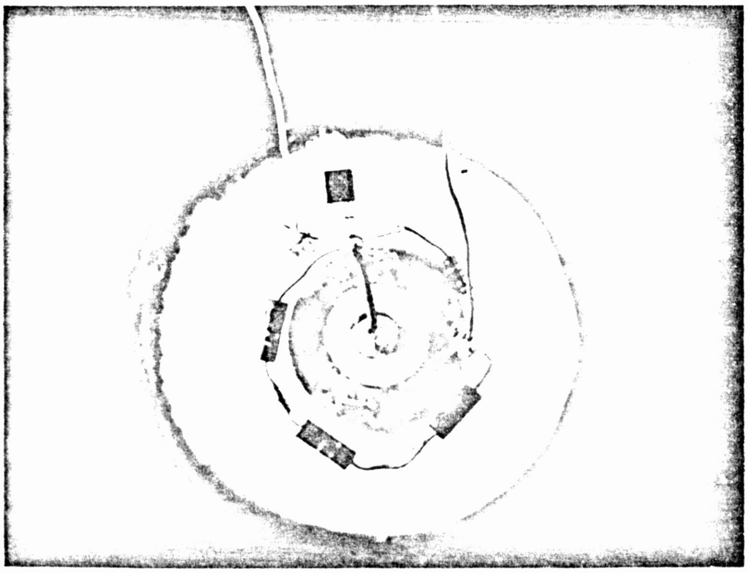


Fig. 3. Crystal preamplifier mounted at the apex of 8" loudspeaker.

Besides building a crystal/preamplifier device, a bridge network was also constructed as shown in Figure 4. This bridge network is used to obtain a voltage proportional to the velocity of the cone motion. The voltage signal derived by this method is to be compared with the acceleration voltage signal from the crystal at various frequencies.

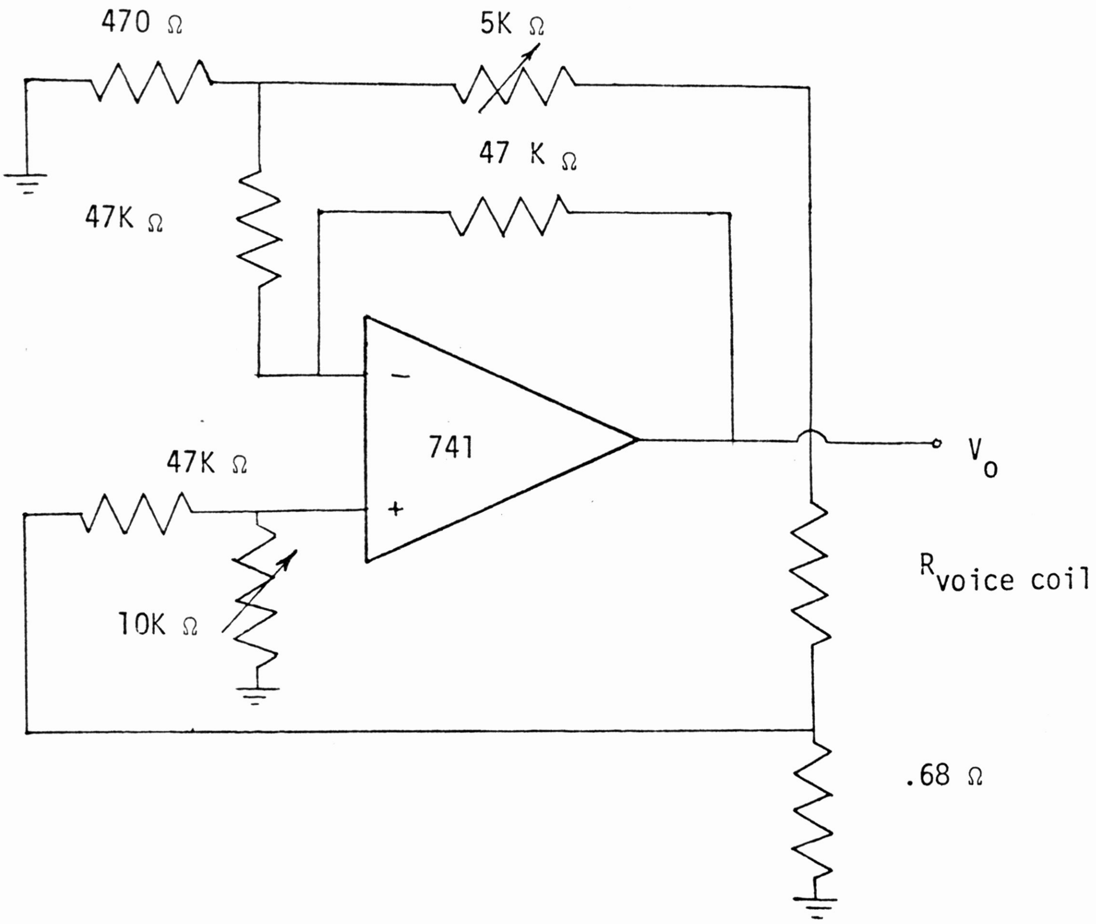
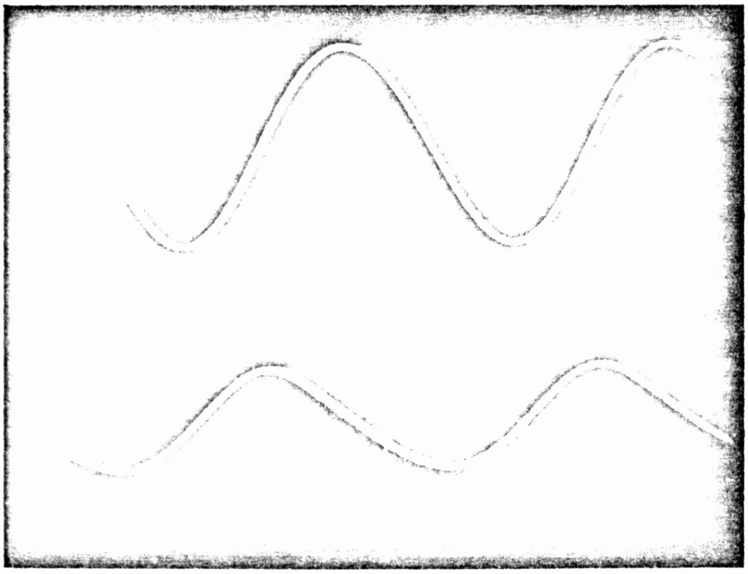


