A FLAW SIZING METHOD USING THE ZEROES IN THE ULTRASONIC SCATTERING AMPLITUDE

D. K. Hsu, V. G. Kogan, J. H. Rose, D. O. Thompson, and S. J. Wormley

Ames Laboratory-USDOE
Iowa State University
Ames, IA 50011

INTRODUCTION

In this paper we report a new method for determining the size of flaws using the zeroes in the real and imaginary parts of the ultrasonic scattering amplitude [1]. It is observed that, for a wide class of flaws, the wavenumbers or frequencies at which the real and imaginary parts of the scattering amplitude go through zero are closely related to the flaw dimension in the scattering direction. This relationship remains remarkably stable for different interrogation directions and thus may serve as a basis for flaw sizing and reconstruction. In the decomposition of the scattering amplitude into its real and imaginary components, this method requires that the phase reference (or the "zero of time") be placed at the centroid of the flaw. In many respects the method of flaw sizing using the zeroes is similar to the one-dimensional version of the inverse Born approximation (1-D IBA) [2]. In fact, it employs the same input data as the 1-D IBA and consequently also shares certain common limitations such as the sensitivity of the sizing results to the zero of time determination and the available bandwidth of the scattering data [3,4]. However, flaw sizing using the zeroes is simpler and more straightforward because the sizes are obtained directly from the frequencies where the zeroes occur.

In this paper we shall discuss flaw sizing using the zeroes in the scattering amplitude for weakly scattering flaws whose uniform material properties are only slightly different from those of the host medium and for strongly scattering spheroidal voids. The flaw geometries treated are spheres and general ellipsoids. A physical interpretation will be presented to explain the relationship between the frequencies of the zeroes and the characteristic dimension of the flaw. Experimental results will be presented for ellipsoidal inclusions and a spheroidal void, and the sizing results will be compared with those using the 1-D IBA [5]. We shall restrict ourselves to the case of longitudinal to longitudinal back scattering and, for the sake of briefness, we shall refer to the zeroes in the real part of the scattering amplitude as the "real zeroes" and denote them as $k_r^n$. Similarly, the "imaginary zeroes" are denoted by $k_i^n$. 
To describe the technique of flaw sizing using the real and imaginary zeroes, it is beneficial to first review the germane features of the 1-D IBA briefly. In the sizing and reconstruction of weakly scattering flaws from the backscattered ultrasonic signals using the 1-D IBA, the size, shape, and orientation of the flaw is described by the characteristic function \( \gamma(f) \), which has a value of unity inside and on the surface of the flaw and is zero elsewhere. The Fourier transform of \( \gamma(f) \) in the frequency domain, known as the shape factor \( \gamma(q) \), is related to the scattering amplitude \( A(q) \) by

\[
A(q) = \text{const.} \times q^2 \gamma(q)
\]  

(1)

For backscattering \( q = 2k_0 = -2k_i \) and \( q/2 = k_i = k_s = k \). For a general ellipsoidal flaw with semi-axes \( a, b, \) and \( c \), the shape factor is

\[
\gamma(q) = 4\pi abc(sinz - zcosz)/z^3
\]  

(2)

where \( z = qr_e \) and \( r_e \) is the distance from the centroid of the flaw to the front surface tangent plane in the scattering direction, as shown in Fig. 1. For the special case of a spherical flaw with radius \( r \), the shape factor reduces to

\[
\gamma(q) = 4\pi r^3(sinz - zcosz)/z^3
\]  

(3)

with \( z = qr \).

Fig. 1. Schematic diagram of the backscatter geometry shows the incident \( (k_i) \) and scattered \( (k_s) \) wavevector and the tangent plane distance \( (r_e) \).
To determine the tangent plane distance of a weakly scattering ellipsoidal flaw in the direction \( q \), the characteristic function is computed as follows:

\[
\gamma(x) = \frac{1}{2\pi^2} \int_0^\infty \gamma(q) \frac{\sin qr}{qr} \, dq = 1, \quad r < r_e \quad 0, \quad r > r_e
\]  

(4)

A complete reconstruction of the flaw is then realized by performing the scattering in a number of different directions.

