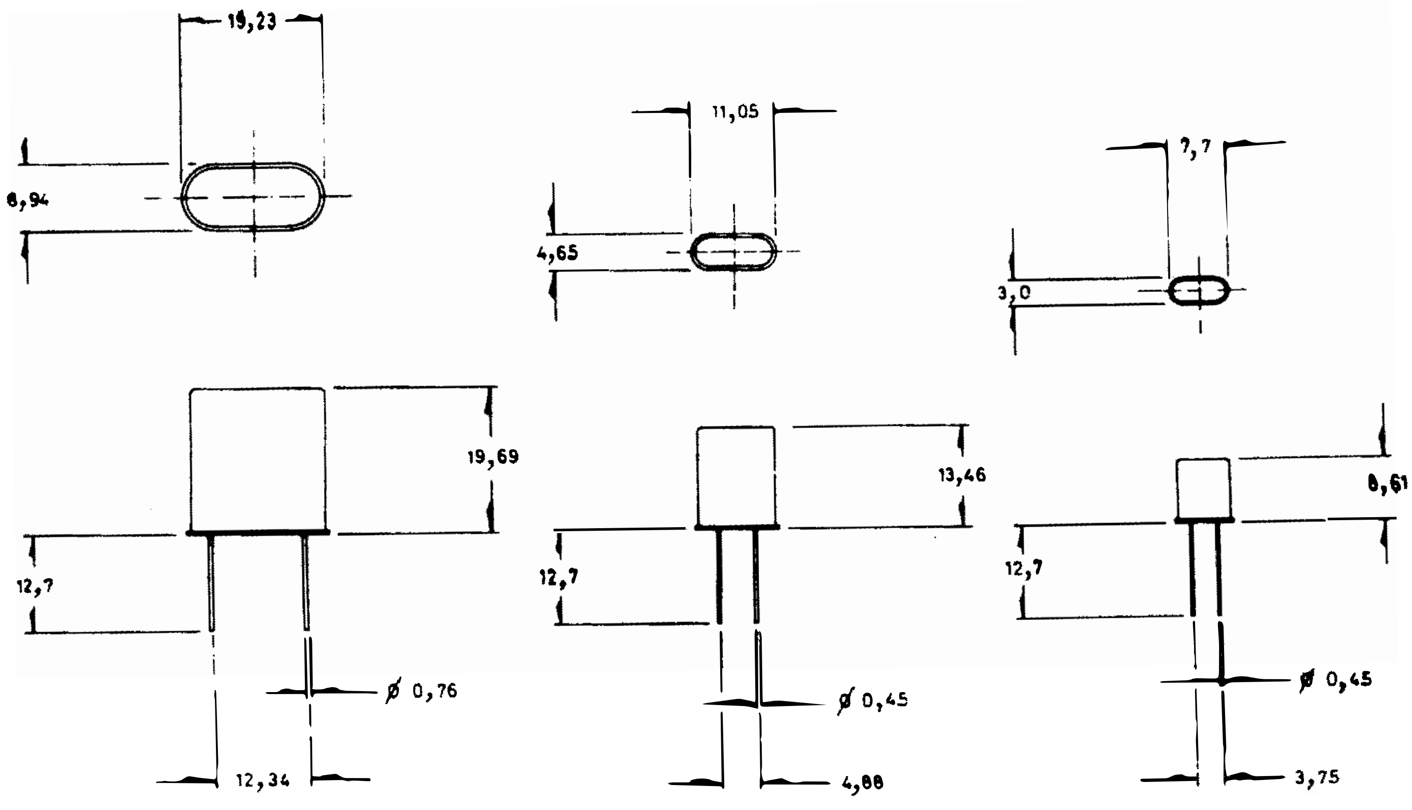
# 7 Characteristics of AT-cut crystal resonators

## 7.1 BLANK DIAMETER AND GEOMETRY

The conventional AT-cut resonator, as opposed to the newer miniature AT bar resonators, is in the first approximation a pure thickness mode resonator (Chapter 2). For circular plates of sufficiently large diameter to thickness ratio $d/t$ this first approximation provides a reasonable guide to resonator behaviour, but as the ratio decreases the effects of the finite lateral dimensions become increasingly important (Chapter 3).

