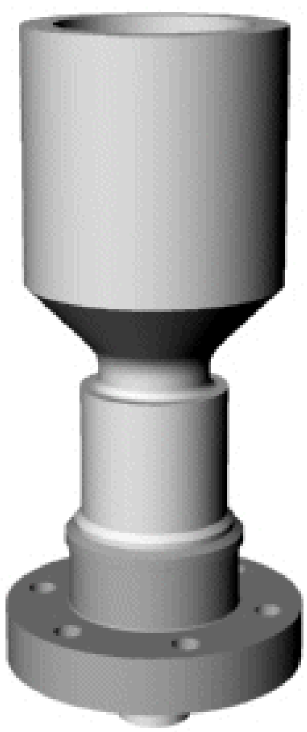
Home | Site Map | What's New | Company Info | Contact Us

Krell Engineering

[Resonator Design] [CARD Software]

Krell Engineering consults in the design of custom ultrasonic resonators (ultrasonic horns / sonotrodes / probes, boosters, transducers / converters) for frequencies between 10 kHz and 100 kHz. These resonators are used for industrial and medical applications.

Industrial resonators	Medical resonators
	

Resonators for welding plastics and nonferrous metals, cutting, abrasive machining of hard materials, fatigue testing, atomization, defoaming, cleaning, liquid processing, sonochemistry (enhancement of chemical reactions), deagglomeration, etc.	Devices for cutting, disintegrating, cauterizing, scraping, cavitating, dental descaling, etc.

The resonators are designed using finite element analysis (FEA) simulation software. This assures that the resonators will meet the performance requirements:

- Correct frequency and vibration mode (while avoiding undesirable modes)
- Proper vibrational amplitude on the input and output surfaces
- Minimum vibrational amplitude on the mounting surfaces
- Low ultrasonic stress for increased fatigue life

In addition to design services, Krell Engineering can also provide complete machining and frequency tuning.

Krell Engineering also provides Computer Aided Resonator Design (CARD) software which facilitates the design of ultrasonic resonators.

Partner sites

- M P Interconsulting -- Multifrequency, wide band, sonic and ultrasonic technology to vibrate any mass without design limits

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Site notes

1. To avoid the need for horizontal scrolling, this site is best viewed with a graphics resolution of 800 x 600 or higher.

2. If you encounter any problems with this web site or have any suggestions, please e-mail webmaster@krell-engineering.com.

Top | Home | Site Map | What's New | Company Information | Contact Us

---

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Home | Site Map | What's New | Company Info | Contact Us

Site Map

Krell Engineering - design of ultrasonic resonators, ultrasonic horns

---

Top | Home | Site Map | What's New | Company Information | Contact Us

---

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What's New

- 10/29/02 -- Within the past month, an older version of Computer Aided Resonator Design (CARD) was inadvertently posted. The correct version (9.00, a major upgrade) has now been posted for downloading.

- 10/02 -- The following pages show actual animated vibrations of various ultrasonic resonators:
  - Bar horns
  - Block horns
  - Spool horns
  - Slotted cylindrical horns
  - Rigid mount boosters

- 6/20/02 -- Computer Aided Resonator Design (CARD) version 9.00 has been released. This is a major upgrade with many enhanced features.

- 6/15/02 -- A new page shows a sectioned view of a typical ultrasonic medical device.

- 6/10/02 -- A new page shows typical ultrasonic industrial resonators, including horns, boosters, and transducers.

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Home | Site Map | What's New | Company Info | Contact Us

Company Info

[Management]

Krell Engineering was founded in 1985 to provide an independent source for the design of ultrasonic resonators at frequencies between 10 kHz to 100 kHz. Krell Engineering's president and founder, Donald Culp, has over 30 years experience in industrial and medical ultrasonics.

Clients

These clients are some who have benefited from Krell Engineering's expertise.

Advanced Medical Applications	Medical devices for ultrasound therapy
Advanced Sonic Processing Systems	Industrial ultrasonic processing equipment
Allred & Associates	Medical product development, surgical handpieces, prototyping
American GFM	Industrial ultrasonics for cutting soft materials
AmTech	Industrial ultrasonics for metal welding
Angiosonics	Medical ultrasonics
Axya Medical	Medical ultrasonics for welding sutures
Baxter International	Medical products
BP Amoco	Energy and petrochemical products
Branson Ultrasonics	Industrial ultrasonics for plastic welding and cleaning

Bullen Ultrasonics	Industrial ultrasonics for machining brittle materials
CAE Ultrasonics	Industrial ultrasonics for cleaning
Chiron Vision	Medical ultrasonics
Dentsply International	Ultrasonic dental scaling equipment
Dukane Ultrasonics	Industrial ultrasonics for plastic welding
Edison Welding Institute (EWI)	Contract research and applications development
FibraSonics	Medical ultrasonics
Herrmann Ultrasonics	Industrial ultrasonics for plastic welding
Hu-Friedy	Ultrasonic dental scaling equipment
ITT Automotive	DC motors
Jade Equipment	Precision automated assembly equipment
Kimberly-Clark	Washroom and skin care products
Medical Technical Products	Medical ultrasonics
Mentor Ophthalmics	Medical ultrasonics
Misonix	Industrial and medical ultrasonics
M P Interconsulting	Consulting in specialized industrial ultrasonic processes
National Feedscrew & Machining	Equipment manufacturer and refurbisher
OmniSonics Medical Technology	Minimally invasive ultrasonic surgical instruments
Solidica	Producer of direct metal rapid prototyping systems
Sonics & Materials (S&M)	Industrial and medical ultrasonics
Sonobond Ultrasonics	Industrial ultrasonics for plastic and metal welding
Storz Instrument	Medical ultrasonics

Swansea Product Development Center	
Triumph Medical	Medical ultrasonics, device development
Ultra Cure	Cosmetic and medical ultrasonics
Ultrasonic Power	Industrial ultrasonics for cleaning
Ultrasonic Surgical Devices	Medical ultrasonics
University of Utah	
Valleylab (U.S. Surgical)	Ultrasonic surgical devices

Membership

Krell Engineering is a member of the following organizations.

- Ultrasonic Industry Association (UIA)
- Ultrasonic and Acoustic Transducer Group (UATG)

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Home | Site Map | What's New | Company Info | Contact Us

Resonator Design

[Up] [Industrial Resonators] [Medical Resonators] [FEA Information]
[Resonator Info Form]

- Industrial resonators shows typical horns, boosters, and transducers. These resonators deliver high energy density in order to substantially affect the materials with which they are in contact. Common uses include welding plastics and nonferrous metals, cutting, abrasive machining of hard materials, fatigue testing, atomization, defoaming, cleaning, liquid processing, sonochemistry (enhancement of chemical reactions), and deagglomeration.

  For detailed information on specific designs, see the following.

  - Bar horns (includes animations)
  - Block horns (includes animations)
  - Spool horns (includes animations)
  - Slotted cylindrical horns (includes animations)
  - Rigid mount boosters (includes animations)

- Medical resonators are used for cutting, disintegrating, cauterizing, scraping, cavitating, and dental descaling.

- FEA Information "Ultrasonic Resonator Design Using Finite Element Analysis (FEA)" discusses the advantages and limitations of finite element analysis for resonator design. This paper was originally presented at the Ultrasonic Industry Association's 1991 technical symposium. It has been updated to reflect current practices.

- Resonator Information Form If you have a resonator design that might be improved by finite element analysis, then you can use this form to submit baseline information.

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CARD Software

Computer Aided Resonator Design (CARD)

Computer Aided Resonator Design (CARD) software applies quantitative techniques to the design of ultrasonic resonators (horns, boosters, and transducers) that vibrate in a longitudinal mode. CARD provides assistance in the design of resonators having low-to-moderate complexity.

For a complete description of CARD, including typical screen images, hardware requirements and prices, click here.

For a description of upgrade options, click here.

For frequently asked questions, click here.

For information on downloading a functional demonstration version, click here.

Top | Home | Site Map | What's New | Company Information | Contact Us

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Industrial Resonators

Industrial resonators deliver high energy density in order to substantially affect the materials with which they are in contact. Common uses include welding of plastics and nonferrous metals, cleaning, abrasive machining of hard materials, cutting, enhancement of chemical reactions (sonochemistry), liquid processing, defoaming, and atomization. Usual frequencies are between 15 kHz and 40 kHz, although frequencies can range as low as 10 kHz and as high as 100+ kHz.

Krell Engineering can design many variations of the resonators shown below, including carbide face inserts and other wear resistant materials. (Note: not all resonators are shown to the same scale.)

Find the resonator below that most closely meets your needs. Then click on "details" to get detailed information, which often includes an animation of the actual resonator vibration.

A typical industrial ultrasonic stack consists of a horn, booster, and transducer (converter).

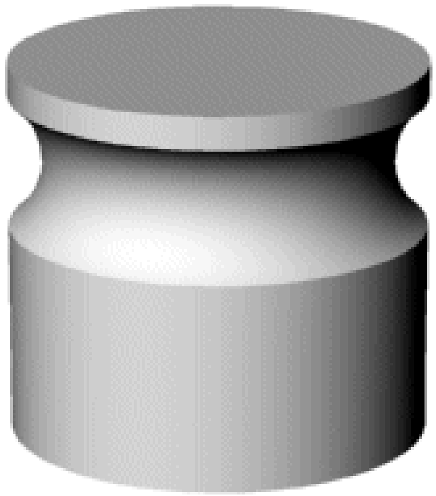
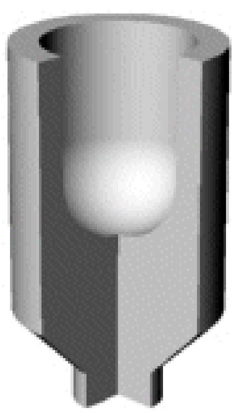
	The horn contacts the load and delivers power to the load. The horn's shape depends on the shape of the load and the required gain. Horns are typically made of titanium, aluminum, and steel. Horns are also called sonotrodes. Small diameter horns are sometimes called probes.

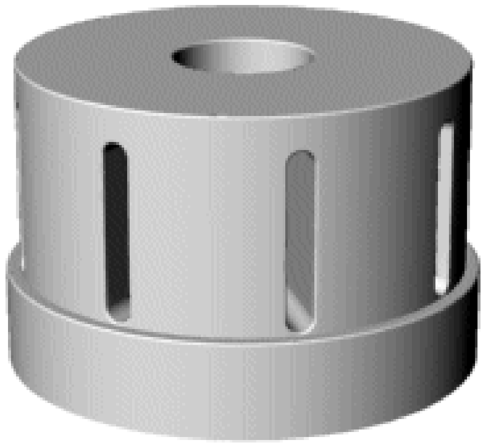
 Ultrasonic stack	The booster adjusts the vibrational output from the transducer and transfers the ultrasonic energy to the horn. The booster also generally provides a method for mounting the ultrasonic stack to a support structure.
	The transducer (converter) converts electricity into high frequency mechanical vibration. The active elements are usually piezoelectric ceramics although magnetostrictive materials are also used. Transducers are also called converters.

Horns

Cylindrical horns

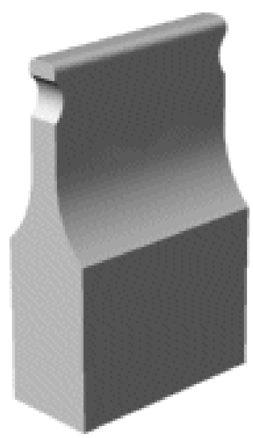
Type	Typical shape	Description

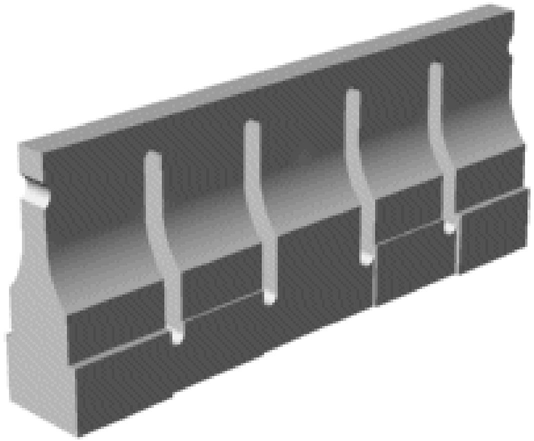
Simple		Solid horns with a simple geometry (stepped, exponential, or catenoidal). May have a replaceable tip. Can have high gain. Used for plastic spot welding and inserting and liquid processing.
Spool		Solid horn with a spool shape and large diameter (up to 1/2 wavelength). Has good amplitude uniformity across the face (generally >= 90%) and relatively low stress. Face must be flat or have only minor relief. Low gain. Used for plastic welding of circular parts and liquid processing. Details
Bell	 3/4 section	Unslotted horn with a cavity that extends to the node. Maximum diameter is generally <= 0.4 * wavelength. Moderate gain. May have considerable radial face amplitude. Used for plastic welding of circular parts and liquid processing.

Slotted		Large diameter horn with radial or cross-slots. Diameter usually >= 0.4 * wavelength. May have a face cavity. Low gain. Used for plastic welding of circular parts. Details

Bar horns

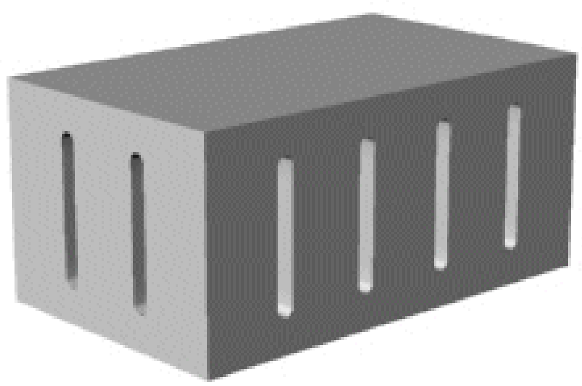
A bar horn has a rectangular output face and is either unslotted or has slots in one direction only. The horn thickness is generally <= 0.35 * wavelength.

Type	Typical shape	Description
Unslotted		Horn width is generally <= 0.4 * wavelength. Moderate gain. Used for plunge and scan welding and for some liquid processing applications (e.g., ultrasonic soldering).

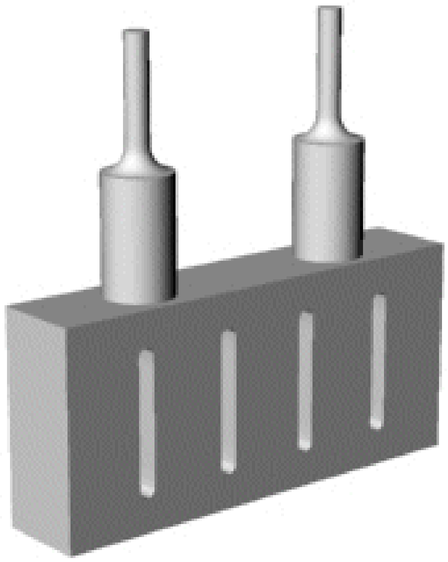
Slotted		Horn width is generally >= 0.4 * wavelength. Special design techniques give optimum face amplitude uniformity. Moderate gain. Used for plunge and scan welding. [Details](#)

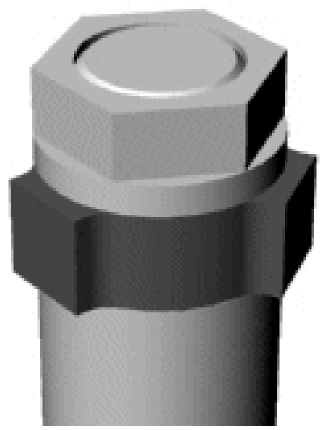
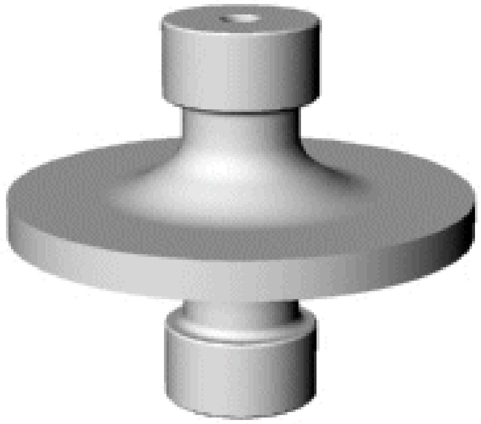
Block horns

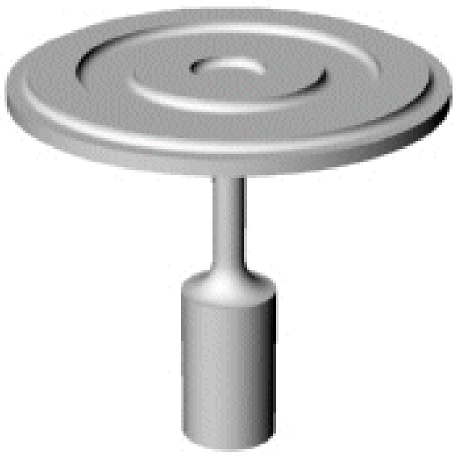
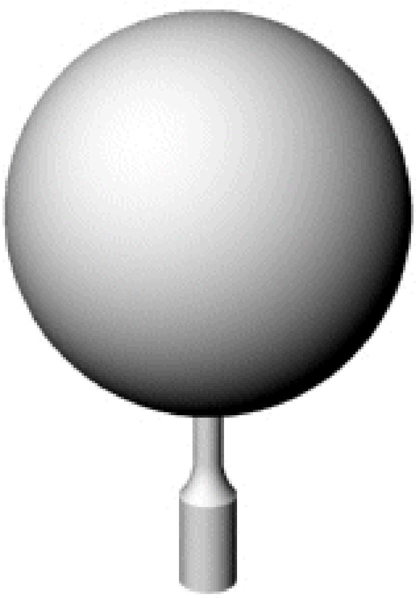
A block horn has a rectangular output face and has slots in two perpendicular directions.

Type	Typical shape	Description
Block		Width and thickness are generally >= 0.4 * wavelength. Unity gain. Used for plastic welding of large, flat, rectangular parts. [Details](#)

Special horns

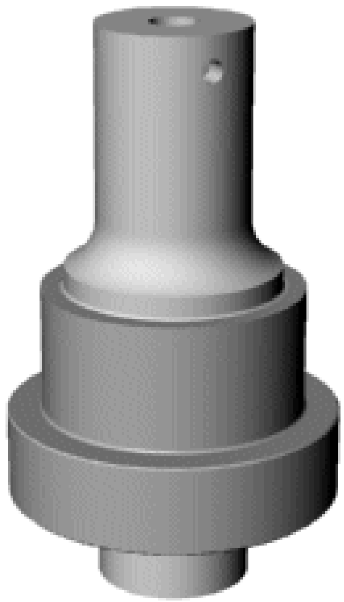
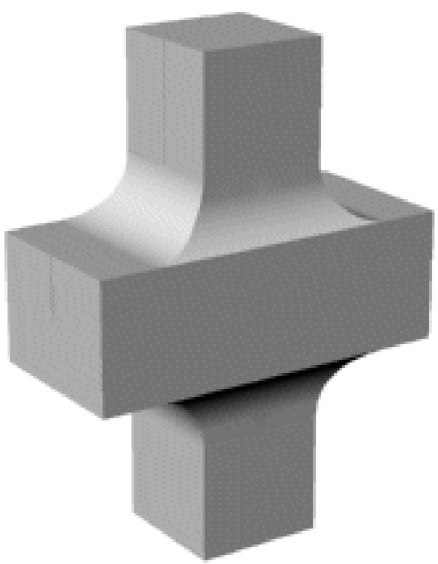
Composite		High gain tip horns are driven by a common mother horn. Used for spot welding of plastics and for liquid processing.
Contoured	____________	A horn that has a complex, often irregular shape machined into its face. Used for plastic welding.
Full-wave bell		This bell horn has an integral booster and is designed for liquid processing. The rigid mount flange provides a hermetic seal against the wall of the pressure vessel.