In practice, the scattering amplitude (and hence the shape factor) is obtained from the backscattering impulse response function \( R(t) \) in the form of a time domain signal via a Fourier transform:

\[
A(q) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R(t) e^{i\omega t} \, dt
\]  

(5)

The impulse response function of a weak scattering ellipsoid is shown in Fig. 2. It gives, in the Born approximation, the ellipsoid's response to an initial displacement pulse, \( \delta(t - \hat{k}_q \cdot \hat{r}) \), that would have reached the flaw center at \( t=0 \) had the flaw not been there. We note that the \( R(t) \rightarrow A(q) \) transformation cannot be made without a choice of the zero of time, otherwise the phase of \( A(q) \) would be undetermined. Once the zero of time is correctly chosen and the origin of the coordinates is placed at the center of the flaw, a weak scatterer with a center of inversion symmetry would have an imaginary part of the scattering amplitude identically zero, and the real part is given by (2) or (3).

Fig. 2. The impulse response function for an ellipsoidal scatterer in the Born approximation. The down going arrows denote delta functions.
FLAW SIZING USING THE ZEROES IN SCATTERING AMPLITUDE

Weak Scatterers

From Eqs. (1) and (2), the scattering amplitude of a weak ellipsoid scatterer is proportional to the function \( \sin z - z \cos z \). The real zeroes are therefore given by the roots of the equation \( \tan z = z \); the first five are

\[ z_{n=1+5} = 4.49, 7.72, 10.90, 14.06, 17.22 \]  
(6)

Recall that \( z = q r e = 2k r e \), we have

\[ k^r_{n=1+5 r e} = 2.25, 3.86, 5.45, 7.03, 8.61 \]  
(7)

This result obviously affords a quick and straightforward determination of the tangent plane distance \( r e \). For example, by locating the wavenumber \( k^r_1 \) at which the scattering amplitude crosses zero for the first time, the tangent plane distance is simply given by \( r e = 2.25/k^r_1 \). In general,

\[ r e = \frac{2.25}{k^r_1} = \frac{3.86}{k^r_2} = \ldots \]  
(8)

Spheroidal Voids

To investigate whether the weak scatter results can be extended to the case of strongly scattering ellipsoidal voids, we examined the first five real zeroes in the backscattering amplitude of an oblate spheroidal void computed by Opsal and Visscher [6] using the method of optimum truncation. The oblate spheroid is in a material with a Poisson ratio of 1/3 and has semiaxes of 0.5 and 1.0. Its axis of symmetry is along the \( z \) direction, from which the polar angle \( \theta \) is measured. Table 1 shows the zeroes \( k^r_{n r e} \) of ReA(k) for different backscattering directions.

Table I. First five real zeroes of a 2:1 spheroidal void. \( <k^r_{n r e}> \) are the average of the respective columns and \( (k^r_{n r e})_{\text{Born}} \) are the corresponding zeroes of a weak scatterer.

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( r e )</th>
<th>( k^r_{1 r e} )</th>
<th>( k^r_{2 r e} )</th>
<th>( k^r_{3 r e} )</th>
<th>( k^r_{4 r e} )</th>
<th>( k^r_{5 r e} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.50</td>
<td>2.26</td>
<td>3.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.52</td>
<td>2.23</td>
<td>3.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.58</td>
<td>2.20</td>
<td>3.89</td>
<td>5.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.66</td>
<td>2.22</td>
<td>3.89</td>
<td>5.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>2.26</td>
<td>3.78</td>
<td>5.49</td>
<td>7.04</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.83</td>
<td>2.27</td>
<td>3.78</td>
<td>5.43</td>
<td>7.05</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.90</td>
<td>2.20</td>
<td>3.82</td>
<td>5.38</td>
<td>7.00</td>
<td>8.61</td>
</tr>
<tr>
<td>70</td>
<td>0.96</td>
<td>2.00</td>
<td>3.85</td>
<td>5.38</td>
<td>6.99</td>
<td>8.57</td>
</tr>
<tr>
<td>80</td>
<td>0.99</td>
<td>1.91</td>
<td>3.88</td>
<td>5.40</td>
<td>6.99</td>
<td>8.55</td>
</tr>
<tr>
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<td>1.89</td>
<td>3.89</td>
<td>5.40</td>
<td>7.00</td>
<td>8.56</td>
</tr>
</tbody>
</table>

