are obtained from samples in the "shorted guard-ring" configuration [75G4].

The measured relationships between piezoelectric polarization and strain for X-cut quartz and Z-cut lithium niobate are found to be well fit by a quadratic relation. In both materials a significant nonlinear piezoelectric effect is indicated. The effect in lithium niobate is particularly notable because the measurements are limited to much smaller strains than those to which quartz can be subjected. The quadratic polymonial fits are used to determine the second- and third-order piezoelectric constants and are summarized in table 4.2. Elastic constants determined in these investigations are summarized in table 3.1 in section 3.1.

Table 4.2
Second- and third-order piezoelectric stress constants of lithium niobate and quartz in the abbreviated notation

Sample	e_{ij} (C/m^2)	e_{ijk} (C/m^2)	e_{ijk}/e_{ij} (C/m^2)
Lithium niobate			
$i = j = k = 3$	1.80 ± 0.016	-21 ± 7	-11
$i = j = k = 2$	2.37 ± 0.036	21 ± 10	$+9$
$i = 1, j = 5$	3.83	...	...
Rotated cut	4.65 ± 0.053	0	...
Quartz			
$i = j = k = 1$	0.171 ± 0.0009	-2.62 ± 0.05	-15.3

In the case of X-cut quartz there is excellent agreement between second-order constants determined in the shock-compression studies and ultrasonic investigations. The third-order piezoelectric constants for quartz determined from the impact experiments are determined far more accurately than those determined from ultrasonic studies.

For lithium niobate, the second-order constants for shock and ultrasonic studies are in good agreement except for the e_{33} constant which is observed to be higher in shock studies than in ultrasonic investigations [77G6]. This discrepancy is thought to be due to the use of incompletely poled material for the ultrasonic work. The third-order constants for lithium niobate are not determined as accurately as those for X-cut quartz due to the relatively low strains which can be applied before the onset of shock-induced dielectric breakdown (see section 4.6). Nevertheless, the errors of these constants are lower than the order-of-magnitude estimates obtainable by ultrasonic means.

Lithium niobate is strongly ferroelectric yet the material behavior under elastic shock loading is apparently fully described by nonlinear piezoelectricity [77G6]. This is not unreasonable since it is well known that domain realignment with field occurs only in the vicinity of the Curie temperature of 1475 K.

The ratio of third-to-second-order piezoelectric constants has also been determined for X-cut quartz with the acceleration pulse loading method described in ref. [77G5]. Two experiments yielded values for e_{111}/e_{11} of 15.0 and 16.6 [77G5] compared to the ratio of 15.3 determined from the 25 shock loading experiments [72G3].

The determination of piezoelectric constants from current pulses is based on interpretation of wave shapes in the weak-coupling approximation. It is of interest to use the wave shapes to evaluate the degree of approximation involved in the various models of piezoelectric response.

Such an evaluation is shown in fig. 4.3, in which normalized current-time waveforms calculated from various models are shown for X-cut quartz and Z-cut lithium niobate. In both cases the differences between the fully-coupled and weakly-coupled solutions are observed to be about 1 per cent, which is within the accuracy limits of the calculations. Hence, for both quartz and lithium niobate, weakly-coupled solutions appear adequate for interpretation of observed current-time waveforms. On the other hand, the adequacy of the uncoupled solution is significantly different for the two materials. For X-cut quartz the maximum error of about 1 to 1.5 per cent for the nonlinear-uncoupled solution is suitable for all but the most precise interpretation. For Z-cut lithium niobate the maximum error of about 8 per cent for the nonlinear-uncoupled solution is greater than that considered acceptable for most cases. The linear-uncoupled solution is seriously in error in each case.

A unique electrical-to-mechanical coupling effect called "piezoelectric rate coupling" has been predicted to occur in the neighborhood of a shock in *nonlinear* piezoelectric solids [75G5]. The effect appears as a strain gradient in the presence of an electric field rate. The strain gradient apparently persists for only a few nanoseconds or is of such small magnitude that it cannot be observed in careful measurements with a VISAR system since such unpublished measurements by Graham and Asay found no evidence for the expected coupling.

Above or in the vicinity of the Hugoniot elastic limit shock-induced conduction and mechanical yielding cause severe distortions to the idealized piezoelectric response. Well above the Hugoniot elastic limit the three-zone model of Neilson and Benedick [62N1] can be employed to describe and interpret certain dominant features [74G2, 79S2]. An early-time transient observed in quartz [74G2] and lithium niobate [79S2] above the HEL is apparently the result of relaxation of strength [78H2]. The piezoelectric response of Z-cut lithium niobate above the HEL is significantly different from that of X-cut quartz.

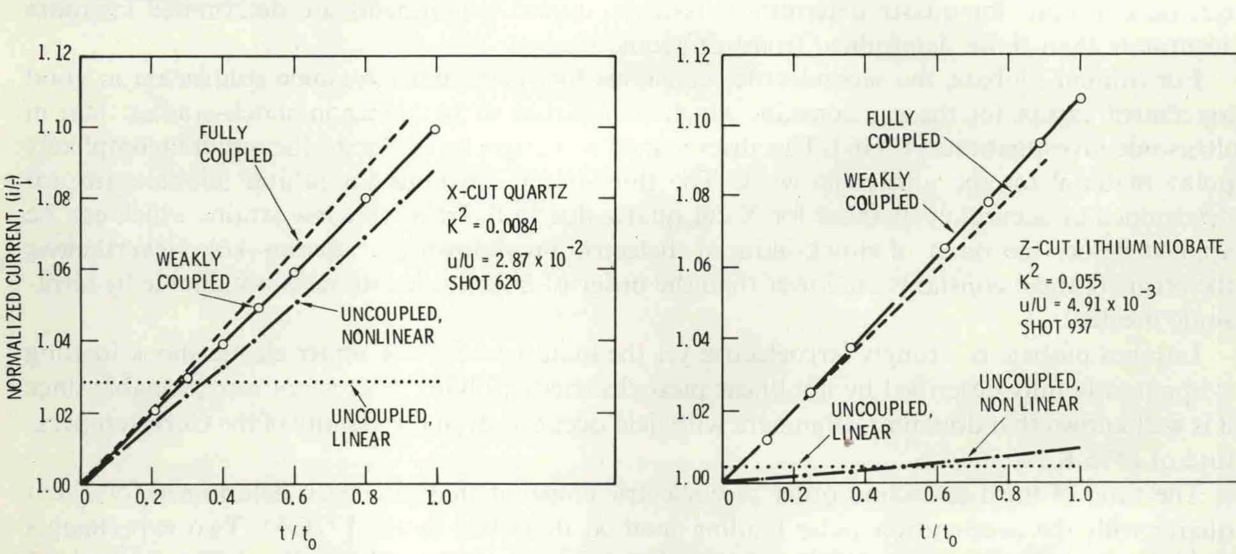

Fig. 4.3. Solutions for normalized current for shock-loaded piezoelectric samples in the linear-uncoupled, nonlinear-uncoupled, weakly-coupled and fully-coupled approximations are shown for X-cut quartz and Z-cut lithium niobate. Lithium niobate has a moderately large electromechanical coupling while quartz has a very small electromechanical coupling. The weakly-coupled solution is that of Thurston [74T1] as modified by Graham [77G6]. In both cases the mechanical boundary conditions correspond to those encountered in the experiments. The experimentally observed current pulses correspond to the fully-coupled solutions within experimental and computational errors. The symbol i is the initial current $i(0+)$.