KRELL ENGINEERING
Ultrasonic Resonator Design

Spool Horn Design Procedure

The following discusses the design procedure for unslotted flat faced cylindrical horns.

Notes:

1. Unless otherwise specified:
    a. References to "amplitude" and "uniformity" will mean those on the horn’s face.
    b. Horns are assumed to be flat faced (i.e., no face contour or cavity).
    c. The suggested dimensions apply to 20 kHz horns. These can be scaled to other frequencies.
    d. The horn material is 7075-T6 aluminum. Results will be similar for other aluminums or titanium, although some dimensional adjustments will be needed.
    e. The stud is ½-20 UNF and extends 15.9 mm into the horn. The stud material is steel.
2. All dimensions are approximate and should be adjusted as needed for the particular horn and/or application.
3. The CARD (Computer Aided Resonator Design) graphs for unshaped cylindrical horns (figures 1 through 3) can be accessed at: Equation\Axial resonance\Cylindrical horns\Unshaped\Performance\Graph\

Unshaped cylindrical horns

For unshaped cylindrical horns, Poisson's coupling gives a face amplitude that is highest at the center of the face and lowest at the periphery. Figure 1 shows the face amplitude distribution for a Ø135 mm horn. The uniformity of this horn is about 25% (i.e., the lowest amplitude (at the periphery) is only 25% of the highest amplitude (at the center of the horn's face)).

Figure 2 shows how the face amplitude uniformity varies with the horn diameter. For horns with diameters up to 60 mm the uniformity is greater than 90%. For larger horns the uniformity falls off quickly. For a Ø135 mm horn the uniformity is only about 25%. Such nonuniformity can cause problems in performing the application.

Figure 3 shows the radial amplitude at the face periphery. Up to Ø125 mm the radial amplitude is less than 2% of the axial amplitude at the center of the horn's face. Above Ø130 mm the radial amplitude increases quickly. At larger diameters the radial amplitude predominates and the horn acts like a radially vibrating disk.

Spool horns

In order to improve the face axial uniformity, a spool shape (somewhat like a spool of thread) is cut into the periphery of the horn behind the face. Figure 4 shows nomenclature and typical dimensions for such a spool horn. (Note: use these dimensions rather than those given in CARD.)

The spool undercut increases the amplitude at the face periphery and in areas adjacent to the periphery by allowing the flange material to "flap". The optimum undercut is achieved when the axial amplitude at the face periphery equals the amplitude at the center of the face. In between these two locations the amplitude will be somewhat lower because the "flapping" is not as effective in this region. Figure 5 shows the amplitude distribution for an optimized Ø135 mm horn.

Characteristics

1. Face cavity. Spool horns (especially the larger diameters) do not retain good uniformity if the horn has a substantial face cavity. (A small cavity like an axial hole for cooling or vacuum may be acceptable.) If a substantial face cavity is required then a slotted cylindrical horn should be used instead.

2. Maximum diameter. The largest reasonable horn diameter appears to be about 135 mm at 20 kHz. At this diameter the radial amplitude is about 37% of the axial amplitude; above this diameter the radial amplitude increases quickly (figure 6), which may affect the application. This radial amplitude is higher than for an unshaped cylindrical horn because the undercut makes the face appear as a radially vibrating disk.

   Also, above Ø135 mm there is a symmetric nonaxial resonance that can adversely affect the axial resonance. Figure 7 shows this mode at 21213 Hz for a Ø135 mm spool horn. (You can see this resonance in CARD at Equation\Axial resonance\Cylindrical horns\Unshaped\Performance\Graph\Resonances -- the red line shows the nonaxial resonance. Although this graph is for unshaped horns, it is approximately true for spool horns.)

3. Excluded diameters. Horns with diameters near 100 mm have an asymmetric shear resonance near 20 kHz. This resonance has a diametral node across the face and stud surface (figures 8 and 9). When this resonance is close to the axial resonance it causes asymmetric amplitudes on the face and stud surfaces. Spool horns with diameters less than 90 mm or greater than 110 mm appear to be relatively unaffected by this resonance; spool horns between these diameters must be carefully evaluated to make sure that any asymmetric face amplitudes will not affect the application or cause other problems (e.g., heating of the horn-booster joint or heating of the transducer).

4. Uniformity. Figure 10 shows the achievable face uniformity for spool horns that are designed according to the drawing of figure 4. The achievable face uniformity decreases sharply for horns above about Ø120 mm.