Metal welding	  Tip and nut details	Metal welding horns have a replaceable annular tip (typically tool steel) that is secured by a nut. The tip has multiple welding lobes.
Radial disk		The resonator is driven axially but the disk vibrates radially. Designed for use with a rigid mount booster. Used for rotary seam welding of plastics.

Flexure disk		The flexure disk is driven axially at its center but vibrates in bending with circular nodes. The amplitude decreases from the center to the edge. Compared to conventional horns, the disk has a large surface area with low mass. With the proper contour, the disk can produce a very narrow, intense acoustic beam. Used primarily for airborne ultrasound (drying, defoaming, agglomeration, etc.).
Radial sphere		The resonator is driven axially but the sphere vibrates with a uniform radial motion. The sphere's diameter is approximately twice the axial thin-wire half-wavelength (about 250 mm at 20 kHz). Used for atomization and cavitation.

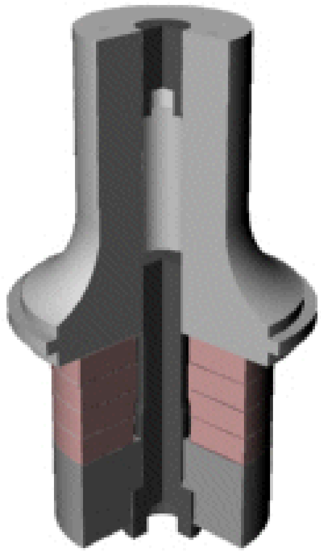
Boosters

Type	Typical shape	Description
O-ring	____________	The mounting ring is isolated from the booster body by O-rings.

Rigid mount		Because the rigid mount booster is constructed only of metal (no compliant elastomers), it has excellent axial and lateral stiffness. Used with heavy loads or where precise positioning is required and for rotating applications (e.g., seam welding; see radial disk). Also used where a hermetic seal at the mounting ring is required (e.g., for mounting through the wall of a pressure vessel); for an example, see the full-wave bell horn. Details
Cross-coupled		With a cross-coupled booster, the input and output surfaces are at 90 degrees, so the booster can essentially transmit ultrasound "around a corner". As with conventional boosters, various gains are possible. For the illustrated booster, the output amplitude from the top surface is 2.5 times greater than the input amplitude from the left surface. Note: the cross-coupled booster can also be used directly as a cross-coupled horn.

Transducers (converters)

Type	Typical shape	Description

Transducer	 3/4 section	Typical transducer with four piezoelectric ceramics, center-bolt (Langevin) design. The housing and electrode leads are not shown. For industrial applications, available power can range from 10 watts to 3000 watts, depending on the operating frequency, duty cycle, cooling, ceramic volume, and other factors.

Also see resonator design by finite element analysis.

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Home | Site Map | What's New | Company Info | Contact Us

Medical Resonators

[Up]

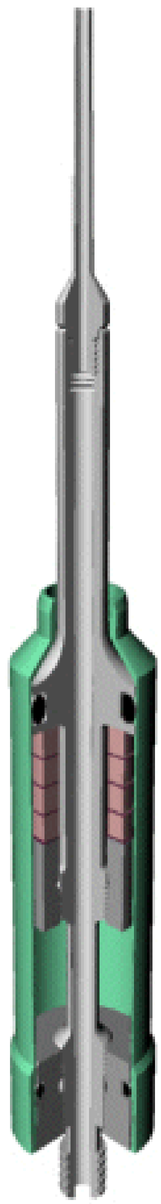
Ultrasonic medical devices are used for cutting, disintegrating, cauterizing, scraping, cavitating, and dental descaling. Because most are handheld, they must be small and light.

Typical design

Ultrasonic devices like this are used for tissue removal or disintegration. This device is driven by four piezoelectric ceramics. The tip is replaceable. The central passage is used either for irrigation or aspiration. (Note: electrical connections are not shown.)

Typical design parameters

Diameter	<= 25 mm
Frequency	20 kHz - 70 kHz
Amplitudes	100 - 300 microns
Cleaning and disinfecting	Autoclaving at high temperatures with steam may be required.

 3/4 section	Other	Irrigation and aspiration are often required. The probe may be bent for better observation of the procedure.

Also see resonator design by finite element analysis.

Top | Home | Site Map | What's New | Company Information | Contact Us

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FEA Information

[Up]

Ultrasonic Resonator Design
Using Finite Element Analysis (FEA)

Table of Contents

Abstract

This paper discusses the methods, advantages, and limitations of finite element analysis for the design of ultrasonic resonators (resonators/sonotrodes/probes, boosters, and transducers/converters) for power ultrasonics. Typical examples are given.

This paper was originally presented at the Ultrasonic Industry Association's 1991 technical symposium, when it was titled "The Application of Finite Element Analysis to the Design of Ultrasonic Resonators". It has been updated to reflect current practices.

Overview

Finite element analysis (FEA) is a computer-based method for analyzing and improving resonator performance. (Note: FEA is sometimes called FEM -- finite element method.) In FEA, the resonator is simulated as a computer model. The computer simulation model consists of a large number of small "elements" that represent (approximately) the shape of the resonator. Each element can be described mathematically by a set of equations. The solution to this set of equations yields a prediction of the resonator's performance -- i.e., the natural frequencies at which the resonator will vibrate and the amplitudes and stresses associated with each of these frequencies. After the performance has been predicted, the resonator's dimensions or materials can be changed within the FEA model in order to improve the performance.

The following discussion will emphasize FEA of medical probes, as used phaco emulsification (cataract surgery) and similar applications. However, FEA is equally applicable to the design of industrial resonators. For examples, including animations, see bar horns, block horns, cylindrical horns, and boosters.

Notes:

1. The resonators discussed below have a nominal axial resonance of 25 kHz, although any design frequency is possible.
2. See the glossary for definitions and symbols.

Requirements for Adequate Resonator Design

In order for a resonator to function properly, consideration must be given to the following performance factors.

1. Primary resonance tuning. The frequency of the primary (desired) resonance must be adjusted to the nominal resonance of the power supply (generator). This frequency must account for the expected operating temperature of the resonant stack.
2. Secondary resonance tuning. The resonator must have sufficient frequency separation between the primary and all secondary (undesired) resonances. Otherwise, the power supply may accidentally "jump" to a secondary resonance, especially during the transient starting conditions or under highly loaded conditions. Such a jump could cause poor or erratic performance and could overstress the resonator. Poor frequency separation may also cause nonuniform or asymmetric resonator amplitudes, which may lead to early transducer failure.
3. Gain. The resonator must have sufficient gain (output amplitude) to perform the application.

4. Amplitude uniformity. The amplitude at the resonator's face must be sufficiently uniform to perform the application. The amplitude at the resonator's input surface must be sufficiently uniform to prevent heating and galling at the joint interface. (These requirements apply mainly to industrial horns, whose face and input surfaces may be relatively large and are therefore prone to significant amplitude variations over these surfaces.)

5. Amplitude direction. The predominate amplitude should be in the desired direction in order to maximize the effectiveness of the ultrasonics while minimizing undesired side effects (heating, scrubbing, wasted power, etc.). The desired direction is generally along the axis of the resonator, although there are notable exceptions -- e.g., radial resonators (disks and tubes) or flexural resonators (plates, strips, disks, tubes, dental prophylaxis probes, etc.).

6. Node location. If the resonator is to be mounted at a node, then the mounting flange must be properly positioned at the node so that minimum energy is transmitted to the support structure.

7. Stress. The stresses must be sufficiently low for long resonator life.

8. Loss. The loss must be low to avoid associated problems (thermal runaway in piezoelectric ceramics, tissue heating, operator discomfort in handheld devices, etc.).

9. Starting. The resonator must achieve the operating amplitude within the time permitted by the power supply. Thus, the energy distribution within the resonator and between the resonator and booster must be considered.

In addition to these performance considerations, the following must also be considered.

1. Materials. Materials must give adequate fatigue and wear/erosion life. For medical probes, the materials that are in contact with tissue must not cause detrimental effects; also, the materials and design must be amienable to sterilization, if required.

2. Geometry constraints. The resonator must fit within a geometry envelope. For a handheld medical probe, the probe must be lightweight and relatively slender. For plastic welding horns, the horn must conform to the shape of the part.

3. Maunfacturability. The resonator must be manufacturable at reasonable cost.

Conventional Resonator Design

First, consider the conventional approach to resonator design.

1. Design the resonator. The resonator's design is based on the engineer's experience and best judgement.

2. Machine and tune the resonator to the desired frequency. Care must be taken not to mistune or tune to a nonprimary resonance.

3. Evaluate the resonator performance. Determine if the resonator meets the performance requirements.

4. Correct the known problems. If the resonator's performance is not acceptable, then modify the existing resonator and repeat step 3 or, if required, start again from step 1.

5. Ship the resonator. Wait for the customer to find additional problems (usually fatigue failure) associated with extended use.

6. Correct the customer's problems. Start over from step 1.

There are at least two problems with this approach.

1. This cut-and-try approach wastes time and material. The resonator performance parameters cannot be determined until a prototype resonator has been machined. If the prototype resonator does not have adequate performance or if it cannot be remachined to achieve adequate performance, then

additional resonators may be required. This rework creates scheduling difficulties and delays delivery.

2. Resonator reliability will be difficult to estimate. This is because certain performance parameters cannot be easily evaluated. For example, there is usually no convenient way to determine resonator stresses, so estimates of resonator life will be crude. (Note: even if holographic or thermographic equipment is used for stress measurement, this equipment will only show surface stresses, not the internal stresses which may be most critical.) Similarly, amplitudes at the joints (e.g., between the resonator and booster) will be impossible to measure, so joint problems will be difficult to detect. Thus, evaluation of resonator reliability is often left to the customer.

FEA Resonator Design

Unlike conventional resonator design, FEA attempts to solve the performance problems *before* the resonator is machined. The process has eight steps.

1. Specify the performance factors
2. Establish the material properties
3. Model the resonator
4. Process the model
5. Evaluate
6. Iterate
7. Machine and tune the resonator
8. Verify the performance

These steps may be applied to a conceptual resonator whose performance is unknown or to an existing resonator whose performance is inadequate.

The following steps will be illustrated with a medical probe (figure 1) whose primary axial resonance is at 25 kHz. The probe is driven by a power supply (generator) which delivers electrical energy to the piezoelectric ceramics. This causes the ceramics (and, hence, the probe) to expand and contract at the probe's resonant frequency.

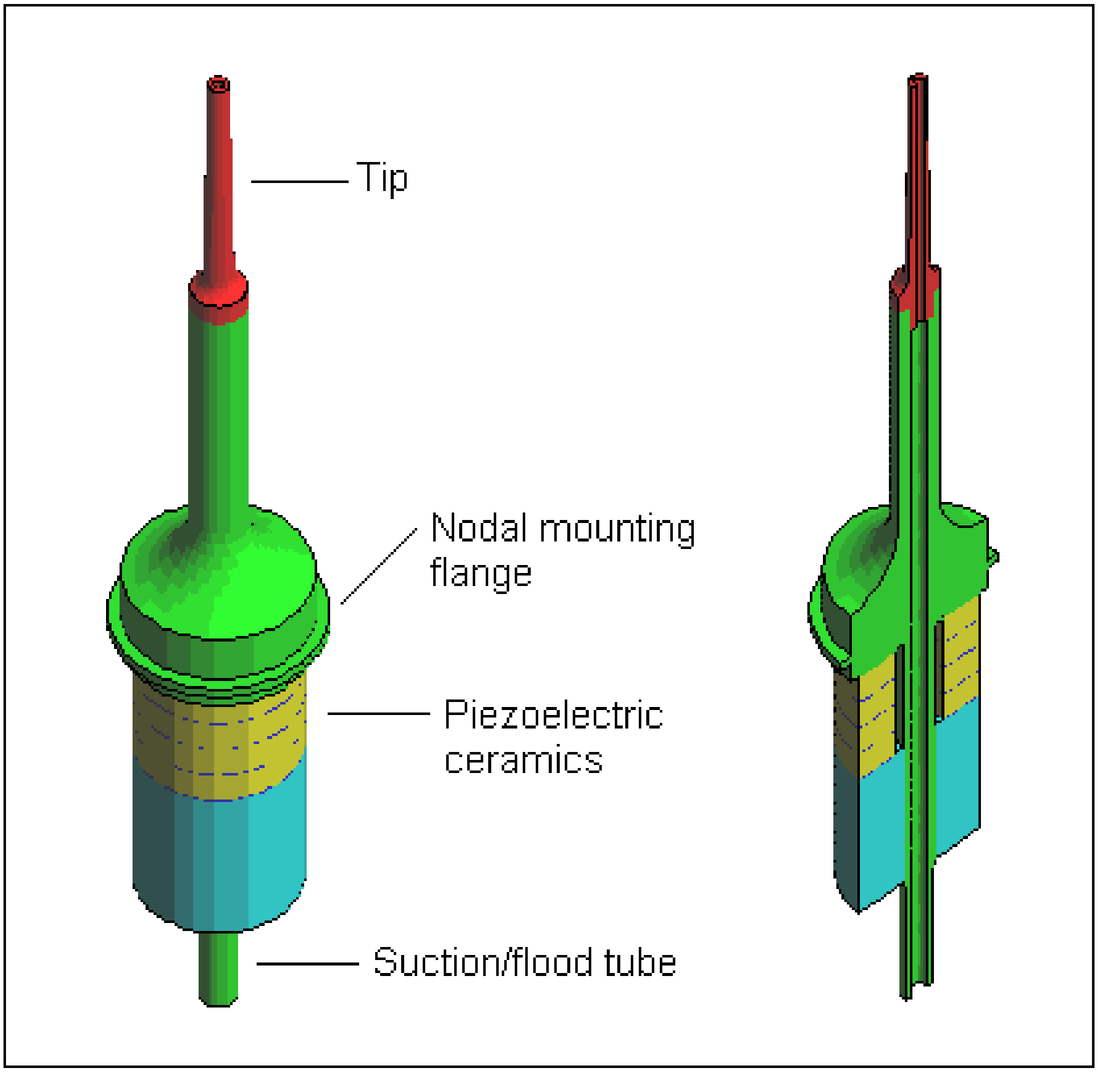

Figure 1. Typical medical probe.
Left: full model
Right: sectioned model

Specify the performance factors

The engineer must first decide what performance factors are important for the particular resonator. This will dictate certain requirements for the computer model, which will determine the time needed to complete the FEA. See Requirements for Adequate Resonator Design.

(Specifics are discussed in the section Modeling Considerations.)

Establish the material properties

The engineer must establish the material properties that will be used for subsequent FEA. These properties can be determined from ultrasonic tests or static tests, or, less preferably, can be estimated from handbook values.

Alternately, the engineer can run a preliminary FEA (as described in the following sections) on an existing resonator that has the same material and similar dimensions to the conceptual resonator. The material properties are then adjusted until FEA adequately predicts the measured performance of the existing resonator.

Model the resonator

During the modeling phase, the engineer constructs an idealized computer model of the actual resonator. The model is composed of a large number of small elements that are sufficient to describe the geometry of the resonator. This is called "creating the mesh". The mesh intersections are called nodes. The mesh elements must be sufficiently small that the solution for the desired results will converge. (See section on Modeling Considerations.) The previously determined material properties are also specified.

In the following figure, only half of the resonator has been modeled because of axial symmetry. By reducing the number of elements, the analysis time is significantly reduced.

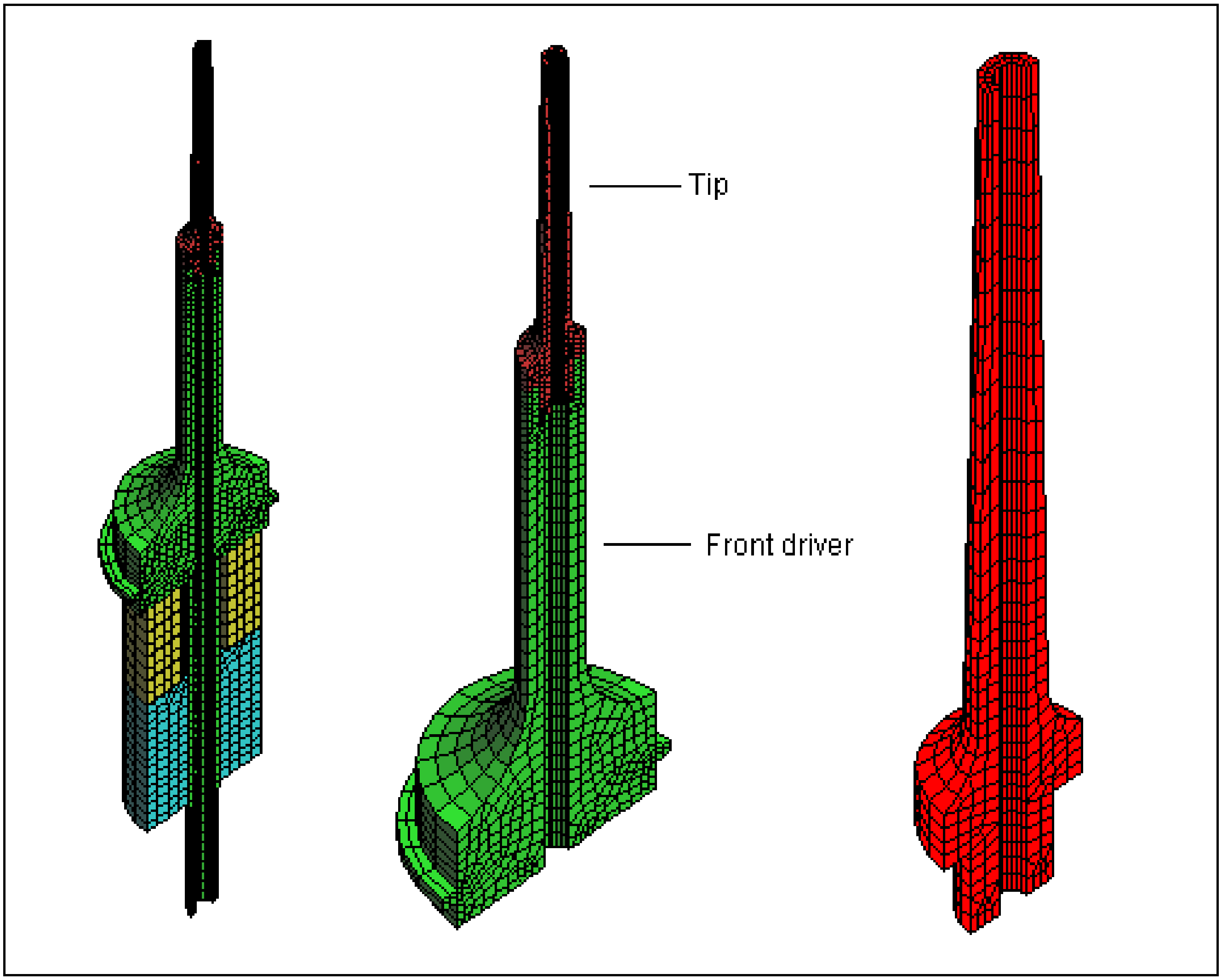

Figure 2. Resonator model (1/2 section) with element mesh (black lines)
Left: Complete resonator
Middle: Enlarged view of tip and front driver
Right: Enlarged view of tip

Depending on the model, the engineer may also have to apply certain boundary conditions so that the model will not vibrate in unrealistic directions.

Most FEA programs have CAD-like preprocessors that aid in constructing the model and the mesh.

Process the model

Once the model has been completed and verified, it is submitted for processing. The computer solves the required equations and outputs the results.

Evaluate

When the processing is complete, the engineer must check the output to determine if the predicted resonator performance is acceptable (e. g., uniformities, stresses, frequency separation, etc.). The following figures show typical results.