For $d/t$ ratios greater than 50, a flat or plano-plano blank design with no bevel or contour will usually provide acceptable performance for fundamental mode crystals. For $d/t$ ratios less than 50 but greater than 30, an edge bevel (partial contour) will generally be necessary, whereas for ratios below 30 a complete spherical contour is required. Provided that $d/t$ remains above 12 a plano-convex design is usually adequate, but for the lowest $d/t$ ratios a full bi-convex contour is required with perhaps a steeper edge bevel in addition. The limiting values of the $d/t$ ratios quoted above are empirical in nature and by no means absolute, particularly in the lower $d/t$ ranges, where for example it might often prove desirable to use a plano-convex design with an edge bevel rather than a bi-convex design to achieve some desired combination of parameters. Nevertheless, the classification given is useful in estimating the probable complexity required in a given blank design. For overtone mode resonators, the limiting values can usually be relaxed as compared to fundamentals so that flat designs can safely be used at $d/t$ ratios below 50, perhaps down to $d/t = 35$. It is, however, difficult to give general rules for contoured overtone resonators since these are little used in general applications, mostly being restricted to limited volume, high precision units at specific frequencies.

When these design rules are combined with information on the maximum blank diameters that can be accommodated in a given holder style, it is straightforward to determine the frequency ranges for that holder style in which bevelled, plano-convex and bi-convex designs need to be used. This is

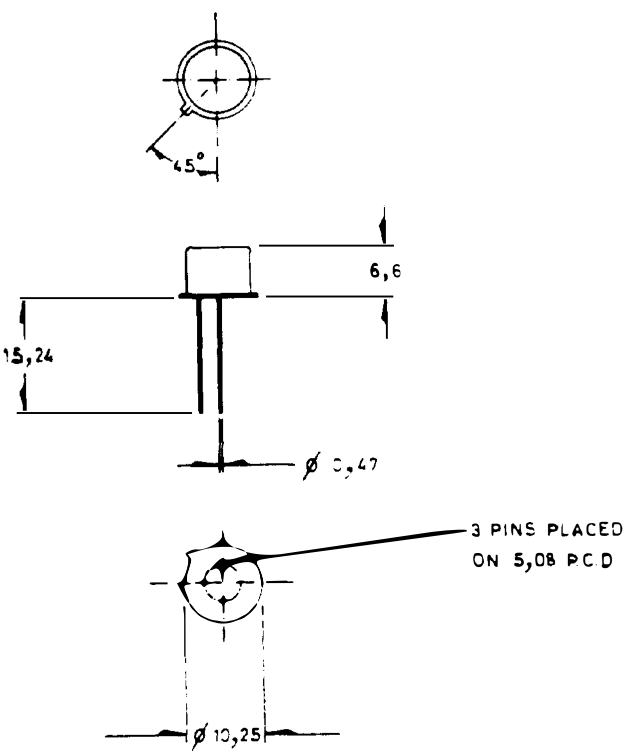



HC-51 style HC-49 style HC-45 style

**Fig. 7.1** Crystal holders.

important both in regard to the obvious differences in the manufacturing costs of say a bi-convex unit as compared to a flat unit, but also in regard to the different performance characteristics that will result in the various frequency intervals.