5. Gain. Spool horns have a gain near 1.0, even though the undercut (reduced mass forward of the node) would seem to indicate a higher gain. The gain decreases as the horn diameter increases (figure 11). (Note: as is common practice, the gain is measured at the center of the horn's face.)
6. Stress. The highest stress occurs in the undercut radius that is closest to the stud surface. The stress for all of the Al 7075-T6 spool horns up to Ø135 mm ranges from 170 – 180 MPa/micron (peak-to-peak) output. These horns have proven reliable at output amplitudes of 50 microns and would likely be reliable at even higher amplitudes.

Design procedure

1. Choose the horn material.
    a. If possible, use aluminum (e.g., Al 7075-T6) which is relatively inexpensive and is easy to machine. If needed, wear resistance can be improved by plating the face (e.g., hard chrome). (Caution: some platings can reduce fatigue life.)
    b. Titanium (e.g., Ti-6Al-4V) can be used where wear or impact resistance may be problems. (Although titanium has better fatigue strength than aluminum, fatigue failures of spool horns are rare so this is usually not a consideration.) However, titanium is relatively expensive. Also see the discussion of Poisson's ratio below.

       Note: large diameter titanium spool horns may be difficult for the power supply to start, especially when driven with a high gain booster. Power consumption will also be high. For example, a Ø135 mm spool horn driven by a 2.3:1 booster draws in excess of 400 watts in air.
2. Specify the dimensions (see figure 4).
    a. Flange length. A 12 mm flange works well.
    b. Undercut radius. A 25 mm radius works well. A smaller radius will increase the amplitude at the face periphery so the undercut diameter will have to be reduced, resulting is somewhat lower uniformity.
    c. Undercut diameter. Make the undercut diameter approximately 85.5% of the horn diameter. For all horn sizes this will give approximately the best face uniformity. (Some adjustment may be needed to compensate for the stud size (see below) and the material. To be safe you can start at the higher percentage (i.e., less deep undercut) and then reduce the undercut diameter in order to achieve the optimum result.)

       Large diameter horns are very sensitive to the undercut diameter (i.e., small changes in this diameter will significantly affect the face uniformity). For example, for a Ø135 mm spool horn, reducing the undercut diameter from 86.0% to 85.3% increases the edge axial amplitude from 86% to 101% of the center axial amplitude. This sensitivity is compounded by the effect of Poisson's ratio (discussed below).
    d. Rear shoulder. Set the shoulder length to 57% of the tuned length of an unshaped cylindrical horn, as given by CARD. This gives the highest gain, although the gain is only somewhat affected by this length.

e. Stud. Up to a stud diameter of approximately 13 mm, the face amplitude and gain are only somewhat affected by the stud dimensions. For example, see figures 12 and 13 for a Ø135 mm spool horn. A Ø75 mm spool horn shows even less effect.

f. Tuned length. With the dimensions of figure 4, the tuned lengths are shown in figure 14. Because the flange length is fixed, the horn must be tuned from the stud surface. For all horns the tuning rate will be about 120z/mm with an attached transducer. (The spool horn will always tune shorter than an unshaped horn of the same diameter. Therefore, the pretuned length of figure 4 can just be set to the length of an unshaped horn of the same diameter.)

Effect of Poisson's ratio

When designing spool horns with FEA, the value of Poisson's ratio can have a significant effect on the resulting amplitude distribution across the horn's face. Figure 15 shows this effect for a Ø125 mm Al 7075-T6 spool horn: as Poisson's ratio varies from 0.32 to 0.35 the amplitude at the periphery decreases by about 15%. This effect is less for smaller horn diameters, as shown in figure 16 for a Ø110 mm Al 7075-T6 spool horn where the amplitude at the periphery varies by about 7%.

The effect of Poisson's ratio is more complicated for titanium, which is orthotropic (the properties depend on the direction in which the material is tested). For example, TIMET reports that ten observations using a two element rosette strain gage gave a range from 0.287 to 0.391. (This is believed to have been sheet material.) "Typical" values have been reported between 0.31 and 0.34. The value will likely depend on whether the material is rod stock or plate stock.

To achieve the best correlation between FEA and the actual horn, specify that the horn should be machined from the same raw stock type (either rod or plate), that the grain direction should always be parallel to the stud axis (for improved fatigue strength, at least in theory) and that the material should always be purchased from the same vendor and, preferably, from the same manufacturer.