Fig. 4. Design of bridge circuit to obtain velocity feedback.

RESULTS AND DISCUSSION

After mounting the crystal structure, a sinusoidal voltage was applied to the input of the loudspeaker. As expected, the output of the crystal was sinusoidal for small amplitude excursions while it became distorted for larger cone excursions. The voltage signal derived from the bridge network was compared with the acceleration voltage signal from the crystal as shown in Figure 5. These two signals are out of phase by 90°. This comparison between the two types of signals is as expected because the derivative of a sine wave (velocity signal) is a cosine wave (acceleration signal). It can also be seen that as the frequency is lowered, the cone excursion is increased resulting in an increased amount of distortion as evidenced by the oscilloscope photographs shown in Figure 6. Consequently, it is apparent that at low frequencies neither method of obtaining the signal seems contradictory.

Research has shown that loudspeakers have considerable distortion below 100 Hertz as shown in Figure 7 [3]. This distortion level increases as the frequency is lowered due to the larger cone excursions required of the driver at these lower frequencies. Essentially this distortion is related to the nonlinearity of the suspension system. Note also that as the power level is increased, the distortion level also increases. If one were to examine the electrical input signal versus the acoustical output pressure, the graphs shown in Figure 8 [3] would be obtained. The acoustical output has been clipped. This clipping always causes harmonic



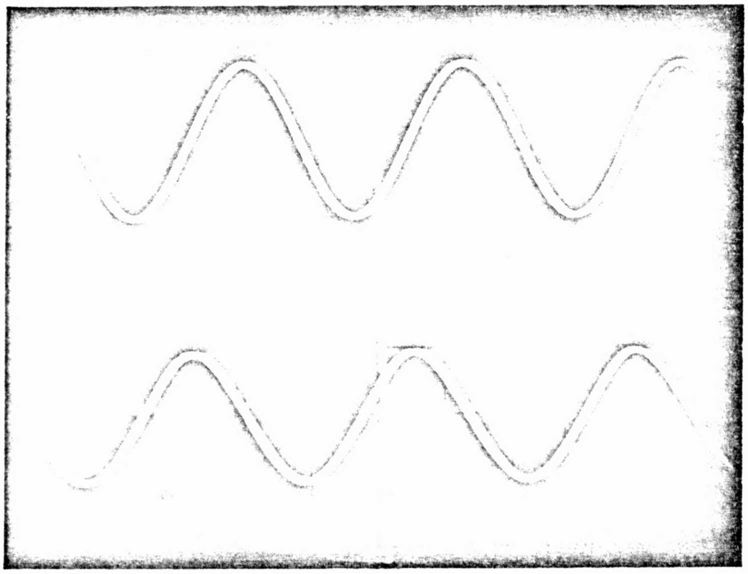
Vertical:

.05 V/DIV.