The maximum diameter blank that can be accommodated in a given holder is determined by the space available. Figures 7.1 and 7.2 give the outline dimensions of some of the more popular crystal holders, and Table 7.1 gives the approximate maximum blank diameters and the frequency ranges applicable to the different types of blank geometry. Again the data in Table 7.1 should be regarded as a guide only, manufacturing practices differing from supplier to supplier. The maximum blank diameter listed in Table 7.1 is a *maximum*, and will not generally be used for all units in a given holder. It is clearly desirable from the manufacturing point of view to use flat blanks, but when the frequency required is such that the necessary $d/t$ ratio can be




HC-35 style

**Fig. 7.2** Crystal holders.

**Table 7.1**

| Holder | Max blank diameter (mm) | Frequency ranges (MHz) Flat | Bevelled | Plano-convex | Bi-convex |
|---|---|---|---|---|---|
| HC-45 | 5.0 | 16 min | 10 - 16 | below 10 | — |
| HC-35 | 6.2 | 13 min | 8 - 16 | below 8 | — |
| HC-49 | 8.6 | 10 min | 5.5 - 10 | below 5.5 | — |
| HC-51 | 15 | 5.5 min | 3 - 5.5 | 1.5 to 3 | below 1.5 |

achieved with blanks smaller than the maximum, then such blanks will generally be used. This results in economy in raw material, and also in mechanically more robust units, since very thin blanks of unnecessarily large diameter are prone to breakage.

## 7.2 MOTIONAL CAPACITANCE AND SHUNT CAPACITANCE

The shunt capacitance or $C_0$ is essentially the sum of the capacitance $C_e$ between the electrodes of the crystal and the capacitance $C_h$ of the holder itself. For flat blanks, neglecting fringing effects and the capacitance due to the electrode tails, the capacitance $C_e$ in pF is approximately given by

$$C_e = 0.04A/t \tag{7.1}$$

where $A$ is the electrode area in mm$^2$ and $t$ the blank thickness in mm. This can be recast in the form

$$C_e = 0.019d^2f/N \tag{7.2}$$

where now $d$ is the electrode diameter in mm, $f$ the nominal frequency in MHz and $N$ the overtone order. To obtain $C_0$, the holder capacitance $C_h$ which is typically of the order of or less than 1 pF must be added to $C_e$ as calculated from Eqn (7.1) or (7.2).

The $C_0$ of contoured crystals cannot be calculated directly from these simple formulae, but nonetheless Eqn (7.2) will give a reasonable estimate, sufficient for most practical purposes.

The motional capacitance of an AT-cut resonator can in principle be calculated from the second of Eqns (2.51), with appropriate values of the material constants. However, this is only valid for pure thickness modes and in practice needs correction to take account of the variation in the amplitude of vibration across the surface of the plate. Empirically it is found that at least for fundamental mode resonators, $C_1$ is given by the approximate formula

$$C_1 = 0.105d^2f/N^3 \tag{7.3}$$

which differs from the formula obtained directly from Eqn (2.51) only in the value of the numerical factor.

Equation (7.3) predicts $C_1$ for fundamental resonators reasonably accurately, but for overtone resonators will only give satisfactory values for units, such as filter crystals, designed according to energy trapping principles. Standard overtone oscillator crystals are usually fabricated with mass loadings far in excess of that required by energy trapping theory (Chapter 3), and have $C_1$ values substantially lower than predicted by Eqn (7.3). Another cause of variation in the $C_1$ of overtone oscillator crystals lies in the commonly used method of final frequency adjustment by evaporation of material on to the central region of the electrodes. If too much material is added in the adjustment process, the result will be that the motional parameters of the unit begin to be governed by the diameter of the adjusting spot, rather than the diameter of the electrodes as originally deposited, because of energy trapping under the spot. Hence the conclusion can be drawn that the control of the motional capacitance of overtone resonators is substantially more difficult than for fundamentals.