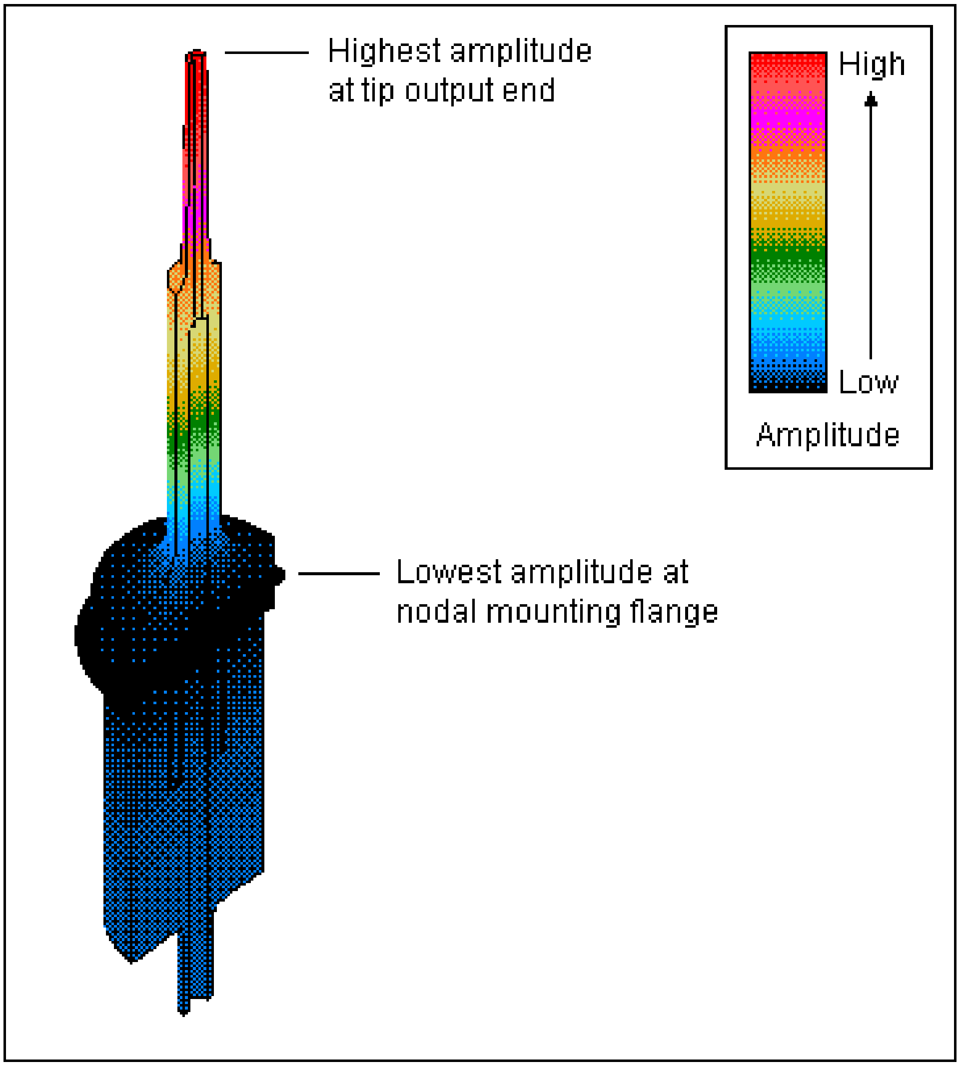

Figure 3. Axial mode at 25.0 kHz: relative amplitudes

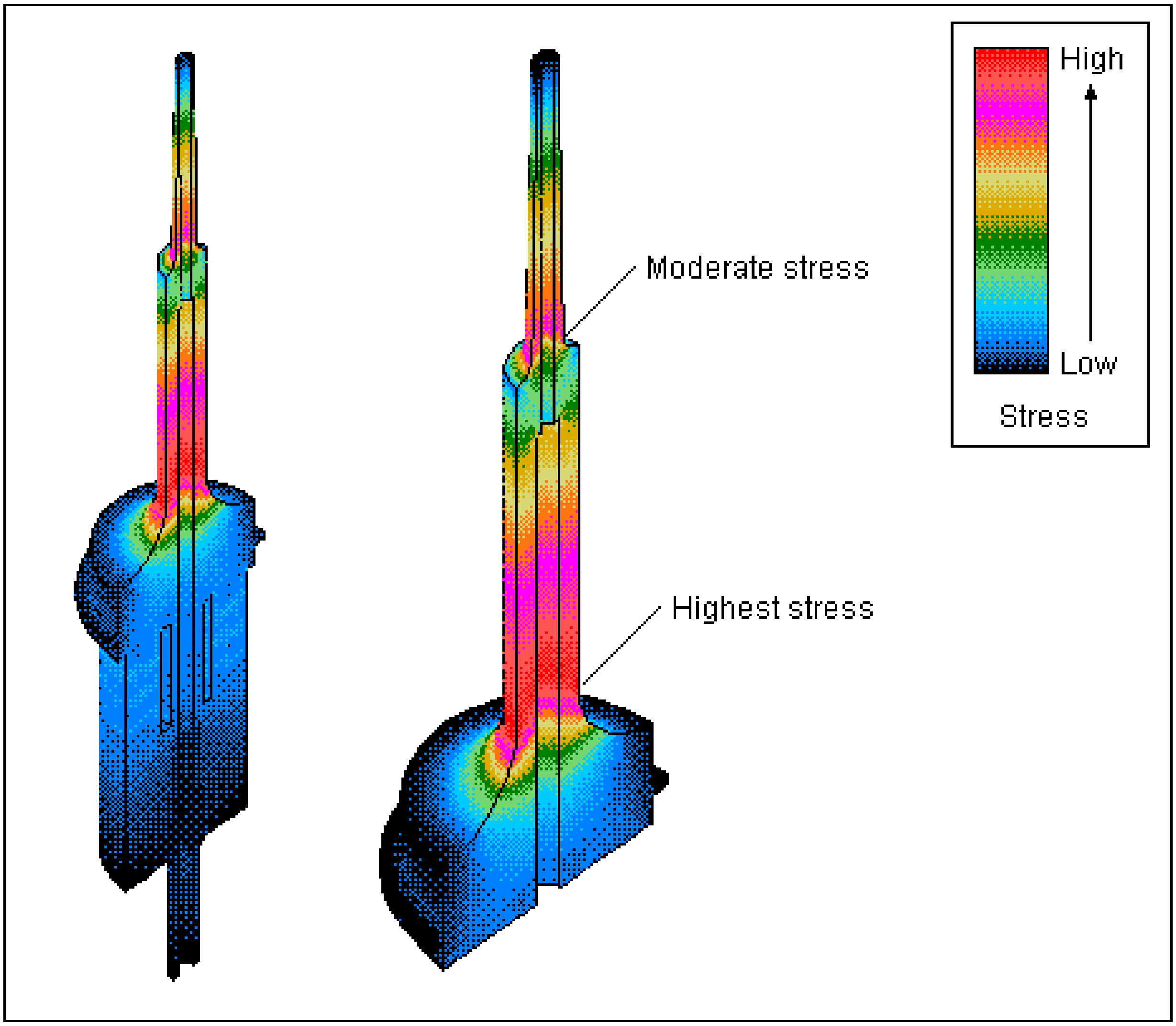

Figure 4. Axial mode at 25.0 kHz: relative stresses.
Left: Complete resonator
Right: Enlarged view of tip and front driver

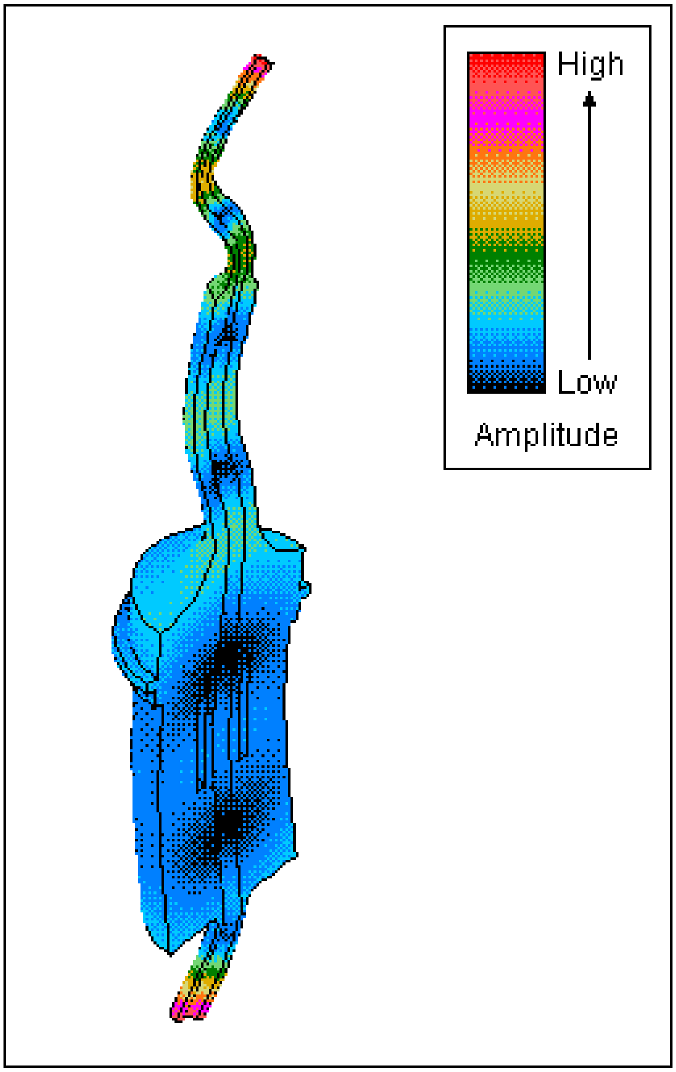

Figure 5. Bending mode at 23.8 kHz: relative amplitudes.

Iterate

If the resonator performance is not acceptable, then the engineer must return to the modeling phase and adjust the resonator dimensions. The revised model is then submitted for processing. This process continues until adequate resonator performance has been achieved, or until no further performance improvement seems possible.

Machine and tune the resonator

After the performance of the FEA model has been correctly adjusted, a resonator is machined to the dimensions of the FEA model. The resonator is then tuned to the specified frequency.

Verify the performance

If the FEA has been performed properly, then the performance predicted by FEA should agree reasonably with the actual resonator performance. Agreement should be especially good if similar resonators have been previously modeled. *Exact agreement should not be expected*, either because of limitations of the FEA or because of measurement errors for the actual resonator.

Frequencies

Frequencies are easiest and most accurate parameter to measure and verify. However, note that FEA may predict more frequencies than can be measured in the actual resonator. These extra FEA frequencies are often bending resonances or resonances where a node that runs through the resonator's axis. Although such frequencies are actually present in the resonator, they often cannot be easily excited by the transducer and are therefore difficult to detect by frequency analyzer equipment. Although these extra resonances can often be ignored, they can sometimes interact with the primary resonance, causing asymmetric amplitudes and high stress.

In some cases, the extra FEA frequencies are caused by boundary conditions that are needed to constrain the FEA model. Such FEA frequencies are erroneous and will not exist in the actual resonator. It is the responsibility of the FEA engineer to recognize this situation.

Amplitudes

Amplitudes are relatively easy to verify, but care must be taken to assure that the amplitudes and their locations are correctly measured. This is especially important where the amplitude changes rapidly (e.g., at the edge of large-diameter unshaped cylindrical resonators). Depending on the sophistication of the amplitude measurement equipment and the care of the operator, 5% amplitude difference between the measured values and the FEA values would not be unusual.

If the FEA frequencies or amplitudes have larger error than expected, this may indicate improper modeling (e.g., not enough of the resonator or improper boundary conditions), inadequate mesh refinement, incorrect material properties, or incorrect measurements.

Stress

Since empirical stress data is usually not available, stress usually cannot be directly verified. However, the FEA stresses will not be correct if the FEA amplitudes are not correct, since stress depends on the amplitude gradient. Even if the FEA amplitudes are correct, the FEA stress may still be incorrect due to poor choice of element sizes or geometry. Some FEA programs permit estimates of FEA stress error and indicate where the mesh needs to be refined to reduce the error.

The inability to verify FEA stresses may not be a problem, since the FEA engineer may not be concerned with absolute stress values; he may only want to know if the stresses have improved between successive FEA designs. This is especially true where the fatigue properties of the resonator material are unknown, in which case the resonator life cannot be predicted anyway. (See the section on Technical Limitations of FEA/ Predicting resonator Life.)

Application of FEA

From the above discussion, the advantages of FEA are apparent. Compared to conventional resonator design, FEA permits a substantially complete resonator design before any machining begins. Because FEA gives information that is not available with conventional resonator design, the resonator performance can be optimized to an extent that would not otherwise be possible. FEA can indicate potential performance problems and, if these cannot be corrected, subsequent reliability testing can focus on these problems.

The use of FEA must be balanced against the payback. The main constraint on FEA is the time required to input the initial FEA model, where the modeling time grows exponentially with the complexity of the resonator, and the time required to optimize the design. Thus, FEA can best be used in the following situations.

Resonator life is critical

If the customer has an application where resonator failure and replacement would be costly (e.g., in an automated assembly line) or might result in injury (e.g., medical probes), then the resonator must be designed for maximum life. FEA allows internal resonator stresses to be analyzed and minimized before the resonator is machined. If the "optimized" stress still appears too high, the application may be redesigned to permit use with resonators of lower stress. If this is not possible, then the customer can be informed of the risks, and the resonator can be given the appropriate warrantee.

The resonator will be produced in large quantities

Such high volume resonators (transducers, boosters, certain resonators) can be analyzed to optimize the design. The resulting FEA cost per resonator is small.

Empirical design would be too costly

Certain resonator modifications do not lend themselves to cut-and-try methods. For example, if a resonator will use angled slots for improved uniformity, it would certainly be more cost-effective to analyze different slot angles by FEA than by machining many different resonators, each with a different slot angle. FEA can also provide information on stresses, which would not be available through cut-and-try.

Empirical design would not provide the needed information

Even after machining, the actual resonator may not provide the information that is needed to evaluate its performance.

Stresses

With conventional resonator design, surface stresses can be measured after the resonator has been made, although this requires sophisticated test equipment. In contrast, FEA can predict both static and dynamic internal stresses before the resonator has been made. For example, if any of the stresses in figure 4 had been excessive, then this resonator could have been redesigned to reduce these stresses. If the fatigue characteristics of the material are known, then the resonator life can be estimated.

Amplitudes

FEA can predict ultrasonic amplitudes throughout the resonator. This can be useful for determining node locations on boosters and transducers (figure 3). It can also be used to determine the amplitudes at inaccessible location (e.g., the amplitudes across interfaces such as horn-booster joints and ceramic interfaces). This can provide insight into problems such as interface heating and galling.

In addition, FEA can predict amplitudes that cannot be easily measured. For example, FEA can predict the transverse amplitudes on the face of a horn, which may cause scrubbing problems or excessive transverse vibration of attached pins (as used for ultrasonic machining of ceramics). Many measurement devices (e.g., lasers) cannot measure such amplitudes.

Modes

FEA can predict asymmetric modes that cannot be readily detected by spectrum analyzers (figure 5). As discussed above in the section on verifying the performance, these modes can interact with the axial resonance, causing asymmetric amplitudes and high stress in the axial mode. Early detection by FEA allows these frequencies to be repositioned with respect the axial resonance, so that their effects are reduced.

Empirical design is too variable

In certain circumstances, the variability of empirically measured data masks the effects of design changes. For example, when machining a transducer to improve its performance, the transducer must often be disassembled between each machining operation. However, each disassembly-reassembly operation introduces additional variables ("noise") which can obscure the effect of the machining operations.

Variability of empirical data also occurs from variability of material properties. For transducers, variability is caused by differing ceramic performance. In titanium, variability may occur between batches of material.

FEA eliminates these kinds of variability problems. With FEA, the effects of any design changes are exactly repeatable and all performance changes can be directly attributed to design changes.

Technical Limitations of FEA

While FEA could conceivably be used to model almost any resonator, it will not be practical or cost-effective in all situations. The following are general limitations which may be overcome in specific instances.

Modeling limitations

Some of FEA's limitations arise from difficulties in creating an adequate model of the resonator. This is especially true for resonators with complex geometries (e.g., heavily contoured resonators or composite resonators) that require three-dimensional models.

As discussed in the section on Modeling Considerations, the model is often simplified in order to reduce modeling and computing time. Such a model will always give somewhat limited or incomplete results. The FEA engineer must have sufficient experience to estimate the effect of such simplifications.

Predicting resonator life

FEA can predict resonator stresses. However, resonator stresses do not allow life predictions unless the fatigue characteristics of the resonator material are known. Unfortunately, there are significant problems in determining fatigue characteristics. Fatigue can be affected by the frequency of vibration, so that conventional (low frequency) handbook data may not predict the fatigue at ultrasonic frequencies. Even where it might be reliable, low frequency data is usually too limited to provide life predictions at ultrasonic frequencies. For example, low frequency tests are often stopped at 500 million cycles, which represent only seven hours of continuous ultrasonics at 20 kHz.

Further, fatigue is affected by the raw stock type (rod, bar, or plate), the raw stock size, and the direction of vibration relative to the material's grain. For nominally equivalent material, fatigue may also vary from heat-to-heat (especially for titanium) or among different manufacturers.

Fatigue is also affected by machining, which can leave residual tensile stresses that shorten resonator life. These stresses are difficult to predict, since they depend on such factors as material removal rate, the type of machining coolant, the tool sharpness, etc. FEA cannot predict these surface stresses.

Thus, unless the material's fatigue properties and the effects of machining are well known, the stresses predicted by FEA probably cannot be used to predict resonator life. However, the FEA stress data can be used to redesign resonators that have known failure problems.

Note: although this is listed as a limitation of FEA, it is also a limitation of any other method of resonator analysis. The resonator life cannot be predicted from stress unless the material's fatigue characteristics are known.

Predicting joint problems

In most cases, joints are simply modeled as if the joined components were welded together. Although this approach works well in predicting most performance factors, it does not allow prediction of joint problems arising from fretting or slippage.

Such joint problems can occur at the booster-resonator joint because of nonuniform amplitude at the interface. Joint problems can also occur in the transducer because of flexing resonators or because of inadequate ceramic clamp force. Other joint problems occur at threads (e.g., for tips, studs, transducer stack bolt).

In order to model such joint problems, the joint friction must be known. However, this friction may change with time as joint fretting progresses.

In some cases joint problems can be predicted based on amplitudes and uniformities at the joint, but the extent of the problem can only be determined when the actual resonator is tested.

Predicting stack loss

Stack loss includes the material loss of the resonator, booster, and transducer, the radiated air loss, and the frictional loss at the stack joints. If the FEA program calculates the stored energy of the model, then the resonator and booster material loss can be calculated if their material's Q's are known. (Q is a material property that relates the energy stored to the energy dissipated per cycle.) The material loss of the transducer is much more difficult to estimate (see below). Prediction of radiated air loss may be possible by FEA. As previously discussed, FEA cannot reasonably predict frictional loss, especially loss caused by flexure.

Predicting performance under load

FEA can predict the performance of a resonator under load. However, the analysis may be extremely difficult. This is because the load may have nonlinear characteristics and the load's characteristics may change as the ultrasonic process progresses. This would be true, for example, in plastic welding and metal welding. Because of these problems, the effect of the load is generally ignored during resonator design.

Although a FEA frequency response analysis can give some insight, FEA cannot predict power supply starting problems or the tendency of the power supply to jump to a nonprimary resonance under heavy load.