Horizontal:

10 m sec/DIV.

Fig. 5a. Cone velocity versus cone acceleration at 20 Hz.



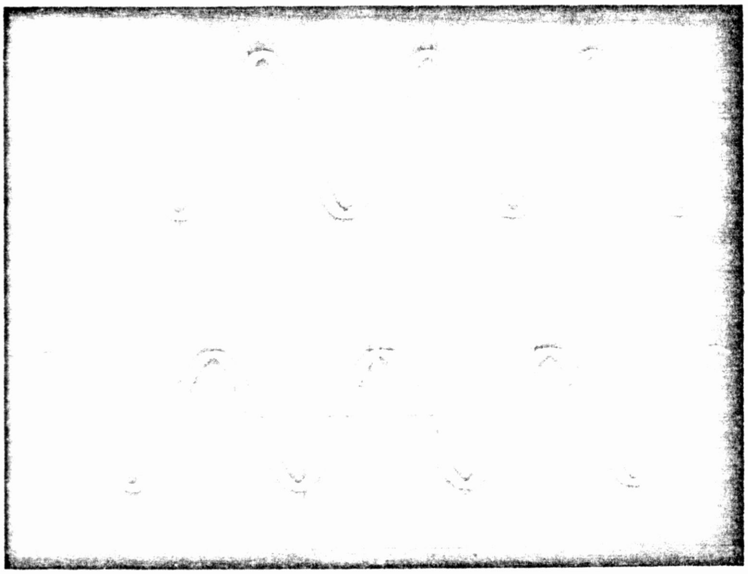
Vertical:

.05 V/DIV.

Horizontal:

10 m sec/DIV.

Fig. 5b. Cone velocity versus cone acceleration at 30 Hz.



Vertical:

.05 V/DIV.

Horizontal:

10 m sec/DIV.

Fig. 5c. Cone velocity versus cone acceleration at 900 Hz.

Input Vertical:

5 V/DIV.

Acceleration

Vertical:

.5 V/DIV.

Horizontal:

10 m sec/DIV.

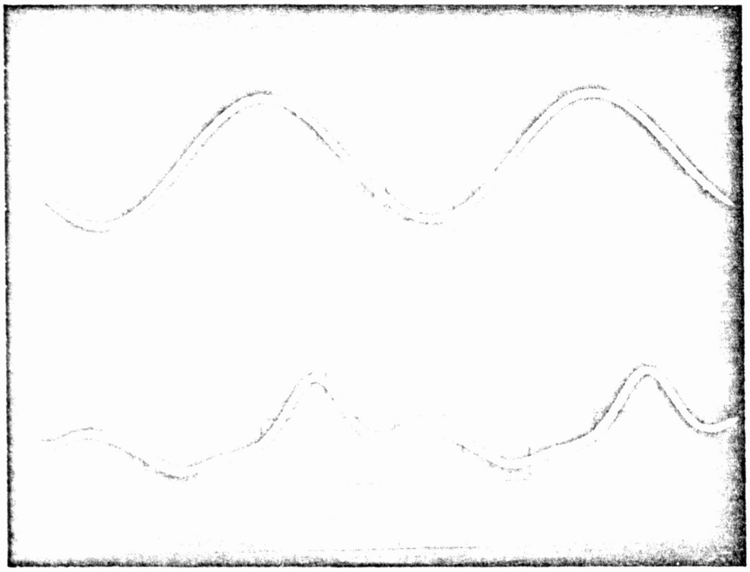
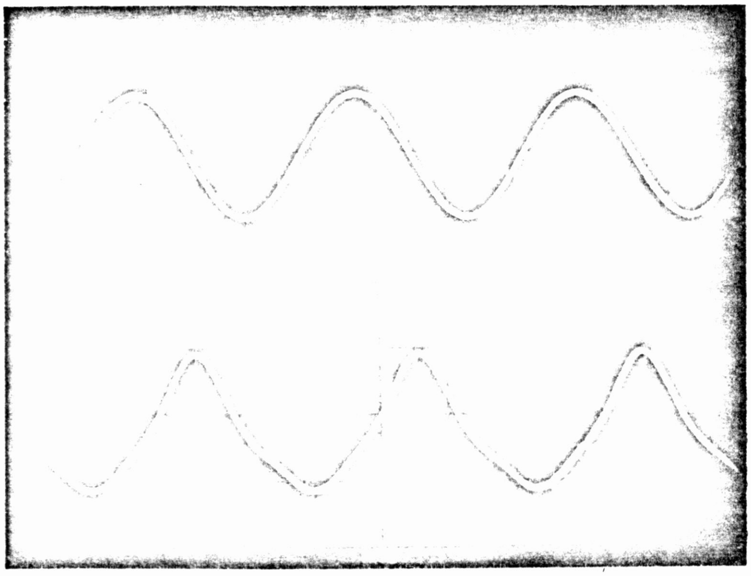