\( <k^r_{n r e}> \) 2.14 3.84 5.42 7.01 8.57  
\( <k^r_{n r e}>_{\text{Born}} \) 2.25 3.86 5.45 7.03 8.61
Table I shows two interesting results. First, the products \( k_{\text{re}} \) show a remarkable stability with respect to the scattering direction \( \theta \). Even though the value of \( k_{\text{e}} \) (not shown) changes by a factor of 2.5 from \( 0^\circ \) to \( 90^\circ \), the product \( k_{\text{re}} \) changes by less than 20\% in the same range and only 3\% from \( 0^\circ \) to \( 60^\circ \). The stability of higher order zeroes is even better. A second and somewhat surprising result is that the zeroes \( k_{\text{re}} \) are very close to the corresponding zeroes of a weakly scattering oblate spheroid of the same size and orientation. Table I also shows that, in principle, one can determine the tangent plane distances \( r_e(\theta) \) using Eq. (8) and obtain an accuracy that is better than 3\% with the exception of using the first zero for \( \theta = 70^\circ, 80^\circ, \) and \( 90^\circ \). In actual experimental scattering data the bandwidth would, in general, not allow the observation of very many zeroes but some redundancy is often possible. Near the two extremes of the bandwidth where the signal-to-noise ratio is poor, caution should be exercised against possible false zeroes.

We have also investigated the stability of the imaginary zeroes using the same computed scattering amplitude for the 2:1 oblate spheroidal void and the results are shown in Table II. One observes that the first imaginary zero \( k_{\text{i}r_e} \) is less stable than its counterpart \( k_{\text{re}} \) whereas the higher order imaginary zeroes are quite stable. For example, \( k_{\text{i}r_e} \) deviates from its average value of 2.99 by no more than 4\%. No comparison can be made with the weak scattering case because the imaginary part of a weak scatter with a center of inversion symmetry is zero when the zero of time is placed at the center of the flaw. The results of the spheroidal void clearly show that the stability of the zeroes is not limited to the weak scattering case. The reason for this stability must lie in features independent of the scattering strength.

Table II. Imaginary zeroes of a 2:1 oblate spheroidal void. The last row shows the average values of the respective columns.

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( r_e )</th>
<th>( k_{\text{i}r_1} )</th>
<th>( k_{\text{i}r_2} )</th>
<th>( k_{\text{i}r_3} )</th>
<th>( k_{\text{i}r_4} )</th>
<th>( k_{\text{i}r_5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.50</td>
<td>1.12</td>
<td>3.10</td>
<td>4.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.52</td>
<td>1.14</td>
<td>3.05</td>
<td>4.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.58</td>
<td>1.20</td>
<td>3.02</td>
<td>4.70</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.66</td>
<td>1.27</td>
<td>3.07</td>
<td>4.61</td>
<td>6.27</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>1.34</td>
<td>3.07</td>
<td>4.62</td>
<td>6.22</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.83</td>
<td>1.40</td>
<td>2.95</td>
<td>4.68</td>
<td>6.20</td>
<td>7.82</td>
</tr>
<tr>
<td>60</td>
<td>0.90</td>
<td>1.46</td>
<td>2.90</td>
<td>4.68</td>
<td>6.23</td>
<td>7.80</td>
</tr>
<tr>
<td>70</td>
<td>0.96</td>
<td>1.50</td>
<td>2.90</td>
<td>4.64</td>
<td>6.23</td>
<td>7.80</td>
</tr>
<tr>
<td>80</td>
<td>0.99</td>
<td>1.52</td>
<td>2.92</td>
<td>4.59</td>
<td>6.22</td>
<td>7.80</td>
</tr>
<tr>
<td>90</td>
<td>1.00</td>
<td>1.53</td>
<td>2.93</td>
<td>4.58</td>
<td>6.22</td>
<td>7.81</td>
</tr>
<tr>
<td>(&lt;k_{\text{i}r_e}&gt;) =</td>
<td>1.35</td>
<td>2.99</td>
<td>4.64</td>
<td>6.23</td>
<td>7.81</td>
<td></td>
</tr>
</tbody>
</table>