Predicting bending modes

FEA can predict bending modes. However, in order to do so, the entire resonator stack must be modeled. For example, to analyze the bending modes for a plastic welding stack, the horn-booster-transducer assembly would have to be modeled. Compared to modeling a single component (typically the horn), this causes the following problems.

1. The modeling time may be much longer. This is because extra components (e.g., the booster and transducer) must be added to the model. In addition, the complexity of the model may increase. For example, where an axisymmetric model might normally be used, extraction of bending modes will require a 1/2 3-D model (minimum).

2. The analysis time will be much longer. With the added components, the size of the model (number of elements) increases. Also, the number of extracted modes increases.

3. Bending modes depend on the stack components. If a stack is analyzed with a particular transducer-booster, then the bending modes will change if another transducer or booster is substituted. Since horns are often required to run with several different boosters or transducers, analysis of all possible combinations is usually not practical.

Also, in those cases where the bending involves microslip of the transducer's ceramics (a nonlinear phenomenon), the FEA predictions may not be accurate. Thus, unless bending modes are suspected of causing problems, they are often ignored, especially in the initial analysis.

Predicting transducer characteristics

Unless the FEA program contains an element type that describes the operating characteristics of piezoelectric ceramic, it cannot predict the output amplitude of a transducer due to a specified electrical input.

FEA can analyze heat transfer problems. However, FEA has limited ability to predict transducer temperatures. This is because the heat generation within ceramics depends on many factors (e.g., the drive voltage, the load, the ceramic age, the time since the transducer was assembled, the static preload, the insulation used on the ceramics to prevent arcing, variations among ceramics, microslippage at ceramic interfaces, etc.). These factors make it difficult to accurately characterize transducer heating.

Despite these limitations, FEA is still useful in transducer design. FEA can predict static preload stresses , resonant frequencies, the node location , the relative amplitude distribution, and stresses relative to the output amplitude. See figures 3, 4, and 5.

Administrative Limitations of FEA

Optimization

If the purpose of the FEA is to analyze an existing resonator design, then this can usually be done within several days. Obviously, the time required will depend on the complexity of the resonator and the complexity (or degree of simplification) of the FEA model.

However, if the purpose of the FEA is to improve (optimize) the performance of a resonator, then the time required can be considerably longer. The time required will depend on the complexity of the resonator and the model, the number of performance factors that must be improved (e.g., uniformity, stress, gain, etc.), the degree of improvement required, and the acoustic engineer's knowledge about how to resolve the resonator's problems. The resonator design must be repeatedly altered and rerun until an acceptable design has been achieved.

A difficult resonator may require a week or more to optimize (excluding the time needed to actually make the prototype resonator and verify the FEA performance). Even with this effort, the results may not meet the optimization goals. Sufficient time must be allocated for this optimization process.

Modeling Considerations

In order to properly compare FEA to conventional resonator design, the considerations for developing the computer FEA model must be understood.

The FEA model is a computer approximation of an actual resonator. The error of this approximation will depend on the refinement of the model. Although refined models give better results, they require more engineering and computing time. The degree of refinement will depend on two factors.

1. Selection of performance factors. The engineer must decide what resonator performance factors (frequencies, amplitudes, stresses) are important for a particular resonator design. The

engineer then constructs an FEA model which will adequately predict the specified performance factors.

2. Convergence requirements. The FEA results will converge to a solution as the mesh is refined and as the mesh more closely approximates the actual resonator geometry. (Note: convergence does not necessarily imply accuracy.)

Performance factors

Frequencies

The refinement of the FEA model will depend on which modeshapes are considered important. Flexure (bending) modes depend on the dimensions of the entire stack (resonator + booster + transducer). Therefore, if flexure modes are important then the entire stack must be modeled in three dimensions. Unless the stack is axisymmetric, the required model may be very time consuming to develop.

Even if such a 3-D model was developed, it would have limited usefulness in predicting flexure. First, flexure modes may involve slip of the transducer ceramics and will, therefore, be amplitude dependent (nonlinear). This will preclude correct prediction of flexure frequencies. Second, flexure modes depend on the specific stack components. If the customer uses a different booster or transducer than was originally modeled, then the model will not predict the customer's flexure resonances. Thus, flexure resonances (which seldom cause problems in actual practice) are generally ignored during initial FEA.

If the flexure modes can be neglected, then reasonable frequency accuracy can usually be achieved by modeling only the resonator (i.e., no transducer or booster). Further, if the resonator is symmetric and certain asymmetric modes can be ignored, then further simplifications of the model are possible. Cylindrical resonators which are symmetric about their stud axis can often be modeled axisymmetrically (a two-dimensional approximation).

While modeling only a section of the resonator will save modeling and computing time, it also limits the FEA results, since asymmetric modes may not be extracted. For example, a 20 kHz 100 mm diameter unshaped cylindrical resonator will have a asymmetric "shear" resonance adjacent to the axial resonance, which will cause significant amplitude asymmetry for the axial resonance. Neither an axisymmetric model nor a 1/2 3-D model would predict the asymmetric resonance; only a full three-dimensional model could do so. Of course, the three-dimensional model is more difficult to design and more time-consuming to run.

All resonators will have flexure and asymmetric modes. A limited FEA model that precludes these modes can lead to unexpected problems when the actual resonator is machined. Unfortunately, the effect of these modes on resonator performance cannot usually be predicted in advance. In some cases, however, experience with previous resonators can provide some guidance.

Amplitudes

The sophistication of the FEA model will depend on which amplitudes need to be predicted. For example, axisymmetric models predict amplitudes across the resonator diameter, but not around the resonator's circumference. If circumferential amplitudes are important, then a 3-D model is required.

Stress

If the engineer is confident that the resonator will not fail, then FEA does not have to give accurate stress predictions. This can considerably simplify the FEA model.

For example, if stresses are unimportant, then slots can approximated as rectangles with "square" ends, rather than rounded ends. This approximation will have little effect on the resonant frequencies or amplitudes. However, such a model could not possibly predict the stresses at the slot ends.

If the resonator stresses are important, then the slots would have to be modeled with rounded ends, which could significantly increase the modeling time. This is because the mesh at the rounded ends may need to be adjusted by hand, especially at slot intersections. The computing time also increases because of the increased number of elements needed to model the rounded slot.

Convergence requirements

FEA estimates the performance of the actual resonator. As the size of the FEA elements is reduced (i.e., as the mesh is refined), each performance factor will converge to its terminal value. The rate of convergence will depend on the particular performance factor and on the skill used to refine the mesh. Note: convergence does not necessarily imply accuracy.

Frequencies and amplitudes

Generally, the frequencies converge most quickly their final values; amplitudes converge more slowly.

Stress

Stress, which depends on the gradient of the amplitude (i.e., the strain), may require a much finer mesh, especially at stress concentrations (e.g., at radii, slot ends, etc.). The required mesh size for stress convergence will depend on the geometry of the particular stress concentrator. Some FEA programs provide estimates of stress error, which indicates where the mesh must be refined to reduce the stress error. (These estimates of stress error assume that the frequencies and amplitudes have essentially converged.)

Thus, consideration of performance and convergence will determine the complexity of the model. As the complexity increases, both modeling time and computing time may increase substantially. Thus, the model should be kept as simple as possible, consistent with the desired results. As discussed above, however, the required degree of simplicity cannot always be judged in advance.

The usual approach is to model the resonator in the simplest manner that the engineer deems prudent. This requires good familiarity with both FEA and ultrasonic resonators. If the FEA results do not adequately predict the frequencies or amplitudes of the machined resonator, then a more sophisticated model will be needed.

FEA Accuracy

FEA will not be useful unless it gives accurate results. As discussed previously, the user must be sure that the FEA solution has converged. However, a converged solution does not necessarily imply an accurate solution. Accuracy will depend on several factors.

Material properties

FEA cannot correctly predict resonator performance unless the resonator's material properties (Young's modulus, modulus of rigidity, Poisson's ratio, and density) are known. For resonators with small lateral dimensions, the density and the modulus of elasticity (which determine the thin-wire wave speed) determine the resonant frequencies. The axial frequency of a 20 kHz resonator will change by 100 Hz for every 1% error in the modulus of elasticity or density.

For larger resonators, the resonant frequencies are affected somewhat by Poisson's ratio. Depending on the resonator's shape, the amplitude can also be significantly affected by Poisson's ratio.

For materials that are reasonably isotropic (e.g., most aluminums), only two elastic property values are needed to completely characterize the material. These properties are relatively easy to determine. For materials such as titanium and piezoelectric ceramics that are orthotropic (i.e, the properties depend on the test direction), nine elastic property values are needed for complete characterization. However, using averaged material values (i.e., assuming that titanium is isotropic) usually gives reasonable results. A further problem with titanium is that its properties may vary from batch to batch and may also depend on the size of the raw stock.

Where resonator frequencies are concerned, a small error in the material properties is usually not critical, since most resonators allow some extra material for tuning. However, fixed-length resonators (e.g., transducers and boosters) do not enjoy this allowance.

In general, then, some FEA error should be expected due to inexact material values.

Modeling fidelity

The FEA model must accurately represent the actual acoustic system. This means that the geometry must be correctly modeled and boundary conditions must be correctly enforced.

Geometry

The model geometry should reasonably approximate the actual acoustic system. (See the section Modeling Considerations for further discussion of modeling fidelity.)

Sometimes a seemingly insignificant change in geometry can dramatically affect the FEA predictions of resonator performance. For example, omitting a stud from a horn with large lateral dimensions (e. g., block horns, spool horns, etc.) can significantly affect the amplitudes and stresses, although the effect on resonant frequencies may be minor.

Effect of transducer-booster

The transducer-booster components usually do not have a significant effect on the primary mode. However, these components can significantly affect the frequencies predicted for other modes. (See Predicting bending modes.) Therefore, if the horn is modeled without the transducer-booster, then the optimized FEA design must allow extra frequency separation between the primary and nonprimary modes in order to compensate for this potential error.

Note: even in the primary mode, the transducer-booster may have an effect if the interfaces are not properly designed. For example, this can occur when a transducer-booster is attached to a flexing disk if the disk has significant bending across the interface joint.

Method of analysis

In order to determine the effects of adjacent resonances on the primary resonance, an estimate of the damping (Q) at each natural frequency will be needed. However, such damping estimates are imprecise, often because the damping characteristics of the transducer may not be well known. This will introduce some error, especially when the damping is high (low Q).

Accuracy estimates

If the resonator has been properly modeled and the solution has converged and the material property values are accurate, then FEA frequencies and amplitudes are usually within several percent of the measured (empirical) values. FEA gain is usually within 5% of measured values.

Remember, however, a measured value is not necessarily an accurate value. This is especially true for gain measurements, which involve indirect measurement of the resonator input amplitude. Thus, disagreement between empirical measurements and FEA values does not necessarily mean that the FEA values are incorrect.

Conclusion

This paper has described the advantages and limitations of FEA as compared to conventional resonator design. As with any tool, FEA is not appropriate for all occasions. However, for those occasions that warrant its use, FEA can provide insight and design opportunities that would otherwise be impossible.

If you have a resonator design that might be improved by finite element analysis, then you can use the Resonator Information Form to submit baseline information or you can contact Krell Engineering directly.

Glossary and symbols

3-D -- three-dimensional.

asymmetric resonance -- a resonance in which the amplitudes are different at symmetric locations on the resonator.

asymmetry -- an aberrant condition in which vibration motion at two or more geometrically identical locations (e.g., the four corners of a block horn) are not identical (within measurement tolerance). This may occur with resonators that have large lateral dimensions (e.g., bar horns and block horns), particularly if a nonprimary resonance interferes with the primary resonance. Generally, the optimum asymmetry is 0. (Also see Uniformity.)

axial resonance -- a resonance where the major amplitudes are generally parallel to the resonator's axis and there are no nodes on either the input or output surfaces of the resonator.

axisymmetric -- a cylindrical FEA model whose shape and material properties do not vary circumferentially around the model (e.g., transducers, boosters, and many cylindrical resonators). Variations in FEA amplitudes and stresses occur only in the axial and radial directions; circumferential variations are not permitted.

flexure -- a vibration mode in which the stack vibrates transverse to its axis, similar to a bending beam.

horn (probe, sonotrode) -- a resonant device that transmits ultrasonic energy to a load.

loss -- power dissipated by the stack when running in air. High loss may indicate a potential reliability problem (e.g., fatigue, galling, transducer failure, flexure, etc.).

nonaxial resonance -- any resonance other than the axial resonance.

primary resonance -- the resonance that has the desired vibration mode. This is often an axial resonance but can also be flexural, radial, torsional, etc.

nonprimary resonance -- any resonance that is not the primary resonance.

stack -- an assembly of resonators. The usual plastic welding stack consists of a transducer (converter), booster, and horn. The usual medical transducer consists of a transducer and probe.

transducer (converter) -- a resonant device that converts high frequency electrical energy into high frequency mechanical vibration. The material that performs the conversion may be either piezoelectric or magnetostrictive.

uniformity -- roughly, a ratio of two amplitudes on a specified resonator surface (usually the resonator face) that describes the degree to which the axial amplitude is the same over the specified surface. Uniformity is denoted by U. Generally, the optimum uniformity is 1.0 (i.e., 100%). (See Asymmetry.)

unshaped resonator -- a resonator whose sides are essentially parallel to the stud axis. Unshaped resonators appear to have no gain.

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Bar horns

A bar horn is a rectangular horn that is either unslotted or slotted only through the thickness. Special design techniques give optimum face amplitude uniformity. Bar horns generally has low-to-moderate gain (1:1 to 4:1). Bar horns are used for plunge and scan welding.

Example

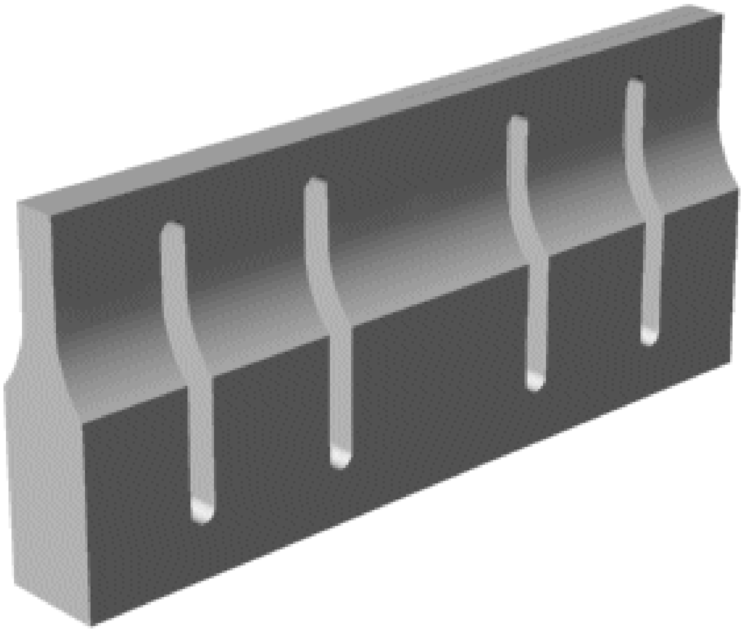
The following example shows a 20 kHz 12" wide bar horn. The horn's thickness has been reduced in the blade section in order to provide reasonable gain. The horn is one half-wavelength long at the axial resonance (the desired resonance), as indicated by the single node that is generally transverse to the principal direction of vibration.

For all images, the output surface (face) is at the top and the input surface is at the bottom. The warmest colors indicate the highest amplitudes. The darkest color traces the axial node(s).

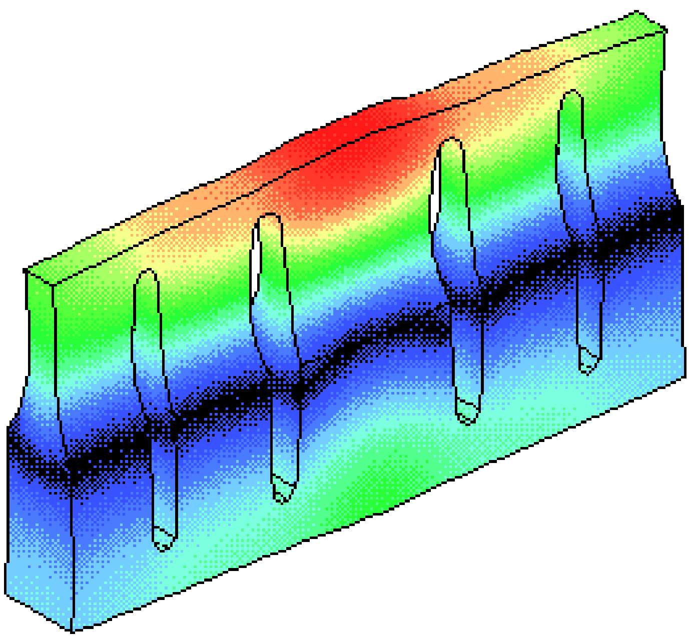
All results are from finite element analysis.

Original design

The following shows the original (unoptimized) design and the resulting amplitude distribution.



Original design -- No optimization.

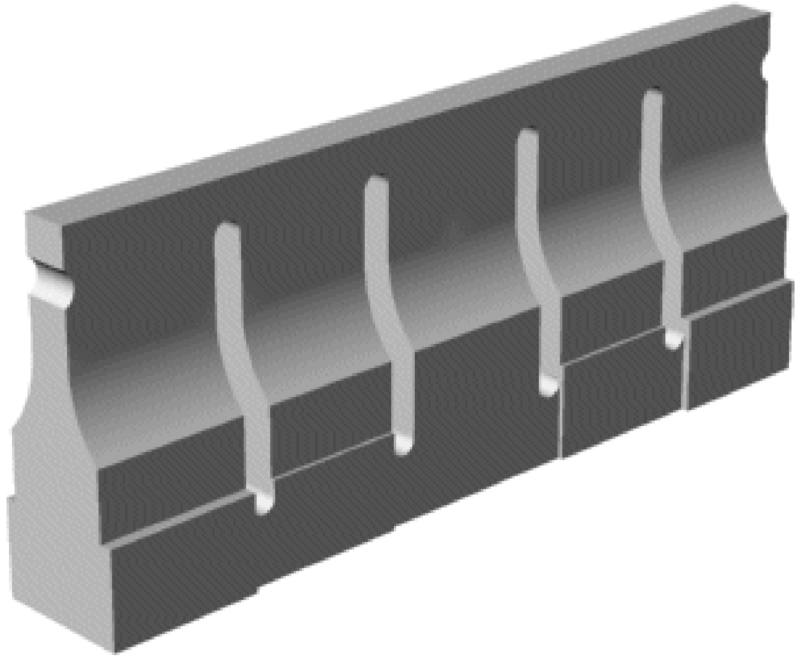


Axial resonance, relative amplitudes -- The amplitude at the end of the face is much lower than at the center. This will cause reduced welding at the ends or over-welding at the center.

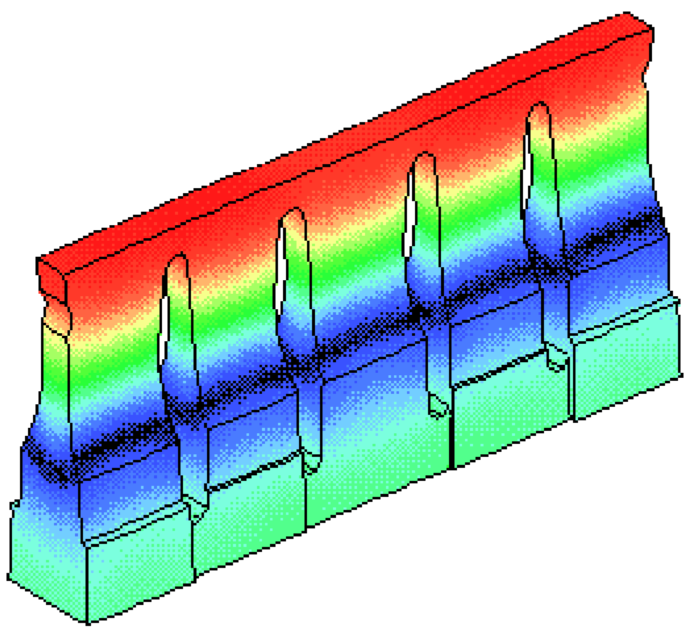
View actual vibration

Improved design

The following shows an improved design that has substantially better amplitude uniformity across the horn's face.



