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Short Note

Intermittent Automodulation Observed in Fe-3%Si Reeds

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Automodulation was observed to occur in Fe-3%Si polycrystalline reed specimens intermittently and rather irregularly. This forms a striking contrast to the continuous automodulation usually observed in such materials as Zn or Mg. This unfamiliar automodulation, which seems to have three different modes, was explained in terms of phase transformation and stochastic processes.

KEYWORDS: automodulation, Fe-3%Si, phase transformation, stochastic process, nonlinear inelasticity

It has been reported that when reeds made of such metals as zinc or magnesium are driven to vibrate under a periodic force of constant magnitude, their amplitude of vibration may spontaneously vary with time; this phenomenon is now termed "automodulation".[1-3] Suzuki *et al.* attributed the occurrence of automodulation to such phase transformation of the metals concerned to deformation twinning or martensite transformation.[1,2] Their computer simulation based on nonlinear differential equations successfully reproduced the automodulation behavior observed. The automodulation they treated was, however, of the ordinary type and hence distinctly different from the type treated here.

We used as specimen reeds ($55\times5\times0.35\ \mathrm{mm}^3$) made of Fe-3%Si polycrystals with a grain size of 2-3 mm. Our experimental apparatus, conventional type for measuring the internal friction of solids, was described in a previous paper.[4] We were able to observe automodulations only when the reeds were vibrated with a driving force seemingly high enough to cause nonlinear inelasticity in them.[4]

Figure 1 is a typical oscillogram obtained; the upper curve represents the periodic input current at a frequency of 74.60 Hz, whereas the lower indicates the displacement of a portion of a reed specimen near its free edge as a function of time. One can clearly see the variation of vibration amplitude—the automodulation. In the automodulation observed by earlier researchers, there are two types ; in Type 1 the phase varies linearly with time and the amplitude is periodically modulated, while in Type 2, both the phase and the amplitude are periodically modulated. It should be stated here that in contrast to these continuous types, the automodulation shown in the lower curve of Fig. 1 is unstable and intermittent; the vibration amplitude and the time and duration of occurrence fluctuate greatly.

Table I. Comparison between experimental and calculated modulation frequency. f_d: driving frequency, f_m: modulation frequency, f_0: characteristic frequency.

f_d (Hz)	f_m (Hz)	$(f_d-f_0)/2$ (Hz)
67.73	4.76	5.66
72.98	2.63	3.035
75.48	1.89	1.785
76.51	1.72	1.27
78.51	0.53	0.27

Through careful examination of many oscillograms, we concluded that the automodulation observed in the present study can be classified into the following three modes as shown in Figs. 2(a)-2(c):

Mode A: Vibration amplitude, after increasing to the maximum, decays to its normal (i.e., unmodulated) value monotonously. In this mode, automodulation occurs independently, i.e., during or immediately before or after the period of this mode, no additional change in amplitude takes place (Fig. 2(a)).

Mode B: Initially increased amplitude does not decrease monotonously but tends to rise again before decaying to the normal value (Fig. 2(b)).

Mode C: Increased vibration amplitude stays practically constant for a relatively long period until returning to the unmodulated state (Fig. 2(c)).

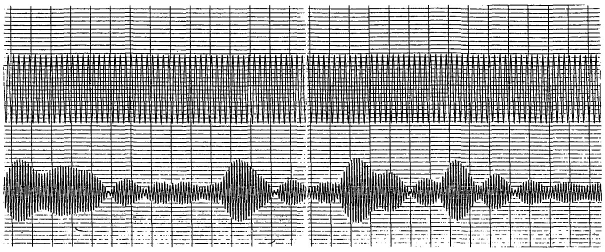

Fig. 1. A typical oscillogram showing the intermittent automodulation of a Fe-3%Si reed (lower). A simultaneously recorded oscillogram of alternating current used for driving the specimen (upper).

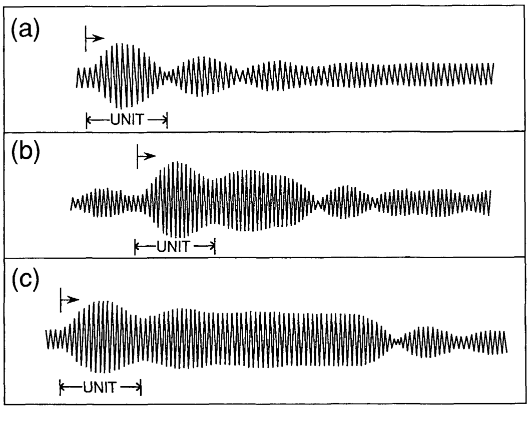

Fig. 2. Three typical modes of automodulation distinguishable from the oscillograms obtained.

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Figures 2(a)–2(c) are worthy of further attention: one can see that the number of forced vibrations contained in such an 'automodulation unit' as shown in Fig. 2 is equal from (a) to (c). In other words, the modulation frequency, f_m, defined as the reciprocal of the duration of the unit, can be taken as constant for a given specimen and a given driving frequency f_d. The characteristic frequency, f_0, of the reed specimen used was 79.05 Hz. Table I shows that f_m is rather close to half of the difference between f_d and f_0.