Fig. 6a. Input voltage versus acceleration voltage at 20 Hz.



Input Vertical:
5 V/DIV.
Acceleration
Vertical:
.5 V/DIV.
Horizontal:
10 m sec/DIV.

Fig. 6b. Input voltage versus acceleration voltage at 30 Hz.

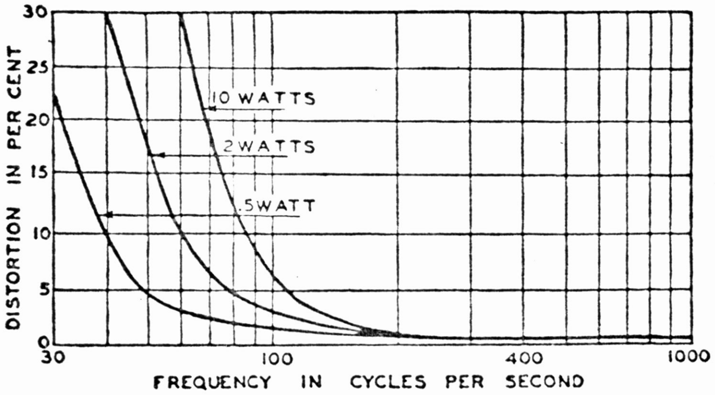
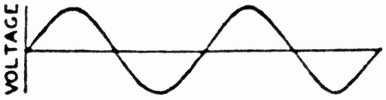
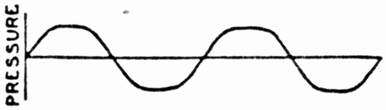


Fig. 7. Graph showing distortion as a function of frequency.



ELECTRICAL INPUT



ACOUSTICAL OUTPUT

Fig. 8. Graphs showing distortion caused by non-linear suspension system.

distortion. Harmonic distortion will produce multiples of the original fundamental frequency. In fact, distortion at the very low frequencies will probably be more easily detected than the fundamental frequency itself due to the sensitivity of the ear at the midrange frequencies [4].

Since the loudspeaker distorts due to the non-linearity of the suspension system, one method of correcting the situation is to incorporate the loudspeaker in a closed loop system with the amplifier. This can be accomplished as shown in the block diagram in Figure 9. The feedback signal can be obtained by either method suggested earlier in this paper; i.e., by using either a crystal, or a bridge network across the voice coil. The second method has the disadvantage of

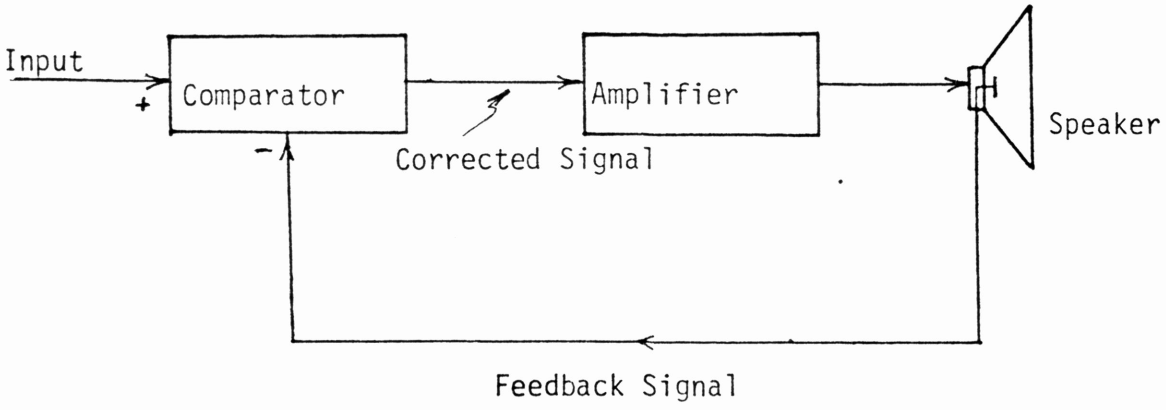


Fig. 9. Block diagram of feedback system.