Improved design -- Uses optimized slots, back masses, and flutes.



Axial resonance, relative amplitudes -- The amplitude is very uniform across the horn's face.

View actual vibration

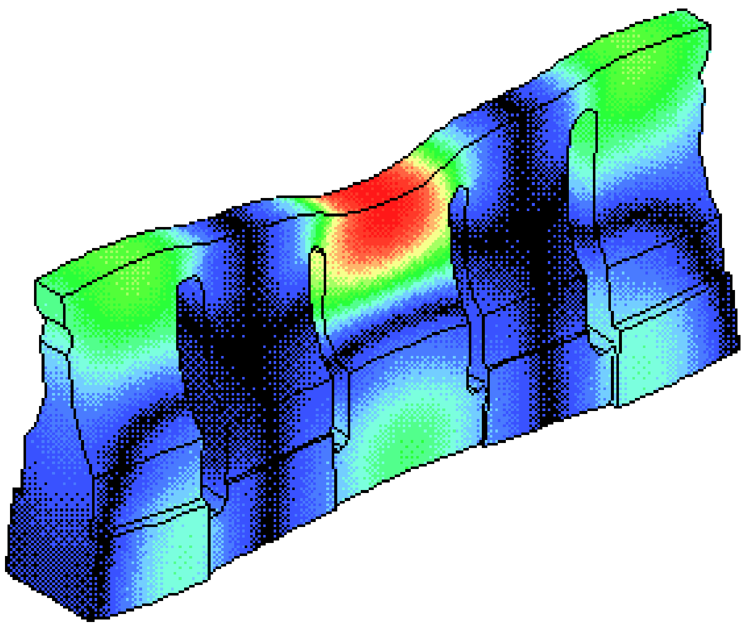
Design considerations

For bar horns that are wider than about 0.35 * wavelength (about 3.5" at 20 kHz), longitudinal slots must be used in order to reduce the transverse coupling due to the Poisson effect. The maximum distance between adjacent slots should not exceed about 0.3 * wavelength (about 3" at 20 kHz). Without such slots the horn will either have very uneven amplitude across the face or may even resonate in a nonaxial manner.

Although slots help to improve the face amplitude uniformity, additional horn refinements are often necessary to further improve the uniformity, depending on the particular application. Unfortunately, the required slots can introduce additional problems, although these can be reduced through careful design.

Secondary resonances

Slots often introduce additional secondary resonances. The following image shows a typical secondary resonance, although many others are possible.



View actual vibration

Such secondary resonances may interfere with the vibration of the axial resonance. In some cases, the power supply may prefer to start on a secondary resonance or may jump to a secondary resonance during the weld cycle. The effects of secondary resonances can be minimized by designing the horn so that the secondary resonances are sufficiently far from the axial resonance.

Stresses

In bar horns, the stresses are generally highest at the end of the slots or at the termination of the nodal radius. High cyclic stresses can cause the horn to fail by fatigue. This problem can be reduced by proper design and by machining the horn from high-strength materials.

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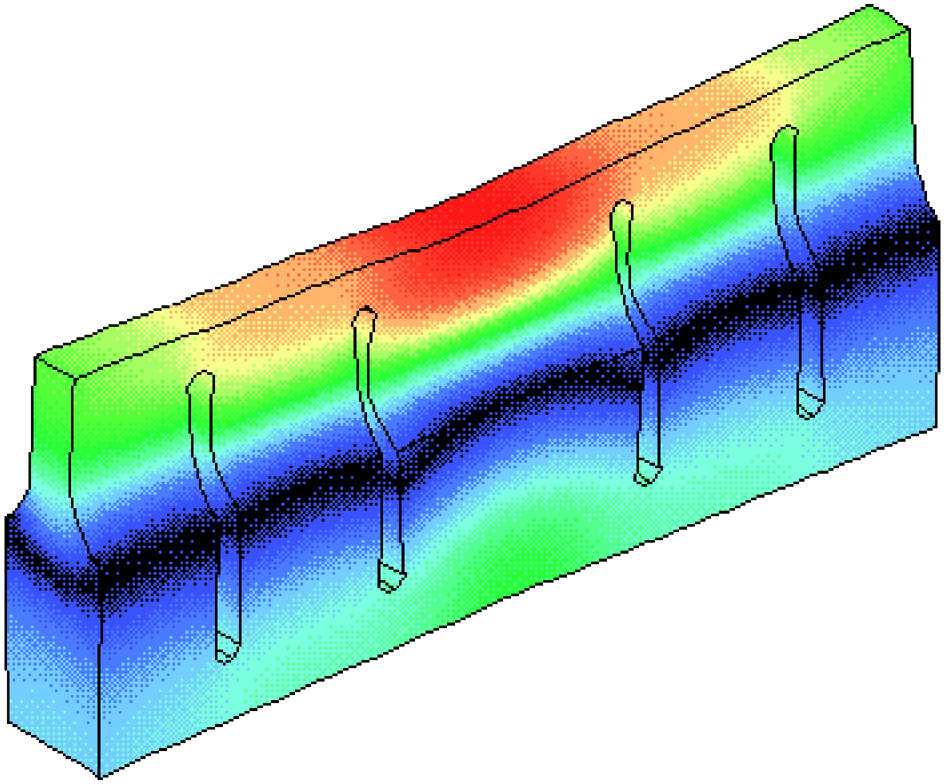
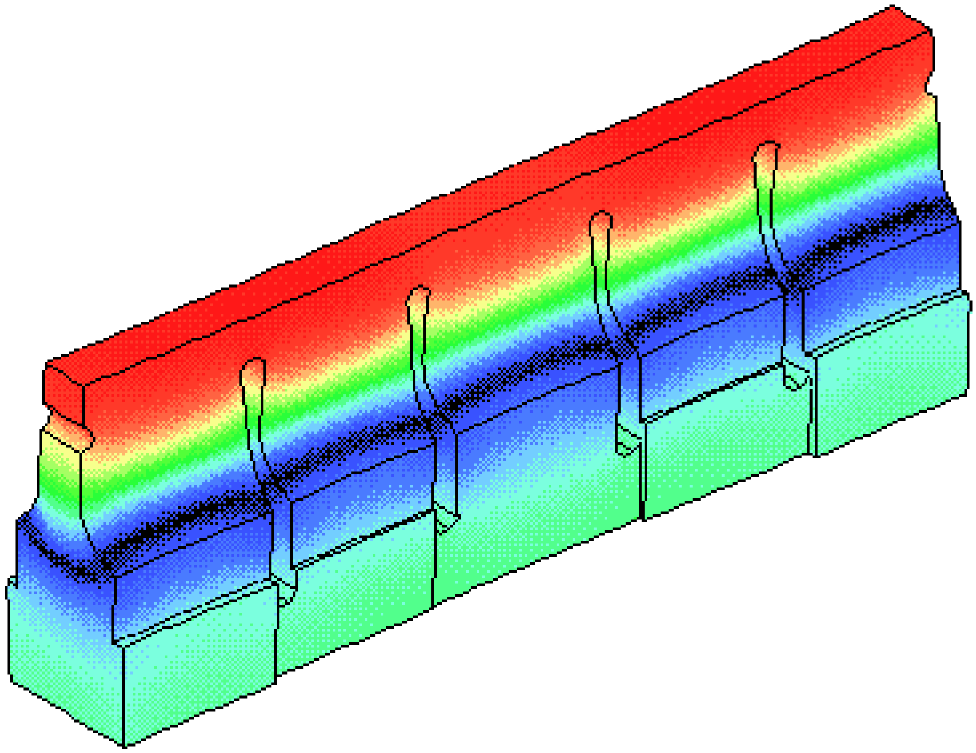


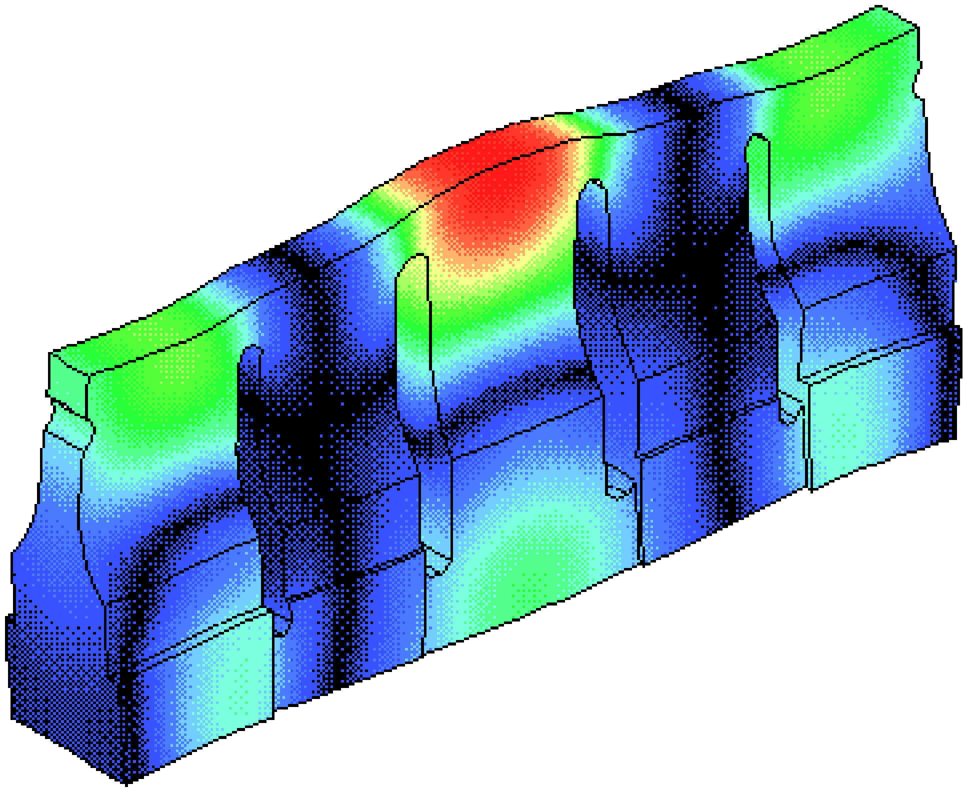
Axial resonance for an unoptimized slotted bar horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Axial resonance for an optimized slotted bar horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Typical secondary resonance for a slotted bar horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.

Block horns

[Up]

A block horn is a rectangular horn that is slotted through both its width and thickness. Block horns have low gain (generally near 1:1). Block horns are used for plunge welding.

Example

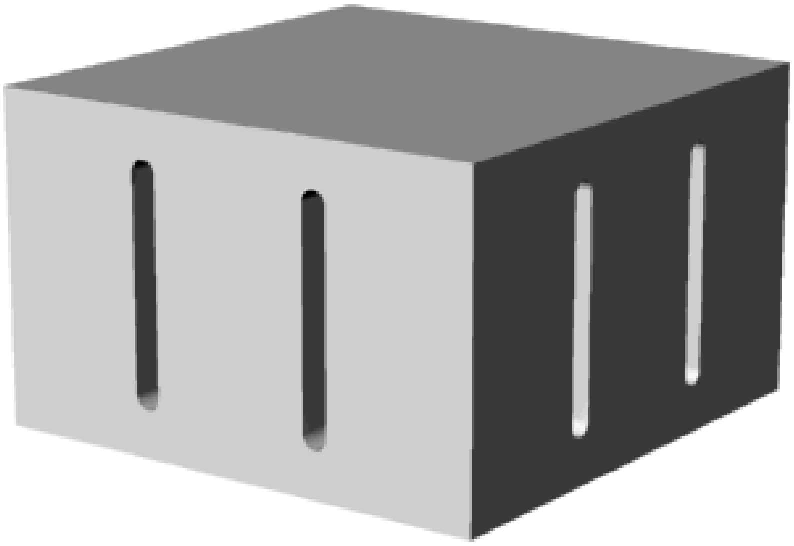
The following example shows a 20 kHz 8" square block horn. The horn is one half-wavelength long at the axial resonance (the desired resonance), as indicated by the single node that is generally transverse to the principal direction of vibration.

For all images, the output surface (face) is at the top and the input surface is at the bottom. The warmest colors indicate the highest amplitudes. The darkest color traces the axial node(s).

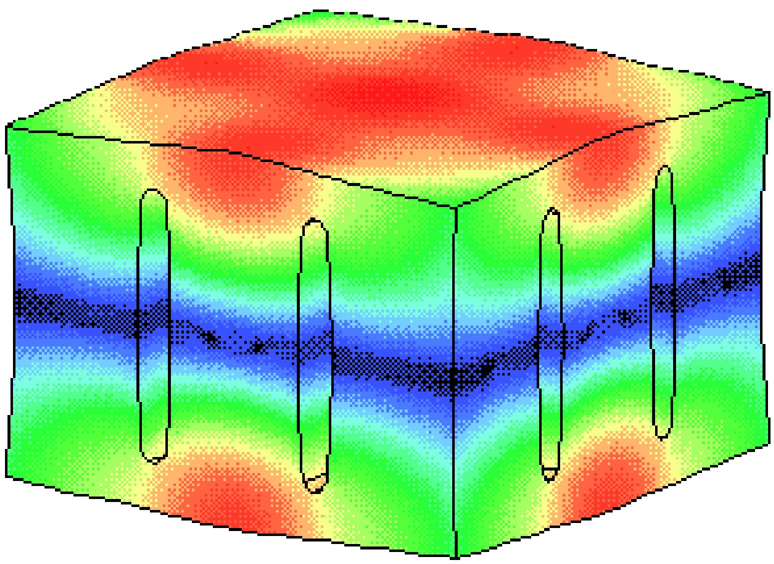
All results are from finite element analysis.

Original design

The following shows the original (unoptimized) design and the resulting amplitude distribution.



Original design -- No optimization.

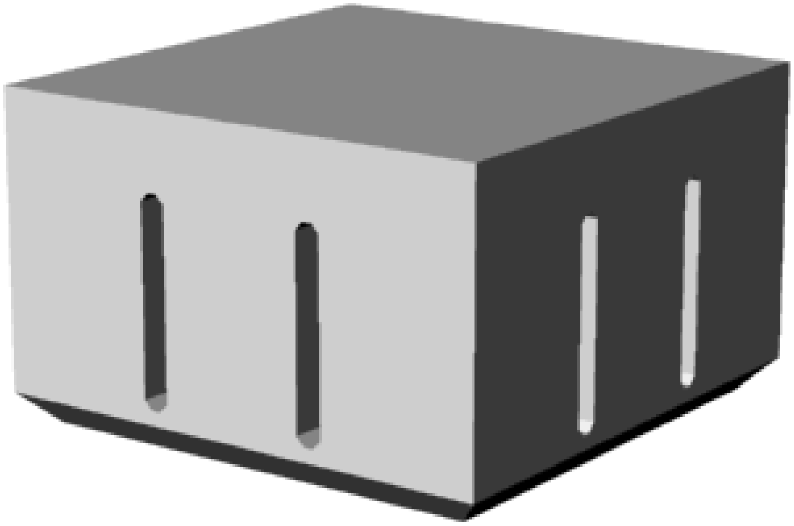


Axial resonance, relative amplitudes -- The amplitude at the corners of the face is much lower than elsewhere. This will cause reduced welding at the corners or over- welding elsewhere.

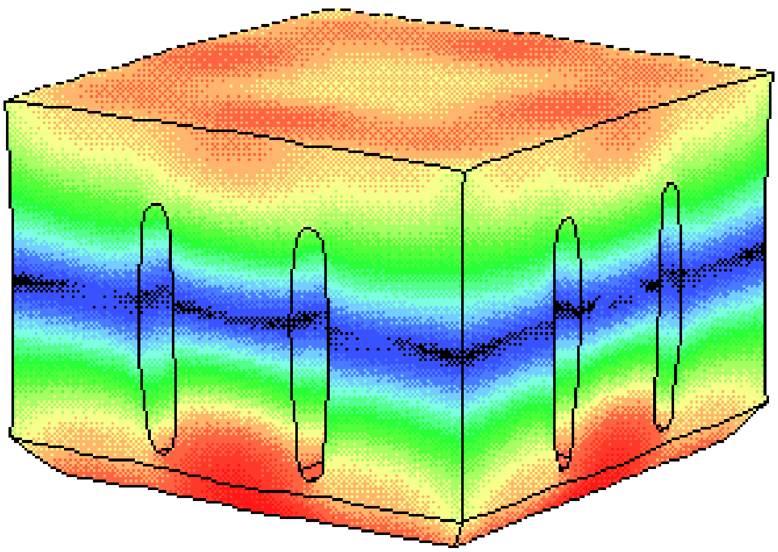
View actual vibration

Improved design

The following shows an improved design that has substantially better amplitude uniformity across the horn's face.



Improved design -- Uses optimized slots and back chamfer.



Axial resonance, relative amplitudes -- The amplitude is much more uniform across the horn's face.

View actual vibration

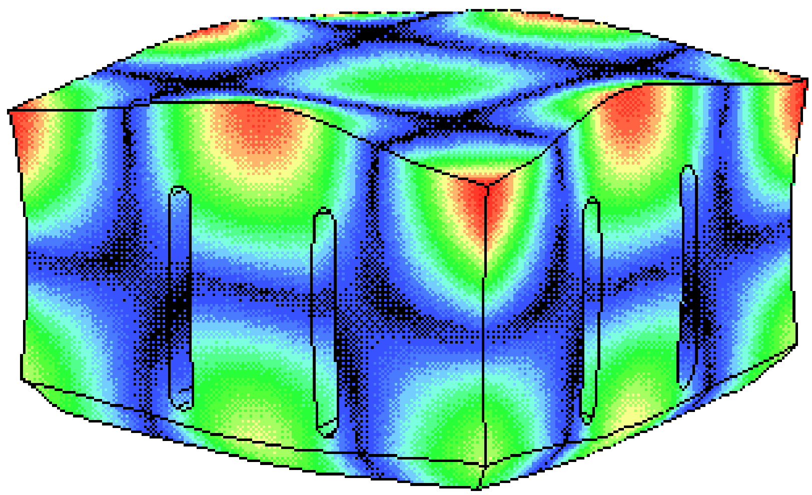
Design considerations

Because of their width and thickness, block horns must have longitudinal slots in order to reduce the transverse coupling due to the Poisson effect. The maximum distance between adjacent slots should not exceed about 0.3 * wavelength (about 3" at 20 kHz). Without such slots the horn will either have very uneven amplitude across the face or may even resonate in a nonaxial manner.

Although slots help to improve the face amplitude uniformity, additional horn refinements are often necessary to further improve the uniformity, depending on the particular application. Unfortunately, the required slots can introduce additional problems, although these can be reduced through careful design.

Secondary resonances

Slots often introduce additional secondary resonances. The following image shows a typical secondary resonance, although many others are possible.