The behaviour of the motional capacitance of contoured crystals is quite different from that of flat crystals. In the latter case, as indicated above, the electrode diameter is the main governing factor. With contoured crystals, however, the energy trapping due to the contour itself limits the vibrating area of the blank, and an effective diameter $d_v$ can be defined in such a way that the amplitude of vibration can be regarded as negligible outside a circle of diameter $d_v$. Then it follows that however much the electrode diameter is increased over and above the value $d_v$, the motional capacitance will remain constant. In contrast, for electrode diameters less than $d_v$ the $C_1$ decreases with electrode area much as for a flat crystal. In practice it is usual for the electrode diameter to be chosen some 20% larger than $d_v$ so that the motional parameters are controlled by the blank geometry; if, as in the case of some filter crystals, it is necessary to use smaller electrode diameters, then another cause of variation in $C_1$ is the orientation of the electrode tails relative to the crystallographic $X$ axis.

Equations (7.2) and (7.3) show that for flat crystals the capacitance ratio $r = C_0/C_1$ has the approximate value 180 $N^2$. This does not take into account the holder capacitance, so that in practice the minimum $r$ value observed for fundamentals is about 200, with larger values for smaller electrode diameters when the holder capacitance is a larger part of the total $C_0$. Because of the departures of the $C_1$ value for overtone crystals from the predicted figures, the capacitance ratio for overtones is generally substantially greater than 180 $N^2$, the discrepancy increasing with the overtone. Likewise for contoured crystals, the capacitance ratio is higher than for flat crystals because of the limitation of the $C_1$ value by the contour already discussed.

Table 7.2 shows some typical values of the motional and shunt capacitance and the capacitance ratio of both contoured and uncontoured fundamental

**Table 7.2** Motional and shunt capacitances

| Frequency and overtone | $C_1$ (fF) | $C_0$ (pF) | $(C_0/C_1)$ |
|---|---|---|---|
| 5 MHz plano-convex fundamental | 7 | 3.2 | 457 |
| 15 MHz plano-plano fundamental | 25 | 5.5 | 220 |
| 45 MHz third overtone | 2 | 5.5 | 2 750 |
| 75 MHz fifth overtone | 0.6 | 5.5 | 9 170 |
| 105 MHz seventh overtone | 0.15 | 3.5 | 23 300 |
| 135 MHz ninth overtone | 0.08 | 3.5 | 43 750 |

mode resonators, and of overtone units up to the ninth overtone. Figure 7.3 shows the dependence of the $C_1$ and $C_0$ of a typical contoured blank on the electrode diameter, and the variation of the capacitance ratio. The electrode diameter corresponding to the minimum in the capacitance ratio curve is in a sense the optimum value, corresponding as it does to a maximum in the pulling sensitivity of the crystal unit.

## 7.3 Q FACTOR AND TIME CONSTANT

The $Q$ of a resonator is inversely proportional to the ratio of the energy dissipated per cycle to the total stored energy. The energy dissipated can be assigned to several different causes, the chief of which are:

(1) Intrinsic acoustic losses in the body of the material, determined by the

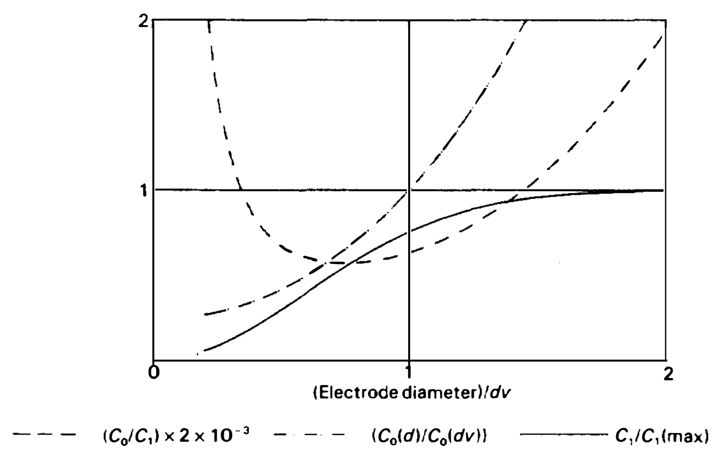



**Fig. 7.3** Variation of $C_1$, $C_0$ and $C_0/C_1$ of a contoured crystal with electrode diameter.

basic physical properties of the material and the defects introduced by the growth process.