**Interpretation**

Observations made in the preceding section leave us with a number of questions. Why are the zeroes spaced in a regular fashion? Why are they related to the tangent plane distances? Finally, why are the real zeroes nearly the same for the weakly and strongly scattering flaws considered?

As shown in Fig. 2, the impulse response function for an ellipsoidal flaw has an initial delta function, which occurs at a time \((-\tau)\) determined
by the tangency of the incident pulse at the flaw surface. This feature is common for both weak and strong scattering. We will show that it is responsible for the regular spacing of the zeroes and for their relationship to the tangent plane distances.

Figure 3 shows the impulse response function computed by Opsal and Visscher [6] for the L to L scattering from a spherical void in an otherwise isotropic and homogeneous elastic solid with a Poisson ratio of 1/3. The delta-function occurs at time \(-\tau\), which is the difference between two elapsed times. The first measures the time it takes an impulse to travel from the transmitter, make initial contact with the flaw, and return to the detector. The second elapsed time assumes the flaw is absent and measures the round trip time for the pulse to propagate from the transmitter to the origin of coordinates and back. For an ellipsoidal flaw \(\tau = 2r_e/v\) if the origin is placed at the flaw center.

Consider now the scattering amplitude which is given in Eq. (5). The regular part of \(R(t)\) following the delta function spans a time interval of the order of \(2\tau\) (see Fig. 3). This means that the dominant Fourier components of this part of the signal correspond to frequencies near \(\omega \approx 1/2\tau\). On the other hand, the delta function has constant Fourier components at all frequencies. Therefore, at large frequencies only the delta function contribution remains: \(A(k) \approx \exp(2ikr_e)\) for \(kr_e \gg 1\). Thus, at large \(k\)'s, one expects the zeroes of \(\text{Re}A\) and \(\text{Im}A\) \((k^r_{n e}, k^i_{n e}\) respectively) to occur at

\[
\begin{align*}
2k^r_{n e} & = \pi(n+1/2) \\
2k^i_{n e} & = \pi n
\end{align*}
\]  

These are, of course, asymptotic high frequency results. They are, however, close to \(<k^r_{n e}>\) and \(<k^i_{n e}>\) of Tables I and II for \(n = 2,3,\cdots\). We give this comparison in Table III along with \(<k^r_{n e}>_{\text{Born}}\) given by (7) and \(<k^i_{n e}>_{\text{Kirchhoff}}\) given by (12) below.

![Fig. 3. The impulse response function for a spherical void in an otherwise isotropic and homogeneous elastic medium. The Poisson ratio is 1/3. The down going arrow indicates the delta function.](image)
Table III. Comparison of the average real and imaginary zeroes from Tables I and II with the zeroes from Born approximation, Kirchhoff approximation, and the high frequency asymptotic results.

<table>
<thead>
<tr>
<th>n</th>
<th>(&lt;k_{n,e}^r&gt;)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=1</td>
<td>2.14</td>
<td>3.84</td>
<td>5.42</td>
<td>7.01</td>
<td>8.57</td>
</tr>
<tr>
<td>(k_{n,e}^r)_{Born} (\omega \rightarrow \infty), Eq. (9)</td>
<td>2.25</td>
<td>3.86</td>
<td>5.45</td>
<td>7.03</td>
<td>8.61</td>
</tr>
<tr>
<td>(&lt;k_{n,e}^i&gt;)</td>
<td>1.35</td>
<td>2.99</td>
<td>4.64</td>
<td>6.23</td>
<td>7.81</td>
</tr>
<tr>
<td>(k_{n,e}^i)_{Kirchhoff} (\omega \rightarrow \infty), Eq. (9)</td>
<td>1.17</td>
<td>3.14</td>
<td>4.60</td>
<td>6.28</td>
<td>7.79</td>
</tr>
</tbody>
</table>