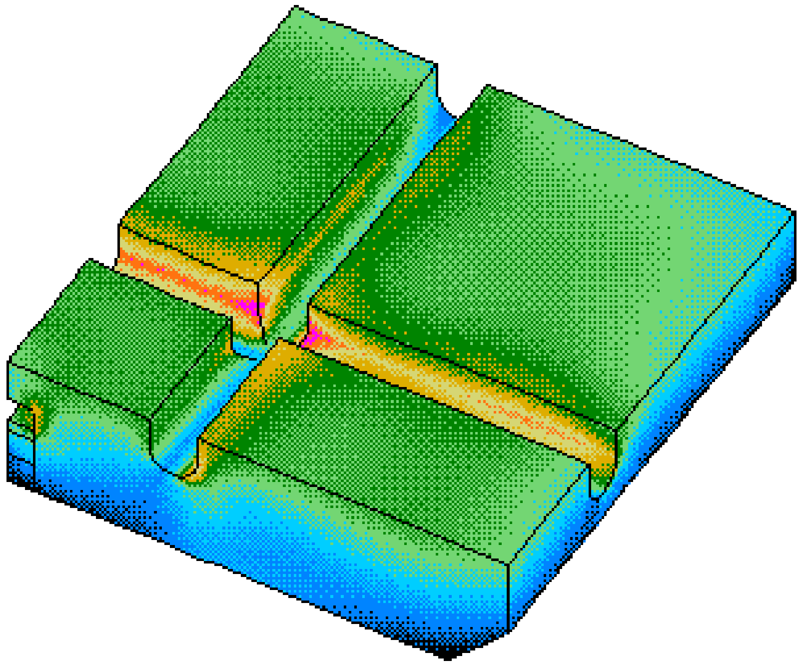
View actual vibration

Such secondary resonances may interfere with the vibration of the axial resonance. In some cases, the power supply may prefer to start on a secondary resonance or may jump to a secondary resonance during the weld cycle. The effects of secondary resonances can be minimized by designing the horn so that the secondary resonances are sufficiently far from the axial resonance.

Slot stresses

In block horns, the stresses are generally highest at the end of the slots, particularly where the slots intersect. The cause of this problem can easily be seen by watching the slots deform as the horn vibrates (see the animation). High cyclic stresses can cause the horn to fail by fatigue. This problem can be reduced by proper slot design and by machining the horn from high-strength materials.

The following image shows the stresses in a cut-away section of a complete horn where two slots intersect. The warmest colors indicate the highest stresses.



Top | Home | Site Map | What's New | Company Information | Contact Us

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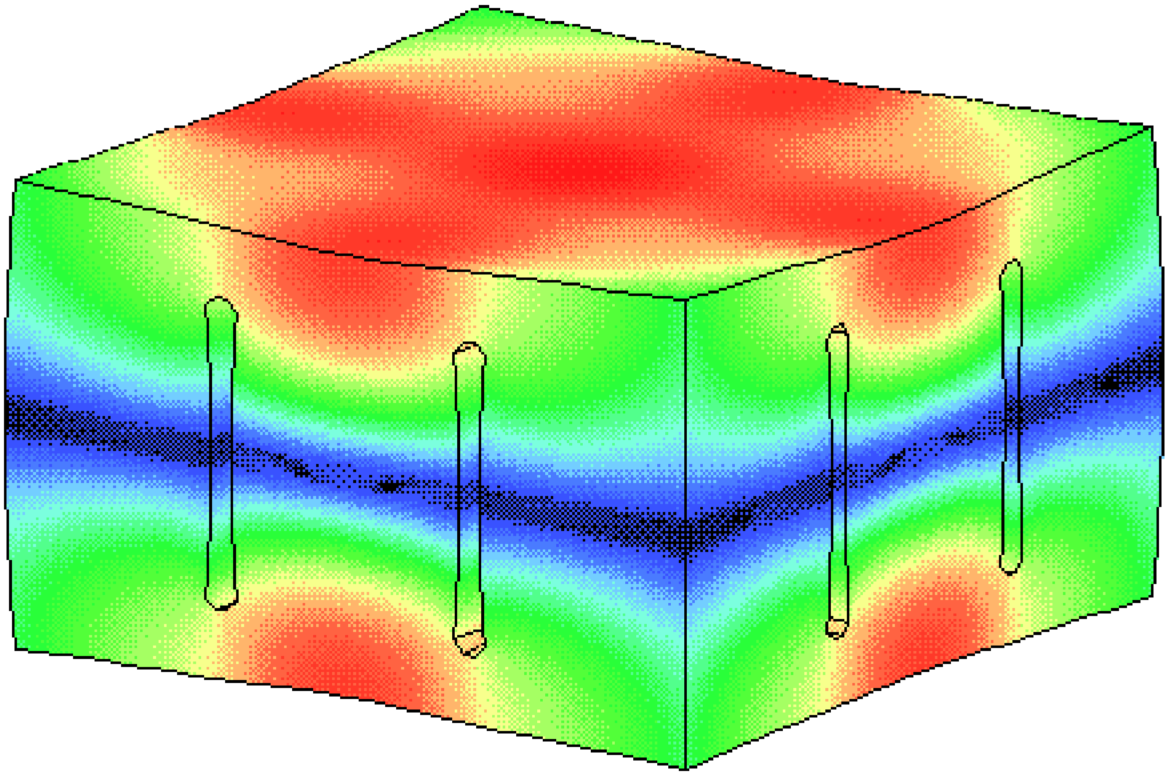
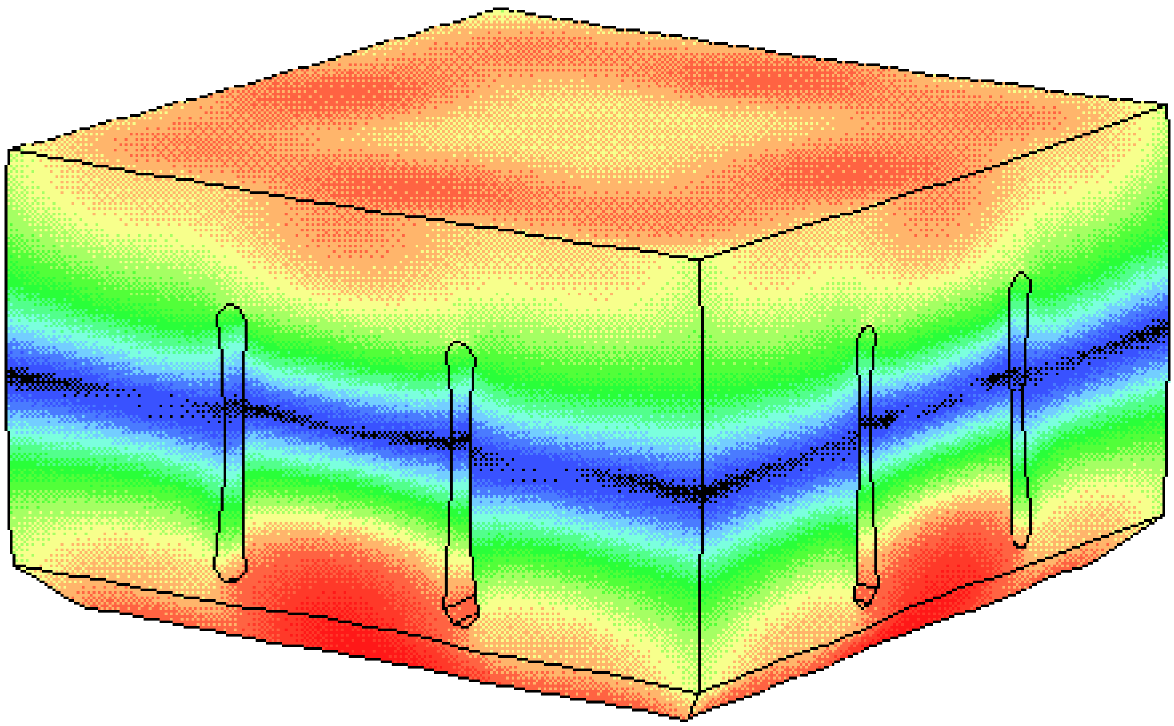


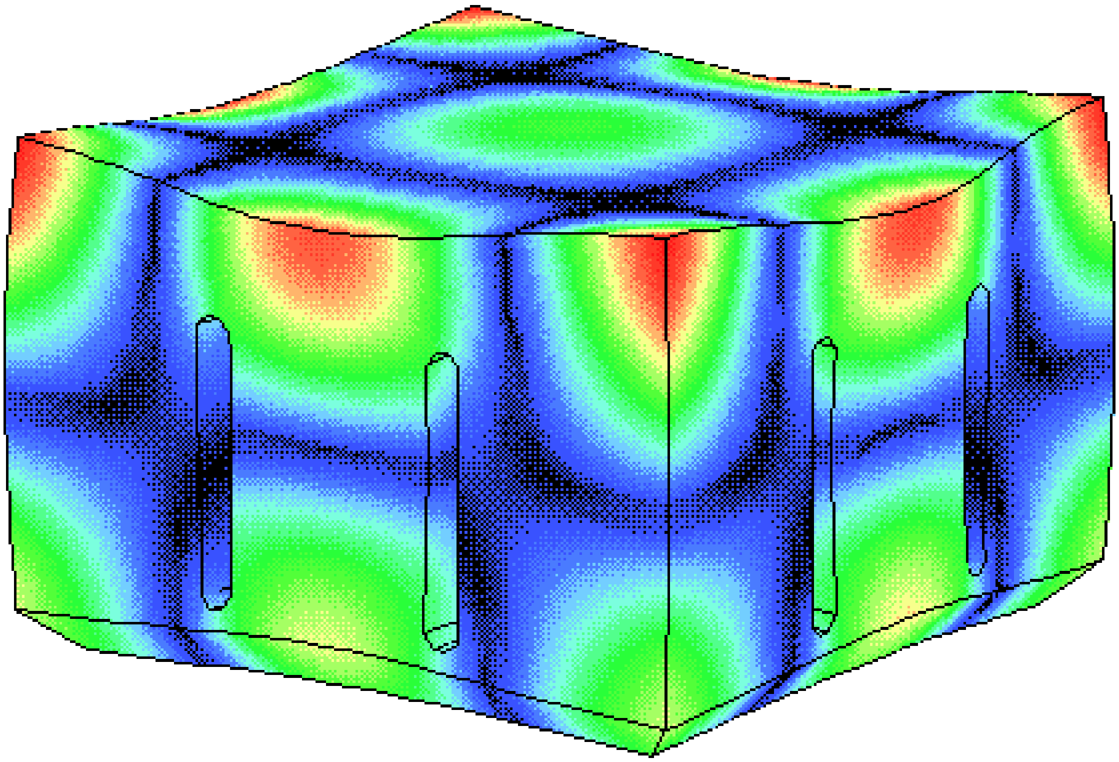
Axial resonance for an unoptimized slotted block horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Typical axial resonance for an optimized slotted block horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Typical secondary resonance for a slotted block horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.

Spool horns

[Up]

A spool horn is an unslotted cylindrical horn in which the sides have been undercut behind the face to form a spool shape. This spool shape improves the face amplitude uniformity. Because a spool horn does not have slots, its stresses are much lower than comparable slotted cylindrical horns and machining costs are much lower. Spool horns generally about 1:1 gain, although somewhat higher gain is possible. Spool horns are used for plunge welding and, occasionally, for liquid processing.

Example

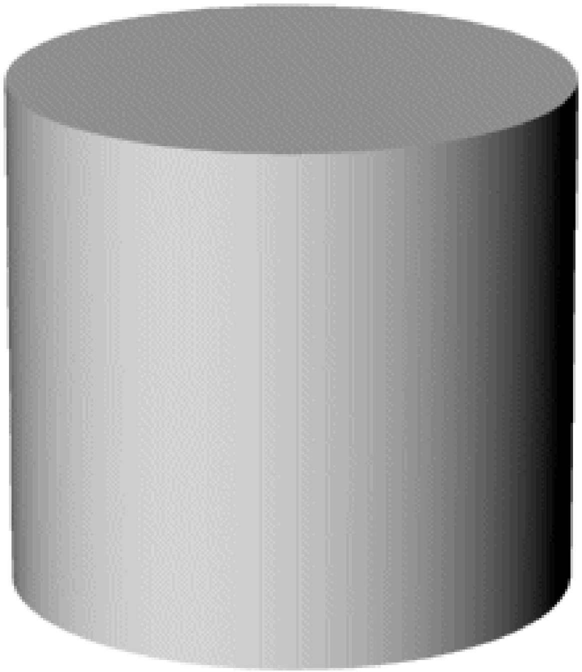
The following example shows a 20 kHz 5" diameter horn. The axial resonance is the desired resonance. The horn is one half-wavelength long at axial resonance, as indicated by the single node that is generally transverse to the principal direction of vibration.

For all images, the output surface (face) is at the top and the input surface is at the bottom. The warmest colors indicate the highest amplitudes. The darkest color traces the axial node(s).

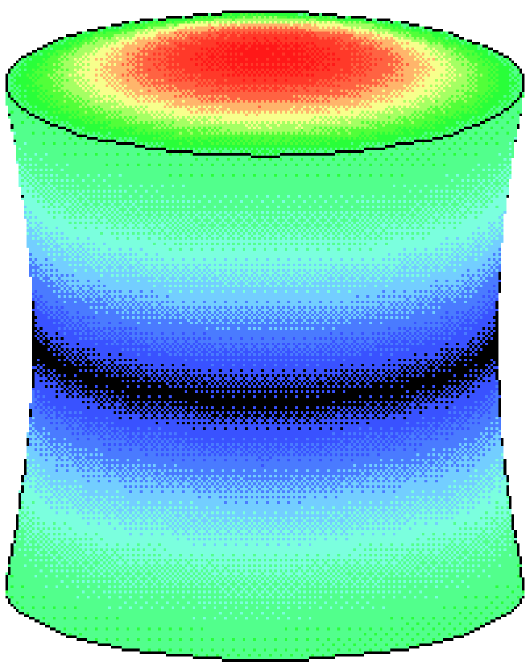
All results are from finite element analysis.

Original design

The following shows the original (unoptimized) design and the resulting amplitude distribution.



Original design -- No optimization

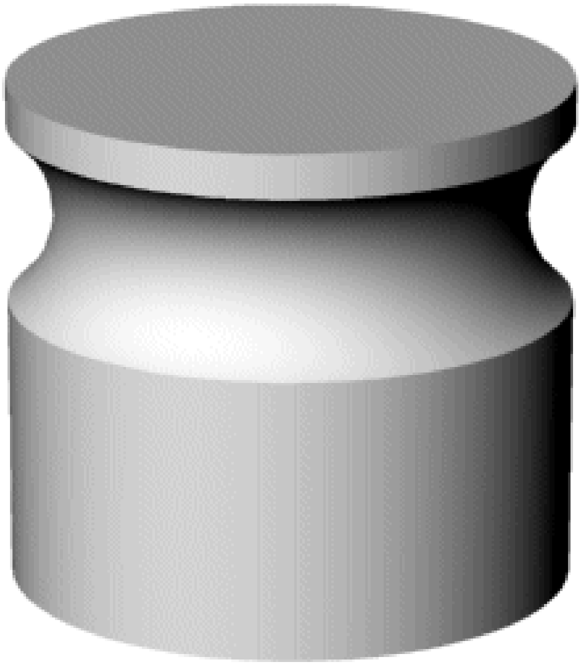


Axial resonance, relative amplitudes -- The amplitude is much lower at the outer face than at the center. This will cause under-welding at the outside or over-welding at the center.

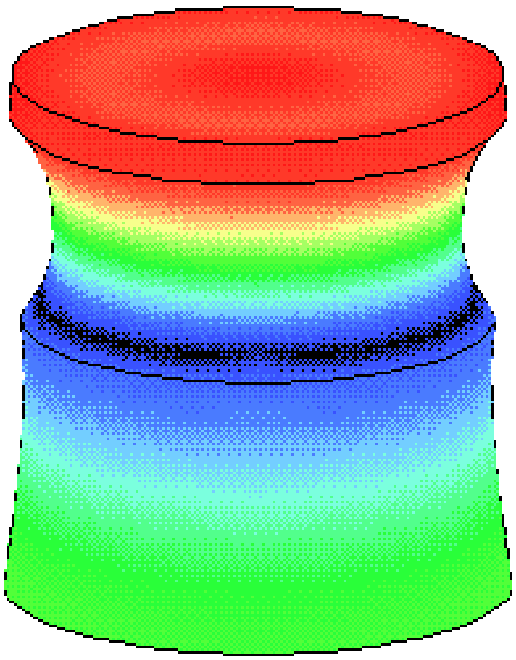
View actual vibration

Improved design

The following shows an improved design that has substantially better amplitude uniformity across the horn's face.



Improved design -- Uses optimized cavity, slots, and back extension



Axial resonance, relative amplitudes -- The amplitude is now very uniform across the horn's face.

View actual vibration

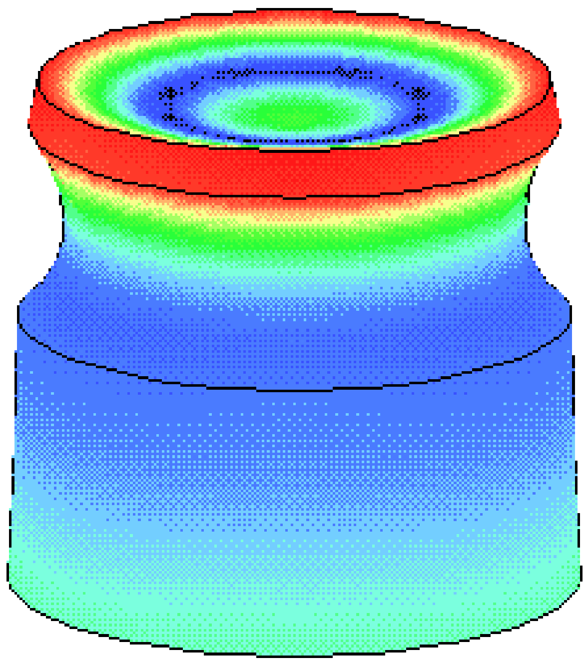
Design considerations

In order to preserve the face amplitude uniformity, spool horns cannot have any significant face cavities.

Size limitations

As the horn diameter increases, the face radial amplitude also increases quickly. If the horn is used for plastic welding, this radial motion can cause marking of the part.

Because of an adjacent secondary resonance (next image), the maximum horn diameter is limited to about 0.55 * wavelength (about 5.5" at 20 kHz). Above this size, the horn must be slotted. See slotted cylindrical horns.



Secondary resonance

View actual vibration

At diameters near 0.4 * wavelength, an adjacent asymmetric resonance can cause poor face amplitude uniformity. Therefore, special design techniques are required for these diameters.