(2) Acoustic losses at the surface of the resonator due to the imperfections produced by the lapping operations.

(3) Electrical and acoustic losses in the electrode material, dependent on the material used, its conductivity and thickness, and film defects owing to poor metallization.

(4) Losses due to mounting which are determined by the resonator design and mounting techniques. The critical parameter is the diameter to thickness ratio.

(5) Acoustic losses due to atmospheric damping, which can be eliminated by sealing the units under vacuum.

If the $Q$ factors due to each of these mechanisms alone are denoted by $Q_k$ with $k$ running from 1 to 5, then the overall $Q$ is given by

$$Q^{-1} = Q_1^{-1} + Q_2^{-1} + Q_3^{-1} + Q_4^{-1} + Q_5^{-1} \tag{7.4}$$

$Q_1$, the $Q$ factor associated with the intrinsic acoustic loss of quartz can be regarded as a limiting value which cannot be exceeded by any improvements in design or processing. Following the discussion in Section 2.4, the intrinsic $Q$ for the slow shear mode in an AT cut resonator is determined by the time constant $\tau$ for that mode, which is in turn determined in terms of the effective viscosity and elastic constant. For high quality electronic grade quartz the value of $\tau$ can be taken as $1.6 \times 10^{-14}$ seconds, equivalent to a $Q_1$ value at 10 MHz of approximately $10^6$. From Eqn (2.55), $Q_1$ is inversely proportional to frequency and so will be $10^7$ at 1 MHz and $10^5$ at 100 MHz.

Table 7.3 shows the theoretical minimum values of the motional resistance for the crystals whose $C_1$ values were tabulated in Table 7.2, calculated from the time constant $\tau = R_1C_1$ and assuming only the intrinsic material losses to be present. Also given are the maximum ESR values taken from standard commercial crystal specifications, and typical values obtained in a production environment. At the lower frequencies, mounting losses and atmospheric damping are important factors in degrading the attainable $Q$,

**Table 7.3** Motional resistances (ESRs)

| Frequency and overtone | $R_1$ (ideal) | $R_1$ (max) | $R_1$ (typical) |
|---|---|---|---|
| 5 MHz plano-convex fundamental | 2.3 | 60 | 20 |
| 15 MHz plano-plano fundamental | 0.6 | 20 | 10 |
| 45 MHz third overtone | 8 | 40 | 20 |
| 75 MHz fifth overtone | 27 | 60 | 40 |
| 105 MHz seventh overtone | 107 | 120 | — |
| 135 MHz ninth overtone | 200 | — | — |

whereas at higher frequencies surface finish and cleanliness, with careful control of plateback to ensure minimum electrode losses become critical.

## 7.4 FREQUENCY-TEMPERATURE CHARACTERISTICS

Bechmann's power series expansion of the frequency–temperature characteristics of AT-cut resonators has already been discussed in Section 2.6. Bechmann's values for the coefficients of the various terms in the power series were obtained by analysis of the results for a wide range of different resonator frequencies and designs, and in practice have to be treated with caution when dealing with specific cases. Most importantly, Bechmann gives as the reference angle for his results the single value −35.25°, whereas in a particular production environment a whole range of reference values has to be used, depending upon the particular design in question.