being affected by operation of the coil in a non-linear magnetic flux field. Its main advantage, however, is that this type of feedback could be used with any loudspeaker without actually modifying the speaker itself. In this experiment, as stated earlier, the crystal was used to monitor the signal obtained from the bridge network. Either voltage signal could be used as a feedback voltage to be fed back to the comparator circuit. If the acceleration signals can be obtained by successively performing the electrical/mathematical operation of integration of these signals; i.e., the integral of acceleration is velocity, and the integral of velocity is displacement. These three types of feedback and their effects on the system response are shown in Figure 10. The displacement feedback signal will increase both the resonant frequency of the system and also whiat is known as the Q of the system. The Q is a figure of merit for the damping of

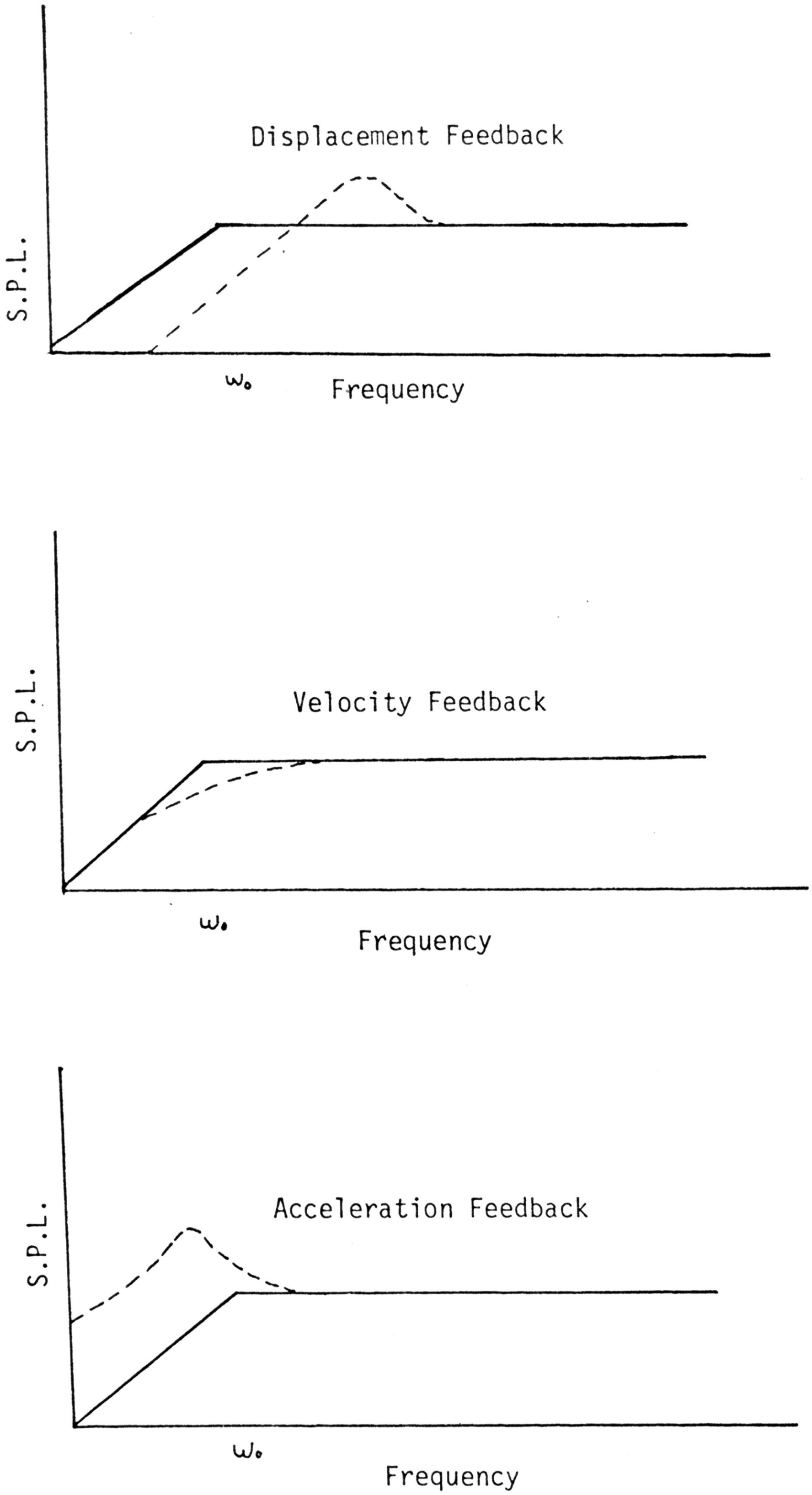


Fig. 10. The effects of 3 types of feedback.

the system. Ideal response of a loudspeaker is shown by the solid line. The added effect of control is shown with a dotted line. Velocity feedback will lower the Q of the system without affecting the resoant frequency. Acceleration feedback, however, will lower the resonant frequency and increase the Q of the system simultaneously. Thus all 3 types of feedback signals can be used to control the response of the system at low frequencies. Any one parameter can now be changed independently of the other parameters. Essentially the feedback will allow the user to control not only the damping of the system at low frequencies, but also the resonant frequency itself. This is important because the reasonant frequency determines where the response begins to decay. The response falls off rapidly below resonance. The trend in the past has been to improve the bass response by mass loading the low frequency loudspeaker which would lower the resonant frequency. There is, however, a conflict: the moving mass is inversely proportional to the efficiency of the system, hence there is a tradeoff involved. The feedback system will effectively control the response so the system responds at a lower frequency and also