From all of these results we consider it very probable that the automodulation observed in the present study was principally the beat of two kinds of specimen vibration: one, the externally driven vibration, the other, a self-induced vibration. Though the mechanism of this self-induced vibration is not very clear, we presume it to be correlated with the phase transition of the specimen material, as suggested by the model of Suzuki et al. employed for the interpretation of continuous-type automodulation. To be more exact, we assume the existence of two kinds of phase, P_1 and P_2, in the material, although we cannot identify the physical structure of the phases at present. Furthermore, we assume that the intense forced vibration of the specimen causes the transition between P_1 and P_2 to occur stochastically, and that the energy released at the time of transition from P_1 to P_2 or from P_2 to P_1 plays a role in inducing the characteristic vibration of the specimen.

In our model, the amplitude of the reed $X(t)$ can be written as

$$X(t)=a(t)\sin(\omega_d t)+\sum_i b_i(t)\sin(\omega_0 t) \qquad (1)$$

$$b_i(t)=u(t-t_i)\exp[-(t-t_i)/\tau] \qquad (2)$$

where $a(t)$ represents the amplitude of the forced vibration with an angular frequency $\omega_d(=2\pi f_0)$, while $b_i(t)$ is the amplitude of the characteristic vibration (angular frequency $\omega_0(=2\pi f_0)$) which is initiated at time t_i. It should be noted that $a(t)$ is not a continuous function of t but takes only two fixed values,* a_1 and a_2, depending on phases P_1 and P_2; this amplitude change is very likely since the phase transformation usually causes a change in elastic modulus. The implication of eq. (2) is as follows: when the transition is initiated, the amplitude of the characteristic vibration increases linearly with the progress of time at first, but soon it begins to decay exponetially with a time constant τ because of internal friction.

Figure 3 is a diagram to make the above-stated concept somewhat more understandable. In view of this model, the three kinds of automodulation mode observed in the present study can be interpreted as follows:

Mode A: The specimen transforms from Phase 1 (P_1) to 2 (P_2) at $t=t_{a1}$ but returns to P_1 immediately. The characteristic vibration of the specimen is simultaneously stimulated at t_{a1}.

Mode B: Mode A transition occurs repetitively before the initially raised amplitude decays to the unmodulated value. Hence, the characteristic vibration is excited not only at t_{b1} but also t_{b2}, $t_{b3}\cdots$ (the case where $i=1$ and 2 is shown in the figure).

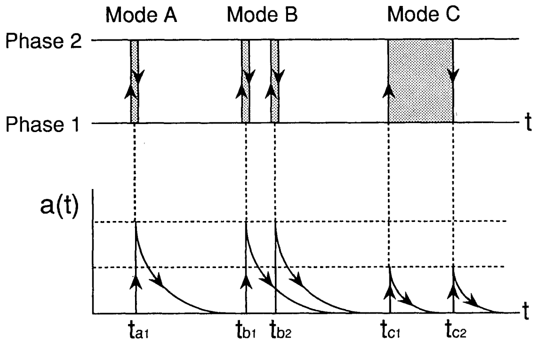

Fig. 3. Schematic diagrams proposed for the interpretation of the three modes shown in Fig. 2. Upper: Phase transition behavior in three modes. Lower: Associated change in the amplitude of the characteristic vibration of the reed excited by phase transition.

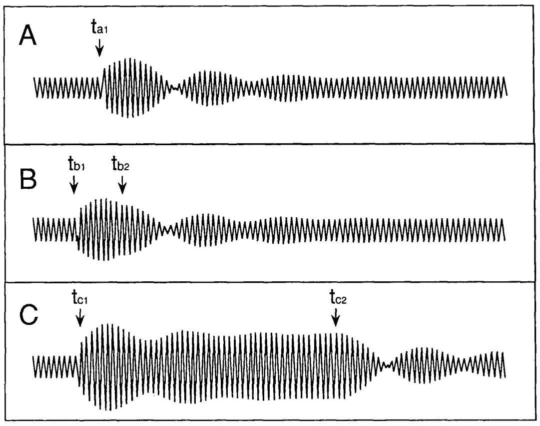

Fig. 4. Three modes of automodulation obtained from a computer simulation of the results of Fig. 2.

Mode C: The specimen phase, which transforms from P_1 to P_2 at $t=t_{c1}$, remains at P_2 until t_{c2}. Hence, the characteristic vibration is stimulated at both t_{c1} and t_{c2}.

Based on this model, we performed computer simulations using eqs. (1) and (2). Figure 4 shows the results obtained. Although we determined from the actual oscillogram the values of a_2/a_1, $b(t_i)/a_1$ and t_i as fitting parameters, excellent agreement is obvious between the simulated and the observed automodulation.

Since this interpretation is only phenomenological, further experiments are apparently necessary to understand the microscopic mechanism, including the meaning of the phenomenological parameters used in the present analysis. In conclusion, a new type of automodulation was observed in Fe–3%Si reeds. This was explained satisfactorily by a model based on the stochastically occurring phase transformation.

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*From the examination of many oscillograms it is certain that the first peak amplitude of this intermittent automodulation is almost constant and independent of the length of intermission from the preceding automodulation.