In most cases it is found that provided the appropriate reference angle is adopted, the normalized curves (Fig. 2.11) resulting from Bechmann's data can still be used to determine the effect of changes in angle from the reference, and also to determine the angular tolerances necessary to meet particular specifications. Figure 7.4 shows curves, derived from those of Fig. 2.11, which show the trade-offs between temperature range, frequency tolerance and angle tolerance. The lower curve shows the best possible theoretical frequency stability for a given temperature range, allowing zero tolerances on the cutting angle, and the upper curves show how the stability requirement must be relaxed in order to allow some tolerance on the orientation. Manufacturing costs rise steeply as the angle tolerance is reduced,

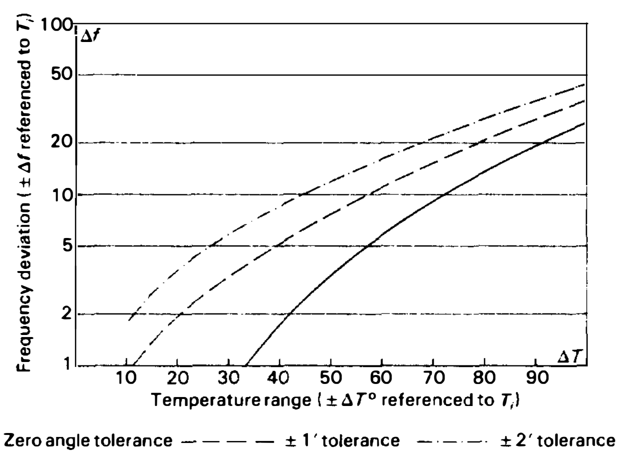



**Fig. 7.4** Temperature range vs frequency deviation vs angle tolerance.

making it wise not to overspecify in respect of frequency-temperature tolerance requirements.

The *inflection temperature* is by definition that temperature at which the second derivative of the frequency-temperature curve vanishes. In terms of the power series coefficients in Eqn (2.74), if $T_i$ is the inflection temperature, then $T_i$ is given by

$$T_i - T_0 = -b/3c \tag{7.5}$$

with $T_0$ the reference temperature. The inflection temperature is mid-way between the upper and lower turning points of the frequency-temperature curve, and the deviations at the turning points are symmetrical with respect to the inflection point.

A standard method of specifying the allowed variation of frequency with temperature is to state a frequency tolerance of $\pm X$ ppm with respect to the actual frequency measured at a specified reference temperature. If the reference temperature is chosen to coincide with the inflection temperature, then the response of each unit will be symmetrical about the reference, so that if the maximum deviation on the high temperature side is $Y$ ppm, the corresponding deviation on the low temperature side will be $-Y$ ppm. From the point of view of the crystal manufacturer, this is the optimum situation since it maximizes the allowed angle tolerance. This follows because every normalized curve that has a total deviation between the turning points of less than $2X$ ppm will meet the specification, whereas if the reference point is displaced from the inflection point, some of these same curves will fail the specification either at high or low temperatures. This is illustrated in Fig. 7.5, which shows two plots of the same normalized curve; the broken line referred to the inflection temperature as reference, the solid line to a reference temperature below the inflection point. The asymmetry in the second curve is obvious.

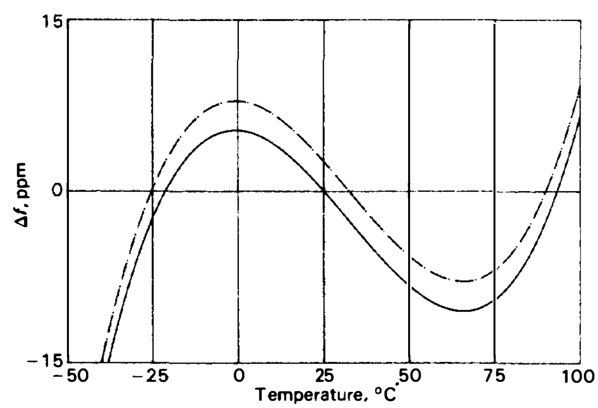



**Fig. 7.5** Normalized curves referred to 25 °C and $T_i$ = 32 °C.

The actual inflection temperature for AT-cut resonators depends on both overtone and blank geometry. For flat fundamental units, $T_i$ varies within a degree or so of 27°C, depending on the precise angle of cut. For overtone units, $T_i$ is a little higher, around 28°C, but for contoured units is much higher. Plano-convex crystals typically have $T_i$ about 32°C, the precise value depending on the steepness of the contour, whereas bi-convex crystals (or alternatively very steeply contoured plano-convex units) can have $T_i$ around 35°C. In such cases, the asymmetry in the curves when referred to a reference temperature of say 25°C can severely limit the allowable angle tolerance in cutting, and it is then advisable for the user to consider the adoption of a higher reference temperature, or else, what is the same thing in the end, to consider the use of an offset frequency tolerance referred to a lower temperature.