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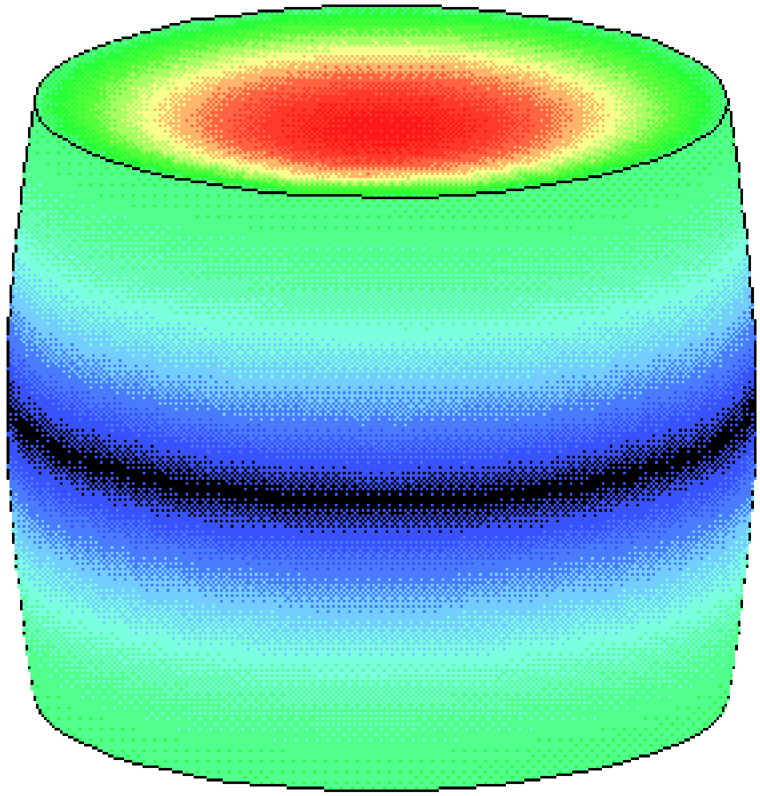
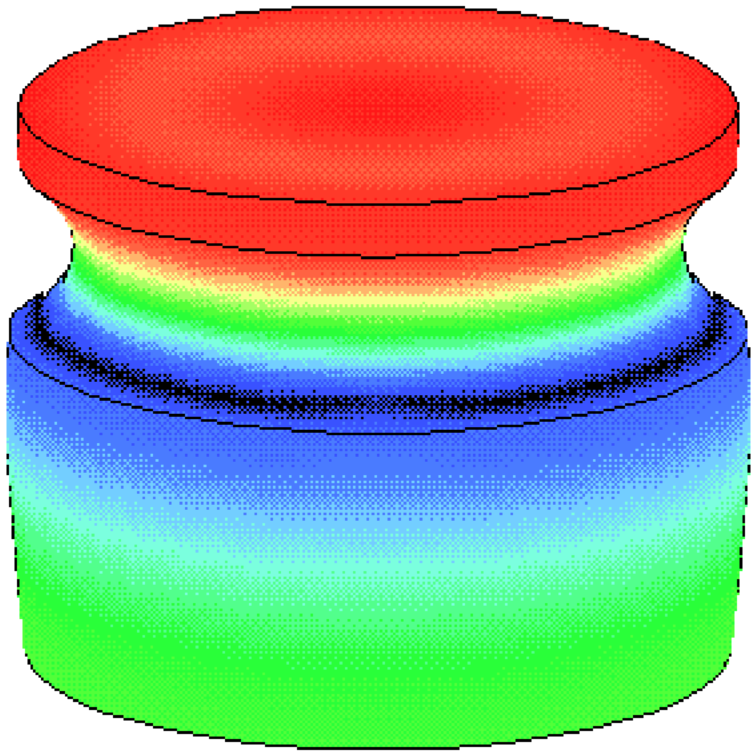


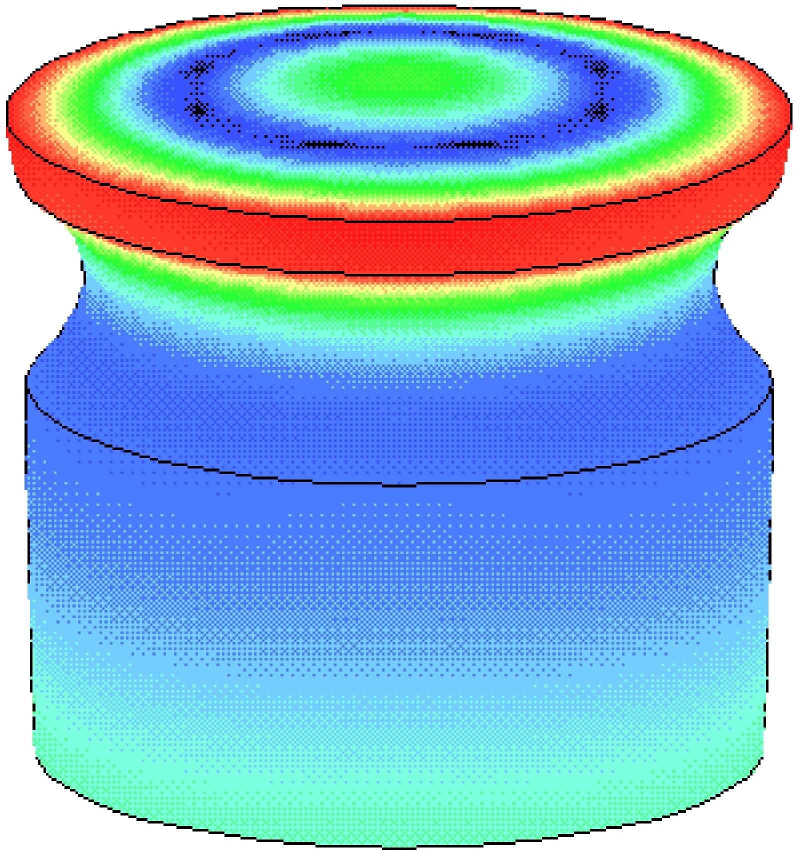
Axial resonance for an unoptimized unslotted cylindrical horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Axial resonance for an optimized spool horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Typical secondary resonance for a spool horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

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Home | Site Map | What's New | Company Info | Contact Us

Slotted cylindrical horns

[Up]

For cylindrical horns whose diameter is greater than about 0.5 * wavelength (about 5" at 20 kHz), longitudinal slots must be used to reduce the transverse coupling due to the Poisson effect. Such slots are usually radial, although other configurations are sometimes useful. Without such slots the horn will either have very uneven amplitude across the face or may even resonate in a nonaxial manner. Slotted cylindrical horns generally have low-to-moderate gain (1:1 to 2:1). Cylindrical horns are used for plunge welding.

Example

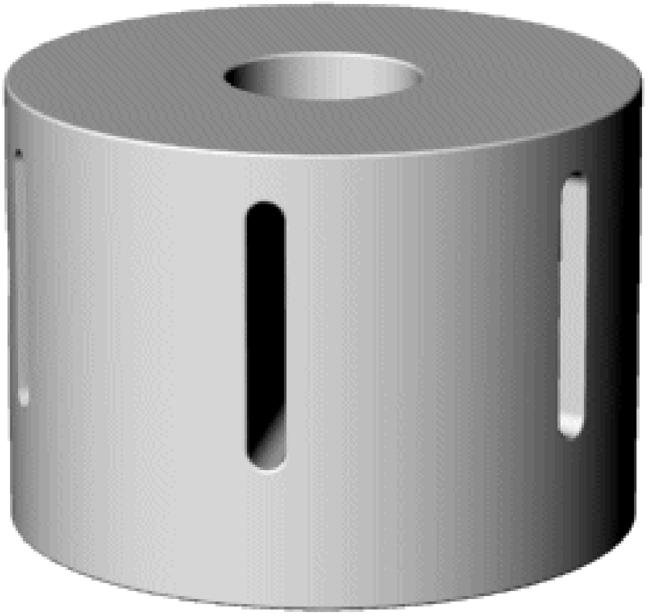
The following example shows a 20 kHz 6.5" diameter slotted cylindrical horn. The horn has a face cavity that extends deep within the horn in order to increase its gain. The axial resonance is the desired resonance. The horn is one half-wavelength long at axial resonance, as indicated by the single node that is generally transverse to the principal direction of vibration.

For all images, the output surface (face) is at the top and the input surface is at the bottom. The warmest colors indicate the highest amplitudes. The darkest color traces the axial node(s).

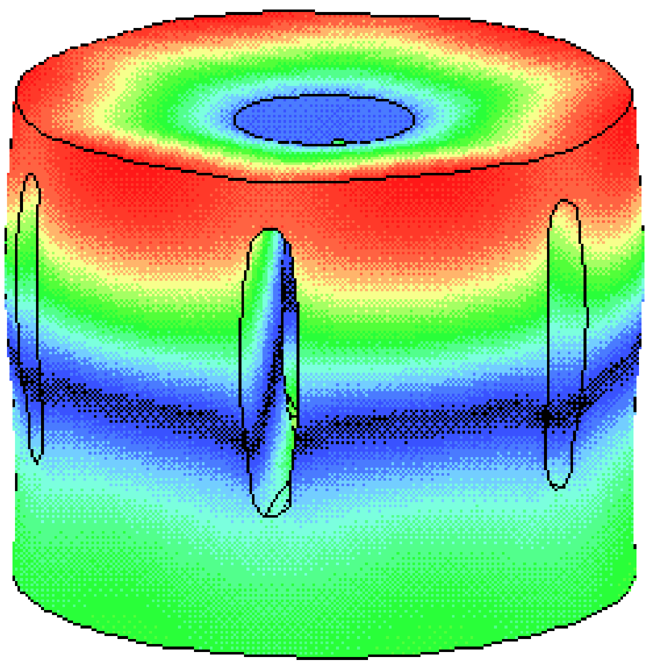
All results are from finite element analysis.

Original design

The following shows the original (unoptimized) design and the resulting amplitude distribution.



Original design -- No optimization

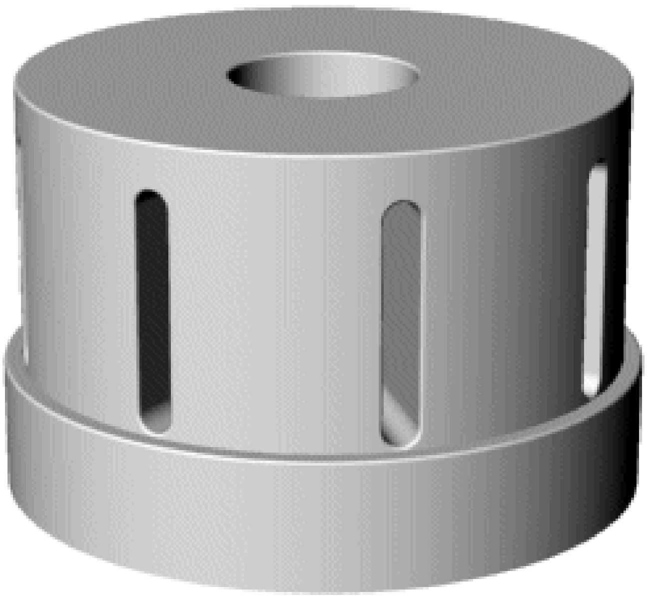


Axial resonance, relative amplitudes -- The amplitude at the outer face is much higher than at the center. This will cause over-welding at the outside or reduced welding at the center.

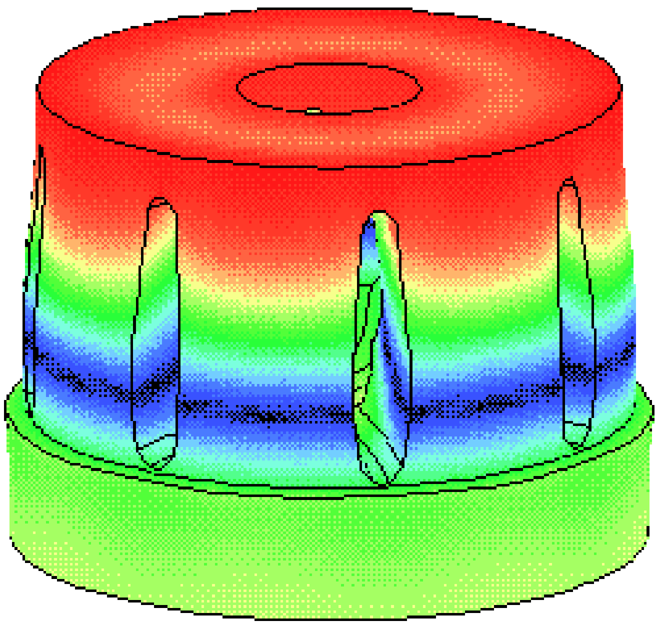
View actual vibration

Improved design

The following shows an improved design that has substantially better amplitude uniformity across the horn's face.



Improved design -- Uses optimized cavity, slots, and back extension



Axial resonance, relative amplitudes -- The amplitude is now very uniform across the horn's face.

View actual vibration

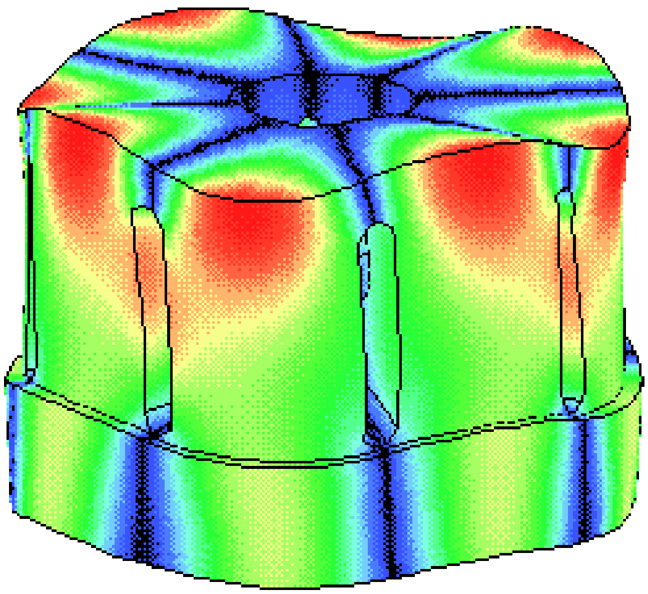
Design considerations

Although the slots help to improve the face amplitude uniformity, other refinements are often necessary to further improve the uniformity, depending on the particular application. Also, the required slots can introduce additional secondary resonances and can cause stress problems, although these problems can be reduced through careful design.

(Note: depending on the application requirements, many smaller diameter horns will not require slots. For example, see spool horns.)

Secondary resonances

Slots often introduce additional secondary resonances. The following image shows a typical secondary resonance, although many others are possible.



View actual vibration

Such secondary resonances may interfere with the vibration of the axial resonance. In some cases, the power supply may prefer to start on a secondary resonance or may jump to a secondary resonance during the weld cycle. The effects of secondary resonances can be minimized by designing the horn so that the secondary resonances are sufficiently far from the axial resonance.

Slot stresses

In slotted cylindrical horns, the stresses are generally highest at the end of the slots. The cause of this problem can easily be seen by watching the slots deform as the horn vibrates (see the animation). High cyclic stresses can cause the horn to fail by fatigue. This problem can be reduced by proper slot design and by machining the horn from high-strength materials.

Top | Home | Site Map | What's New | Company Information | Contact Us

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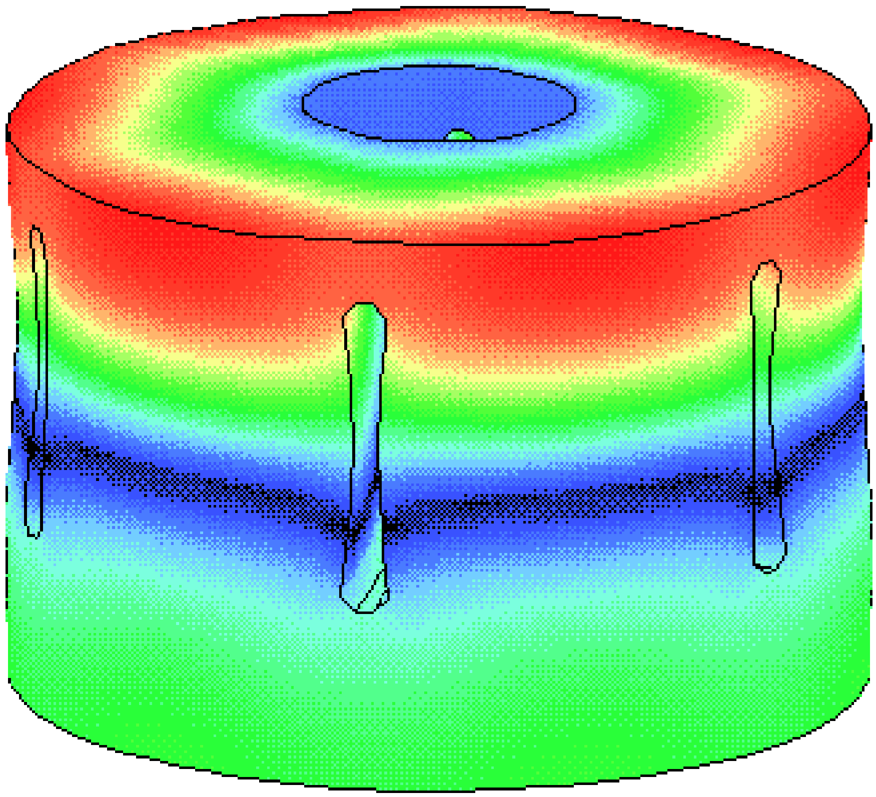
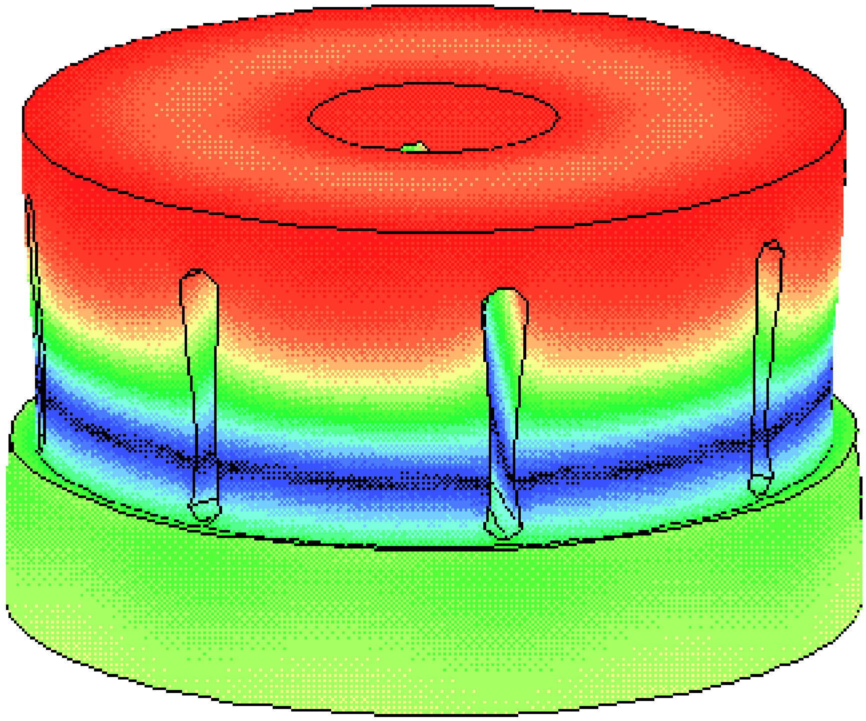


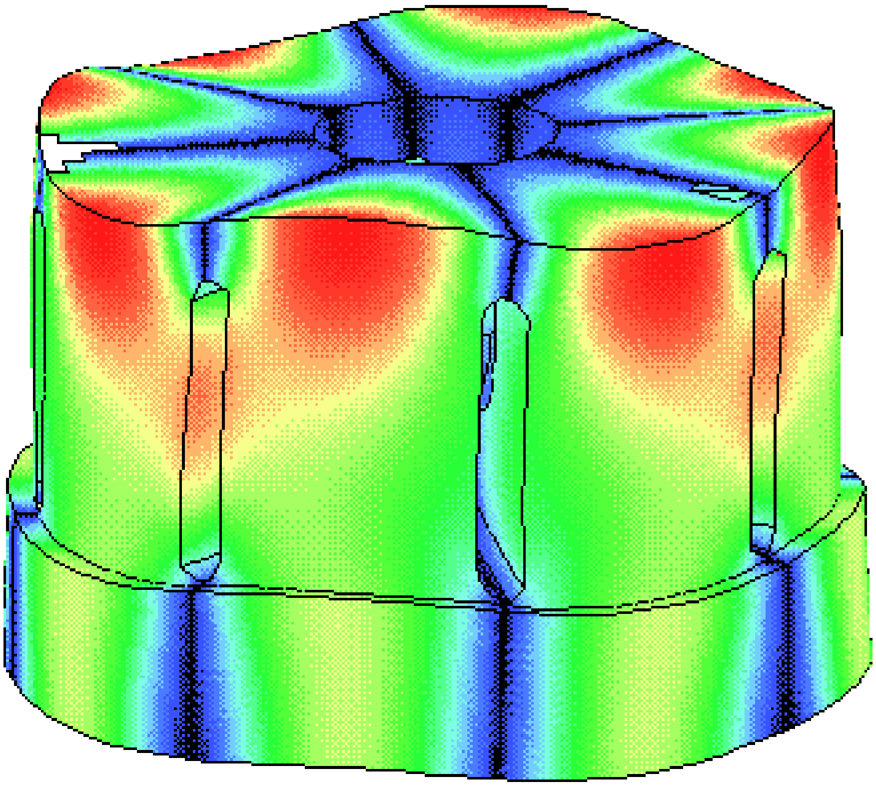
Axial resonance for an unoptimized slotted cylindrical horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Axial resonance for an optimized slotted cylindrical horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.