The deviations of the "low frequency zeroes" from high frequency asymptotics, Eq. (9), arise in two ways. One is simply the bulk of the slowly varying signal to the right of the delta function. The second is the relatively sharp trailing structure; this structure is attributed to surface "creeping waves". In accounting for the position of the low frequency zeroes we will ignore the second effect and concentrate entirely on the first.

Two approximate formulae can be used to understand the position of the low frequency zeroes. The first is the Born approximation which, as already discussed, is appropriate for weak scatterers. The impulse response for this case is shown in Fig. 2, and the first five real zeroes \(2k_{n,e}^r\) are given in (7). The second is the Kirchhoff approximation [7] which is commonly used to model scattering from voids and cracks. The L to L impulse response in the Kirchhoff approximation for an ellipsoidal scatterer is shown at the left of Fig. 4.

These approximate response functions, Born and Kirchhoff, are similar in certain ways. Both initiate with a delta function at \(t = -2r_e/v\). Both are constant for \(-2r_e/v < t < 0\) and zero for \(t < -2r_e/v\). The two approximations differ in their overall magnitudes. Beyond this the Born approximation is symmetric about \(t=0\); while the Kirchhoff result is identically zero for \(t>0\).

The real part of the scattering amplitude depends only on the symmetric part of the impulse response function. To see this we represent the impulse response \(R(t)\) as a sum of symmetric, \(R_s\), and antisymmetric, \(R_a\), parts, where \(R_s = [R(t) + R(-t)]/2\) and \(R_a = [R(t) - R(-t)]/2\). Equation (5) then yields:

\[
\text{Re} A = v \int_{-\infty}^{\infty} R_s(t) \cos \omega t \, dt, \quad (10)
\]

\[
\text{Im} A = v \int_{-\infty}^{\infty} R_a(t) \sin \omega t \, dt. \quad (11)
\]
The graphic representation of $R_S$ and $R_a$ is given in Fig. 4 for the Kirchhoff case. The symmetric extension of the Kirchhoff result about $t=0$, $R_S$, has the same form as the Born estimate for the impulse response function. Consequently, the locations of the real zeroes are identical for these two approximations. The imaginary zeroes can be found from

$$\text{Im}A(k) = \frac{\text{const}}{k} \left( \cos 2kr_e - 1 + 2kr_e \sin 2kr_e \right)$$  \hfill (12)  

in the Kirchhoff approximation. Table III gives the value at which the first five real and imaginary zeroes occur. The results of Opsal and Visscher are compared with the Born and Kirchhoff results.

**Experimental Results**

In this section we present experimental results for flaw size determination using the zeroes of the scattering amplitude. Ellipsoidal flaws were used so that we could compare the proposed method and the 1-D IBA. Results are discussed first for a prolate spheroidal stainless steel inclusion imbedded in thermoplastic and then for an oblate spheroidal void in titanium. Detailed accounts of a 1-D IBA study of these flaws were reported earlier.

For an ellipsoidal flaw the size, shape, and orientation are completely defined by six parameters: the three semiaxes $a_x$, $a_y$, and $a_z$, and the three Euler angles $\theta$, $\phi$, and $\psi$ which specify the orientation of the flaw in the laboratory frame of reference. For the prolate spheroidal inclusions, the actual values of the six parameters are $a_x = a_z = 47 \mu m$, $a_y = 96 \mu m$, $\theta = 7^\circ$, and $\phi = \psi = 0$. Figure 5 shows the real part of the scattering amplitude of this flaw at six scattering directions. The data are taken in an ultrasonic backscattering (pulse-echo) measurement and the centroid of the flaw (the "zero of time") is determined using the
maximum area function criterion [4]. The orientation of the flaw is such that the distance $r_e$ from the centroid to the front surface tangent plane increases as the polar angle of the scattering direction increases. As can be seen, the first zero in the real part of the scattering amplitude occurs at progressively smaller frequencies as the polar angle increases. The distances $r_e$ determined from the first zero in the real part using $k_0 r_e = 2.25$ agree with those from the 1-D IBA for 24 pulse-echo interrogation directions. As can be seen, the agreement between the two methods is generally good. It should be noted that the two sets of results are based on the same ultrasonic data and the same "zero of time" determination.