A further point that should be borne in mind in applications is that the reference angle for crystals operated with a load capacitance $C_L$ has to be adjusted depending on the value of $C_L$. This adjustment results from the shift in the operating point of the crystal between the series resonance and anti-resonance frequencies, which have, as pointed out in Chapter 2, quite different temperature coefficients. The adjustment is only generally significant for flat fundamental mode designs, but in those cases a significant difference in the frequency variation over the temperature range can be expected if a unit designed to operate at series resonance is operated with load capacitor, or vice versa. Figure 7.6 illustrates the case of a 10 MHz fundamental mode unit at series resonance, and with a 30 pF load capacitance.

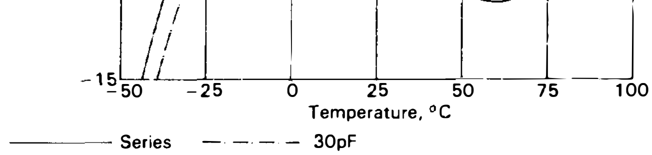



**Fig. 7.6** 10 MHz crystal at series resonance and with a 30 pF load capacitor.

## 7.5 UNWANTED RESPONSES

Following the discussion of Chapter 3, unwanted responses in AT resonators can be said to be due either to inharmonic modes found at frequencies just above the desired response and having similar temperature characteristics to the wanted mode, or to flexural, face shear, or extensional modes which can essentially occur at any frequency and have large temperature coefficients. In poorly designed oscillator crystals the inharmonic responses can have motional resistances comparable to or even less than that of the main mode, causing spurious oscillations or frequency jumping in the oscillator circuit. The second group of modes more commonly show themselves in the form of 'activity dips' or 'bandbreaks', that is anomalies in the frequency–temperature characteristics of the crystals as described in Chapter 3.

Activity dips are more likely to be observed in low-frequency designs where the coupling to unwanted modes is stronger, but with proper choice of blank dimensions and contour should not cause a serious problem. The characteristics of inharmonic modes in fundamental mode resonators depend on whether the blank is contoured or not. In the former case, the spacing of the inharmonics from the main mode is controlled by the steepness of the contour, and the location and level of the modes is predictable and repeatable. For flat fundamental designs, the inharmonic modes generally occur considerably closer to the main response but their precise location is difficult to predict. Proper use of the energy trapping criteria of Chapter 3 can result in resonators that are practically free from inharmonic responses, which is necessary in filter crystal applications. For oscillator applications, the energy trapping rules are often over-ridden by requirements for large $C_1$ values and low $R_1$ values, but nevertheless reasonable compromises between these requirements and unwanted mode suppression can usually be made.

In the case of overtone crystals, the energy-trapping rules become much more difficult to apply as the overtone order $N$ increases. Consequently it is in general true that the suppression of unwanted responses becomes progressively more difficult to achieve as the frequency and the overtone order increase.

## 7.6 AGEING AND SHORT-TERM FREQUENCY STABILITY

The frequency stability of crystal resonators is usually considered under two heads, the *long-term* stability or *ageing*, and the *short-term* stability. In the former, the frequency drift of the resonator over periods of weeks, months and years is of interest, whereas in the latter it is the fluctuations in frequency between successive measurements at intervals of the order of seconds or fractions of a second that is important. The general topic of frequency stability and the various statistical methods used to describe it are discussed in detail in the books by Kartaschoff (1978) and Gerber and Ballato (1985).