reduces the distortion. Besides these two advantages, the active loudspeaker with feedback has the potential advantage of being more efficient than a passive loudspeaker. In other words, the active loudspeaker does not need to be mass loaded since feedback will be used to control the response below resonance. Hence, if the cone is made lighter in weight the efficiency will have been improved.

CONCLUSIONS

A review of the literature has shown studies of feedback using either the back emf or the crystal to monitor the motion of the cone. In this paper, both methods were compared against each other to determine if both types of measurements are in agreement.

This was accomplished by mounting a crystal preamplier on the loudspeaker cone to monitor its motion. An operational amplifier bridge network was constructed to obtaine the velocity feedback signals.

Distortion from the loudspeaker was observed and compared using both these methods. The distortion increased as the frequency was made lower. This is to be expected becuase the cone excursion is increased as the frequency is lowered. As the cone excursion is increased, the loudspeaker will begin to distort due to the non-linear suspension system. Consequently, either method of measuring the feedback voltage is satisfactory. The bridge network appears to be more practical since no modifications have to be made to the loudspeaker.

From a mathematical standpoint, three types of feedback; acceleration, velocity, and displacement, can be used to completely control the response near the resonant frequency.

By controlling the frequency response near resonance with feedback, one can lower the resonant frequency thus obtaining more bass response, reduce the harmonic distortion caused by the non-linear suspension system, and potentially increase the efficiency of the system.

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APPENDIX

DESIGN OF JFET PREAMPLIFIER

COMMON SOURCE WITH UNBYPASSED SOURCE RESISTANCE.

$$\frac{V_{out}}{V_{in}} = \frac{-\mu R_d}{r_d + R_d + (\mu+1)R_s}$$

WHERE $r_d = 36.8K$

$g_m = 8.43\,m℧$

$\mu = r_d g_m = 310.2$

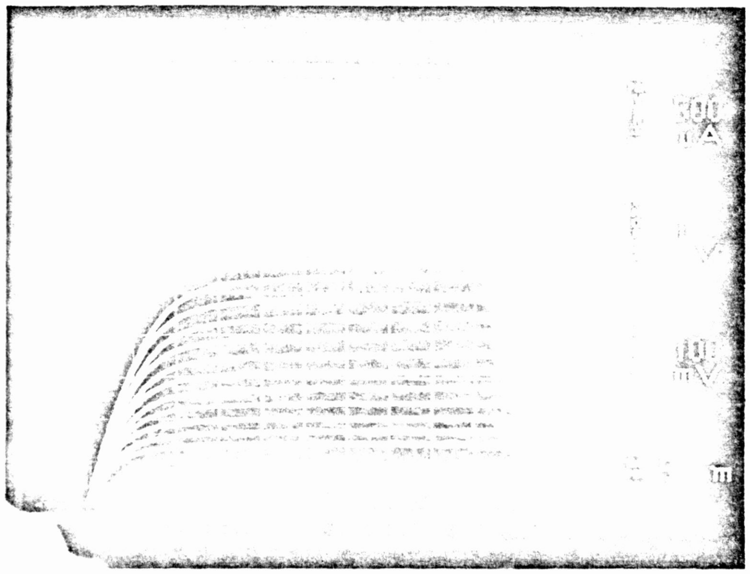
$$\frac{V_{out}}{V_{in}} = \frac{-(310)(2K)}{36.8K + 2K + (311)(1.3K)} \approx 1.4$$