In determining the effective radius of a flaw, both the 1-D IBA and the method using the zeroes in the scattering amplitude rely on an accurate determination of the "zero of time" (i.e., the location of the centroid of the flaw). To investigate the effects on the radius estimate caused by inaccuracies in the zero of time determination, we first determined the "correct" zero of time from the area function (or its derivative) computed from the scattering amplitude. Then we obtained radius estimates, using both the zero crossing method and the 1-D IBA, while intentionally shifting the zero of time from the correct value. We conducted this test on several different flaws, both for inclusions and voids. It was found that the radius estimates from the two methods generally tracked each
Fig. 6. Effective radii of the oblate spheroidal void in titanium determined from the first zero of the real part of the scattering amplitude (circled dots) and from the 1-D IBA (solid dots).

other fairly closely. Figure 7 shows the radius estimates using the two methods as a function of the error in the zero of time determination. The data in Fig. 7 were taken on a copper wire inclusion (80μm radius and 400μm long) imbedded in plastic. The pulse-echo scattering direction is perpendicular to the axis of the wire. The radius estimates using the zero crossing method are based on the first zero in the real part.

As can be seen, both methods give results quite close to the actual radius of 80μm at the correct zero of time. The zero crossing data show more scatter than the IBA result. For real data the scattering amplitude curves are not always smooth and the presence of noise causes a certain amount of error in the determination of the zero crossing frequency. The noise problem is more serious near the two ends of the frequency bandwidth where the signal to noise ratio is poor.

Presumably, the IBA results are somewhat more stable since they use the entire scattering amplitude. As expected, this use of redundant data reduces the effect of noise. Based on experimental results for a number of different flaws, we have observed empirically that the radius estimates based on the first zero in the real part of the scattering amplitude are usually slightly greater than the radii determined by the 1-D IBA. Some discrepancy is probably to be expected because the signal processing protocol of the 1-D IBA involves certain approximation criteria. It is also observed that zeroes of higher orders -- second zero in the real part, and second zero and third zero in the imaginary part -- yield larger radius estimates than the first zero in the real part, usually by about 10%. The cause
DISCUSSION

As discussed before, the stability of the zeroes is expected when the scattering is dominated by the front surface delta function response of the flaw. When other features such as surface creeping waves and focusing are present, it is expected that the pattern of the zeroes will become more complicated. Calculations [1] show that this method should give reliable sizing for inclusions whose material properties are either very similar or very different from those of the host. In the last section, we examined empirically the results of errors in the absolute phase and found that errors in the estimated radius increase roughly linearly with small errors in the phase or zero of time determination. Errors in phase will degrade this method to essentially the same degree that the 1-D IBA is degraded. To explore the application to cracks and crack-like flaws,
we examined [1] the real and imaginary zeroes in the computed L-L backscatter amplitude for a flat penny-shaped crack. We found that the first real zero $k_{la} = 1.16 \pm 0.11$ in the range of $\Theta = 0$ to $90^\circ$ and is thus largely independent of the angle of incidence. It can therefore be used to determine the radius, $a$, of the crack. The first imaginary zero, $k_{lre}$, on the other hand, varies between 1.5 and 2.1 over the same angular range. However, when the trailing "creeping" wave signal is artificially removed from the time domain signal, the resulting $k_{lre}$ becomes very stable and has the value $k_{lre} = 1.88 \pm 0.06$. The truncation of late arriving signals in general is believed to improve the stability of the zeroes.

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