The physical mechanisms responsible for the short-term instabilities of resonators are much less well understood than those responsible for their long-term drift. As stated in Chapter 9 in reference to the short-term stability of crystal oscillators, the best that can be said at this time is that there appears to be a confirmed correlation between crystal $Q$ and at least one component of the observed instability, but that otherwise the short-term stability seems to depend on such process-dependent factors as surface finish, cleanliness and electrode adhesion.

The long-term stability of crystal resonators has been the topic of extensive research over many years and the chief mechanisms responsible are well understood. These are reviewed in detail by Gerber in Gerber and Ballato (1985), but can be summarized as follows:

(1) stress effects, for example stress relaxation in the mounting structure and the electrode films;
(2) mass loading effects, for example the adsorption of contaminants from the atmosphere;
(3) material effects, such as chemical reactions at the electrode-quartz interface, or structural relaxations in the quartz itself;
(4) other effects, such as changes in hydrostatic pressure due to leaks in the enclosure.

In high-precision resonators, all these factors are important, but in the low to medium precision units that form the vast bulk of resonators used, the first two factors are most critical. The vital importance of cleanliness can be seen from calculating the mass loading effect of a monomolecular layer on the surface of a typical resonator. Gerber (Gerber and and Ballato, 1985) quotes a frequency shift of $F$ ppm in an $F$ MHz resonator as being caused by the adsorption or desorption of contamination equal in mass to $1\frac{1}{2}$ monolayers of quartz, that is 5 ppm in a 5 MHz resonator for example. Even assuming that the blank cleaning process is effective initially, the subsequent sources of contamination in a typical crystal production facility are manifold, including oil molecules from mechanical and diffusion pumps, human skin oils, airborne particles, outgassing from the bonding paste during curing, and outgassing from the crystal holder pieceparts during and after sealing. Although the expense of a complete clean room facility, or of an in-line processing system in which all process steps after cleaning are carried out without breaking vacuum, is probably not justified except for the highest precision requirements, it is nonetheless essential in crystal processing to take all possible practical precautions against contamination. If this is done and proper use is made of high-temperature bakeout procedures before critical process steps, ageing rates of typically 2 or 3 ppm in the first year can be achieved in volume production using resistance weld or cold weld holders.

## 7.7 NON-LINEAR EFFECTS

The principal non-linear effects observed in crystal resonators can be classified into three groups, those occurring at small signal levels, those occurring at large signal levels, and those involving small signals superimposed on a larger static deformation. In practice, the first group is the more troublesome, since the relevant phenomena seem to be process dependent and relatively difficult to quantify. Comprehensive reviews of the large signal effects and those involving small signals superimposed on large static biases have been given by Gagnepain and Besson (1975) and Gagnepain (1981). These effects involve the non-linear behaviour of quartz as described by the field equations developed in Appendix 3, and include the shift in resonator frequency with signal level (frequency–amplitude effect), the shift in frequency with applied stresses (force–frequency effect) and the shift in resonator frequency with an applied electric field.

The most important small signal effect is the increase in motional resistance that may be observed when the crystal current is reduced to very low levels, commonly known as the 'second level of drive' effect. Since when a crystal oscillator is first switched on the only signals present are noise signals at low level, this increased resistance at low drive can lead to failure of the oscillator to start. In some cases, the phenomenon is only observed after the crystal has been inactive for some time, and can be rectified temporarily by operating the crystal in a high drive level oscillator circuit. The crystal is then colloquially known as a 'sleepy' crystal. The dependence of motional resistance on drive level at low signal levels seems to be entirely dependent on the degree of surface finish of the resonator, its cleanliness and the quality of the electrode film (Bernstein, 1967, Nonaka *et al.*, 1971). It seems probable also that these same factors are responsible for the intermodulation observed in crystal filters at low signal levels (Chapter 10).