OUTPUT IMPEDANCE $R_o \approx R_d$

$R_o \approx 2K\Omega$

INPUT IMPEDANCE $R_i \approx 50\ M\Omega$

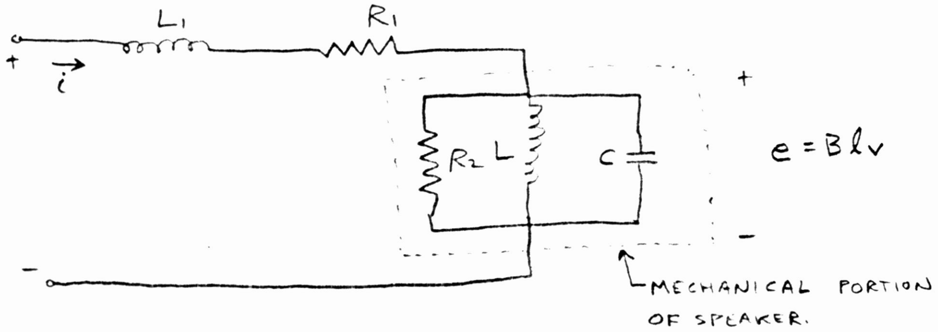
MEASURED VALUES AGREE CLOSELY WITH CALCULATIONS.



CHARACTERISTICS OF JFET USED.

MATHEMATICAL ANALYSIS OF FEEDBACK

EQUIVALENT MODEL FOR LOW FREQUENCY RESPONSE. SINCE THE ANALYSIS IS FOR LOW FREQUENCIES, L_1 CAN BE NEGLECTED.



CALCULATE TRANSFER FUNCTION

$$e = \left[sL \,\|\, \frac{1}{sC} \,\|\, R_2\right] i$$

$$= \left[\frac{\frac{sL}{sC}}{sL + \frac{1}{sC}} \,\|\, R_2\right] i$$

$$= \left[\frac{\frac{L}{C}}{sL + \frac{1}{sC}} \,\|\, R_2\right] i$$

$$= \left[\frac{sL}{s^2LC+1} \,\|\, R_2\right] i$$

$$= \left[\frac{\frac{sLR_2}{s^2LC+1}}{\frac{sL}{s^2LC+1} + \frac{R_2(s^2LC+1)}{s^2LC+1}}\right] i$$

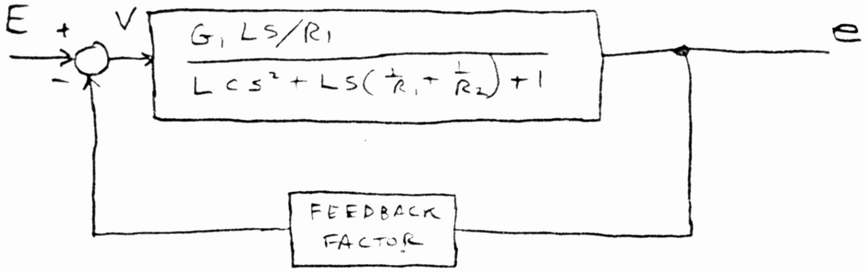
$$e = \left[\frac{sLR_2}{sL + R_2s^2LC + R_2}\right] i$$

$$V = \left[sL_1 + R_1 + \frac{sLR_2}{sL + R_2s^2LC + R_2}\right] i$$

NEGLECTING L_1:

$$\frac{e}{V} = \frac{sL/R_1}{s^2LC + Ls\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + 1}$$

IN BLOCK DIAGRAM FORM:



FEEDBACK FACTOR: gs FOR ACCELERATION F.B.

g FOR VELOCITY F.B.

$\frac{g}{s}$ FOR DISPLACEMENT F.B.

G_1 IS GAIN FACTOR.

ACCELERATION F.B.

$$\frac{e}{E} = \frac{\dfrac{\frac{G_1 Ls}{R_1}}{Lcs^2 + Ls(\frac{1}{R_1} + \frac{1}{R_2}) + 1}}{\dfrac{Lcs^2 + Ls(\frac{1}{R_1} + \frac{1}{R_2}) + 1}{Lcs^2 + Ls(\frac{1}{R_1} + \frac{1}{R_2}) + 1} + \dfrac{\frac{G_1 Ls^2 g}{R_1}}{Lcs^2 + Ls(\frac{1}{R_1} + \frac{1}{R_2}) + 1}}$$

$$= \frac{\frac{G_1 Ls}{R_1}}{Lcs^2 + Ls(\frac{1}{R_1} + \frac{1}{R_2}) + 1 + \frac{G_1 Ls^2 g}{R_1}}$$

$$= \frac{G_1 Ls}{s^2 L(c + \frac{G_1 g}{R_1}) + \frac{Ls}{R_3} + 1} \qquad \text{WHERE } 1/R_3 = \left[\frac{1}{R_1} + \frac{1}{R_2}\right]$$

$$= \frac{\dfrac{G_1 Ls}{(LcR_1 + G_1 g)}}{s^2 + \dfrac{LsR_1}{R_3(LcR_1 + G_1 g)} + \dfrac{1}{Lc + \frac{LgG_1}{R_1}}}$$

THIS IS OF THE FORM FOR A SECOND ORDER SYSTEM:

$$\frac{K}{s^2 + \frac{2\delta s}{\omega_0} + \omega_0^2}$$

CLOSED LOOP RESONANT FREQUENCY:

$$\omega_0' = \frac{1}{\sqrt{LC + \frac{LgG_1}{R_1}}}$$

IN TERMS OF ω_0, THE OPEN LOOP RESONANT FREQUENCY: $\omega_0 = \frac{1}{\sqrt{LC}}$

$$\omega_0^2 = \frac{1}{LC}$$

$$LC = \frac{1}{\omega_0^2} \quad \text{AND} \quad L = \frac{1}{C\omega_0^2}$$

THEN

$$\omega_0' = \frac{1}{\sqrt{\frac{1}{\omega_0^2} + \frac{gG_1}{R_1 C}}}$$

$$\boxed{\omega_0' = \frac{\omega_0}{\sqrt{1 + \frac{gG_1}{R_1 C}}}}$$

THUS, ACCELERATION FEEDBACK HAS REDUCED THE RESONANT FREQUENCY OF THE SYSTEM.

EFFECT OF ACCELERATION F.B. ON THE Q-FACTOR

$$Q = \frac{1}{2\xi} = \frac{R_3}{L\omega_0} \quad \text{WHERE} \quad \frac{1}{R_3} = \left[\frac{1}{R_1} + \frac{1}{R_2}\right]$$

$$Q' = \frac{R_3}{L\omega_0'}$$

WITH FEEDBACK $Q' = \frac{R_3}{L}\sqrt{LC + \frac{LgG_1}{R_1}}$

IN TERMS OF Q IN THE OPEN LOOP SITUATION:

$$\frac{R_3}{L} = Q\omega_0$$

$$Q' = Q\omega_0\sqrt{LC + \frac{LgG_1}{R_1}}$$

$$Q' = Q\frac{1}{\sqrt{LC}}\sqrt{LC + \frac{LgG_1}{R_1}}$$

$$\boxed{Q' = Q\sqrt{1 + \frac{gG_1}{R_1C}}}$$

THUS, ACCELERATION FEEDBACK HAS INCREASED THE Q OF THE SYSTEM.

BY PERFORMING A SIMILAR TYPE OF ANALYSIS FOR VELOCITY AND DISPLACEMENT, THE FOLLOWING RESULTS ARE OBTAINED:

VELOCITY:

$$\boxed{w_o' = w_o}$$

$$\boxed{Q' = \frac{Q}{\frac{1}{LC} + \frac{G_1 g R_3}{L R_1 C}}}$$

DISPLACEMENT:

$$\boxed{w_o' = w_o\sqrt{\frac{G_1 g L}{R_1} + 1}}$$

$$\boxed{Q' = Q\sqrt{\frac{G_1 g L}{R_1} + 1}}$$