Typical secondary resonance for a slotted cylindrical horn
Warmest colors = highest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.

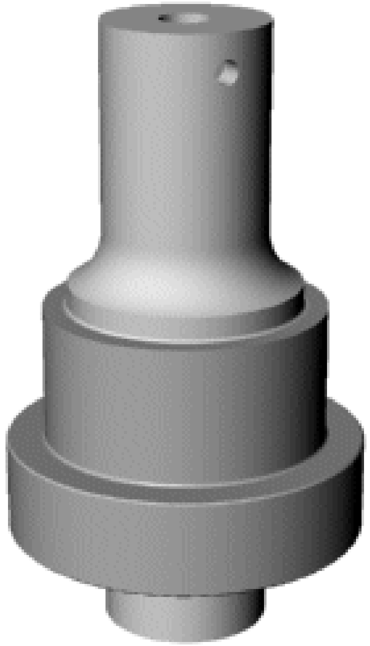
Boosters

A booster is a coupling resonator that is placed between a transducer and horn in order to change the horn's amplitude and/or as a means of supporting the resonator stack. Each booster has a fixed gain (ratio of output amplitude to input amplitude), generally between 0.5:1 and 3.0:1. Boosters are often color coded to indicate the nominal gain. The following colors are used by several manufacturers:

Color	Gain
Blue	0.6:1
Purple	0.75:1
Green	1.0:1
Gold	1.5:1
Silver	2.0:1
Black	2.5:1

Example

The following example shows a 20 kHz 1.5:1 rigid booster. This design is used with heavy loads or where precise positioning is required and for rotating applications (e.g., seam welding). It is also used where a hermetic seal at the mounting collar is required (e.g., for mounting through the wall of a pressure vessel).

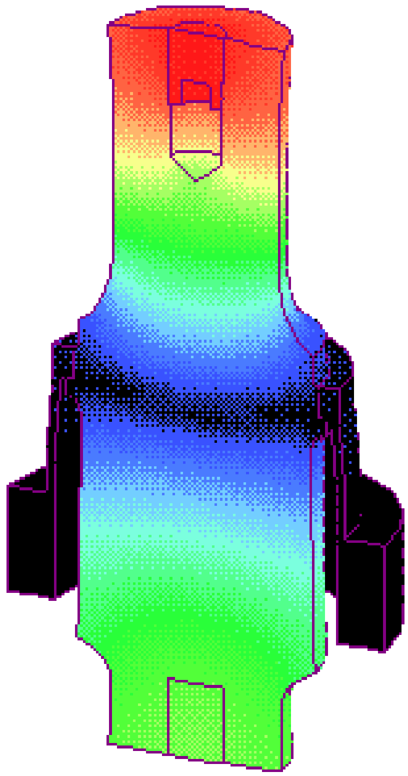


Lighter material = booster body

Darker material = tuned collar

The booster body is rigidly supported by a collar that is electron-beam welded to the booster's node. Because the rigid booster is constructed only of metal (no compliant elastomers), it has excellent axial and lateral stiffness. For additional stiffness a second collar can be incorporated into a full-wave design.

The collar is tuned to isolate the motion of the booster body from the support structure. This is shown is the following image of a displaced booster, where the coolest colors indicate the lowest amplitudes.



View actual vibration

Notes: For all images, the output surface (face) is at the top and the input surface is at the bottom. All results are from finite element analysis.

Design considerations

The nominal resonant frequency of the booster is the same as the nominal resonant frequency of the ultrasonic stack in which it is used.

The maximum booster gain is usually limited to about 3:1 (depending on the output amplitude of the transducer) in order to to avoid fretting problems at front (output) interface. In some cases, the booster is integrated directly into the horn (a one-piece design) or electron-beam welded to the horn to avoid such problems.

Boosters with gains up to about 1.5:1 can be made of aluminum. Higher gain boosters are generally made of titanium in order to reduce fatigue failures.

Top | Home | Site Map | What's New | Company Information | Contact Us

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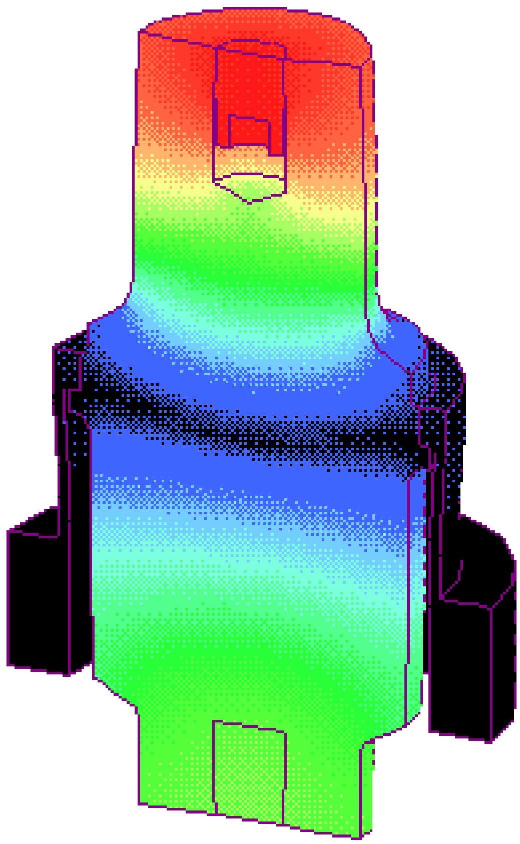

Axial resonance for a rigid mount booster.
Note the low amplitude of the mounting collar.
Coolest colors = lowest amplitudes
(Vibrational amplitudes are exaggerated)

Press your browser's Back button to return to the previous page.

Resonator Info Form

[Up]

In order to evaluate your resonator requirements, you can use the following form to submit baseline information. This information will be useful for subsequent discussions. Of course, you can also contact Krell Engineering directly.

- This form will only be used for discussion of your resonator. It does not imply any commitment by either you or Krell Engineering.
- Please be as complete as possible. If an item does not apply or if the information is confidential, then just leave that item blank.
- Required items are shown in green.
- All information will be kept confidential.

Resonator Information Form

Application description	
Specifications	

Resonator type	Horn / probe / sonotr
Frequency (kHz)	
Material	
Dimensions (approximate)	
Output amplitude (specify microns or mils, peak-to-peak)	
Output amplitude uniformity (for large horns, %)	
Gain (output amplitude / input amplitude)	
Power throughput (for transducers/ converters, watts)	
Operating temperature range (specify °C or °F)	

Problems with current design	
Additional information	
Desired completion date	
Name	
Position	
Company	
Address	
Telephone	
Fax	
E-mail	
Web site	
Contact you by:	Telephone (best time/day) E-mail

After you click "Submit Request" below, this form will be e-mailed to Krell Engineering. This may take several seconds. Then a confirmation form will be displayed; scroll to the bottom of the confirmation form and click "Back to the form" or use your browser's Back button to return to this form.

Submit Request | Reset Form

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Description

[Up]

Computer Aided Resonator Design (CARD)

Description, Equipment Requirements, Support

Notice

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Table of Contents

Description

Overview

Computer Aided Resonator Design (CARD) is software that applies quantitative techniques to the design of ultrasonic resonators (horns, boosters, and transducers) that vibrate in a longitudinal mode. CARD provides assistance in the design of resonators having low-to-moderate complexity.

With CARD, alternative resonator designs can be quickly evaluated without machining and testing. The effects of proposed resonator modifications can be easily determined. CARD is especially useful for designing low-stress resonators, resonators with a specified gain, and resonators with a specified node location.

CARD automatically tunes the horn to the desired frequency by adjusting the resonator dimensions. The adjustable dimensions include the length, thickness or diameter, and location of a transition radius. In addition, CARD can automatically adjust the gain and minimize the stress. (Note: see below for limitations for block horns.)

CARD calculates numerous acoustic parameters, including tuned length, tuned frequency, gain, node location, maximum stress, stored energy, loss, overall quality factor (Q), and weight. When calculating the stress, CARD considers the effect of stress concentrations at radii and slot ends. CARD graphically displays the calculated amplitude, stress, and strain-loss distributions at each point along the length of the resonator. (See figures 1, 2 and 3 for typical results.) Analysis results can be viewed, printed, and saved to a file.

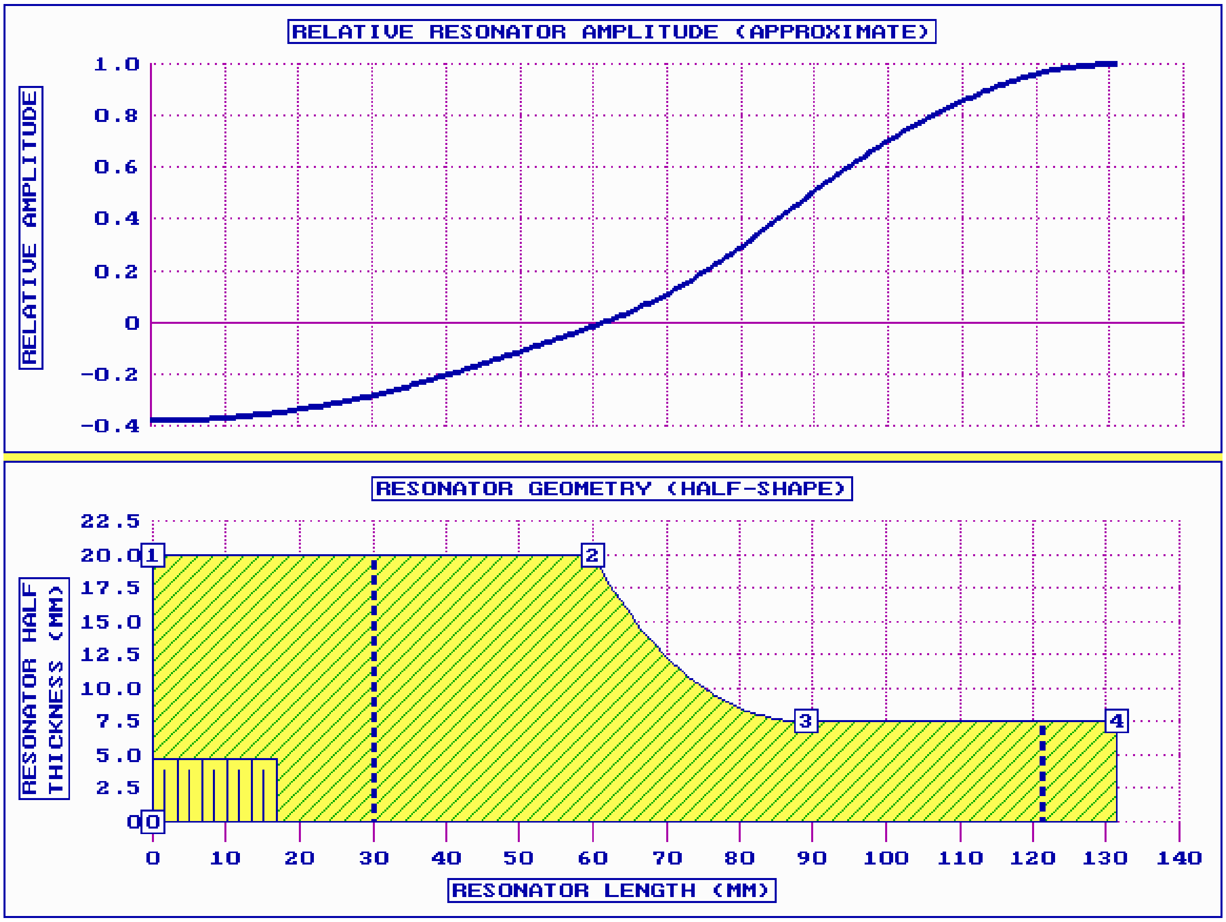

Figure 1. Amplitude distribution for a slotted bar horn

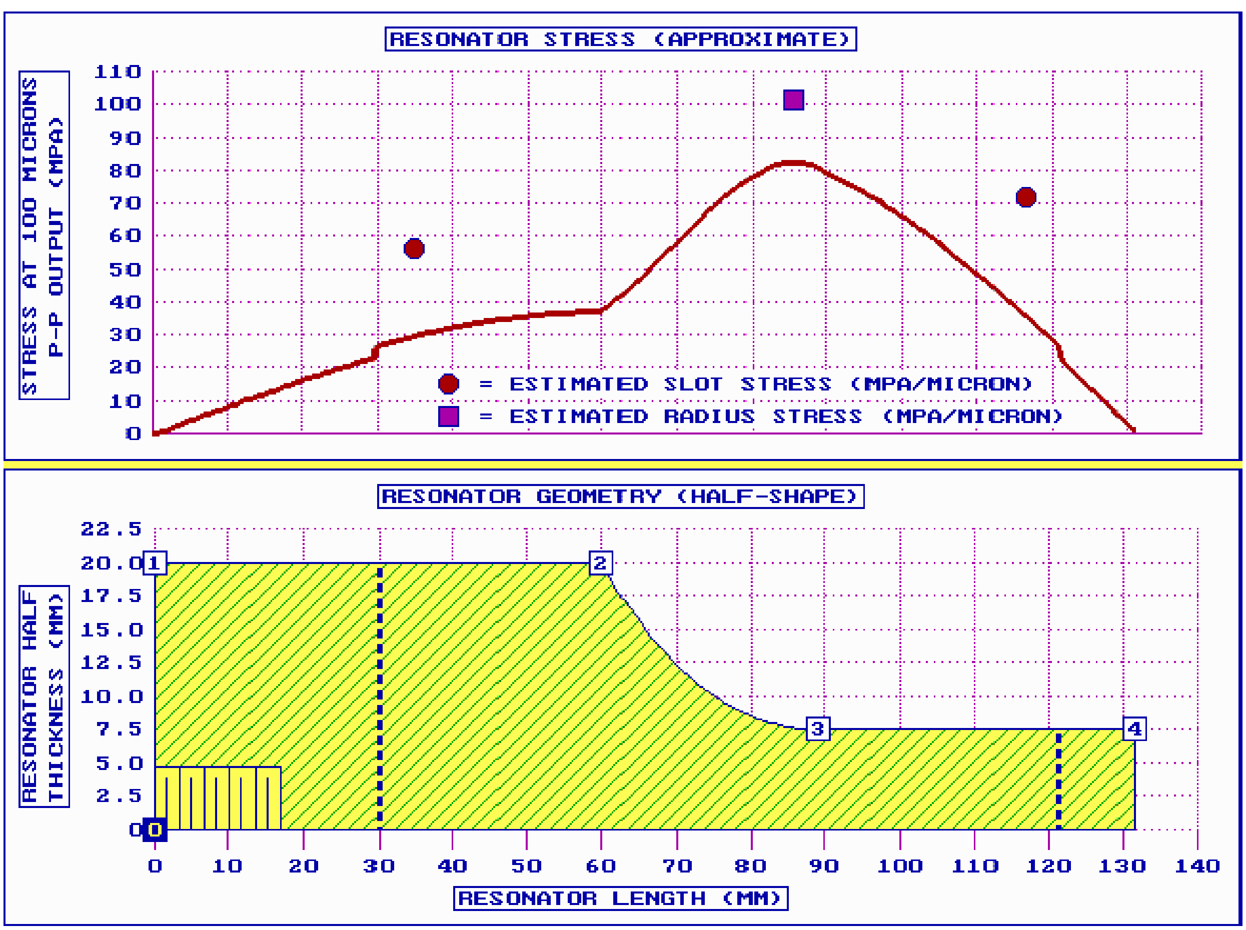

Figure 2. Stress distribution in a slotted bar horn.

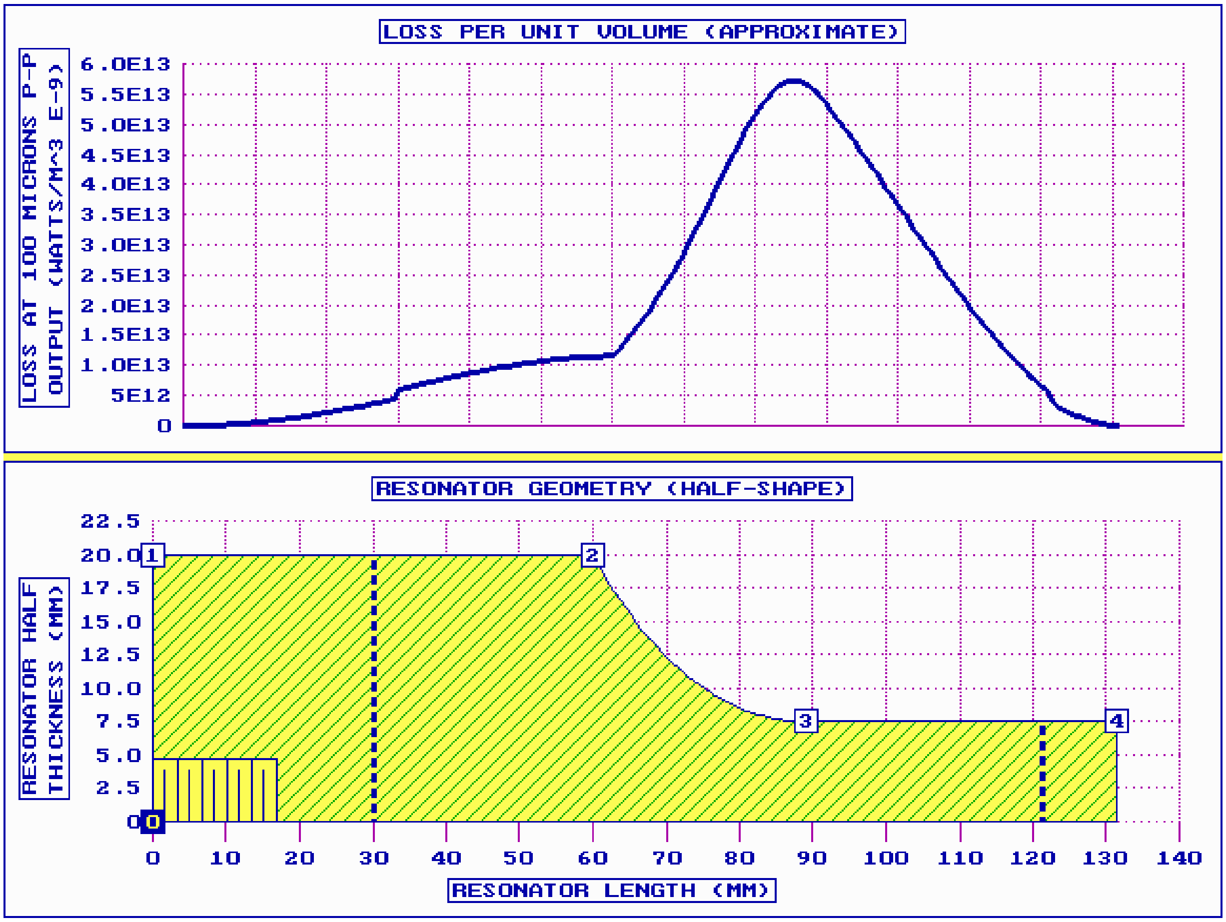

Figure 3. Loss distribution in a slotted bar horn.

CARD uses a spreadsheet format for easy input of the resonator shape. (See figure 4.) The resonator shape can consist of any combination of straight, curved, exponential, and catenoidal surfaces, arranged in any order.

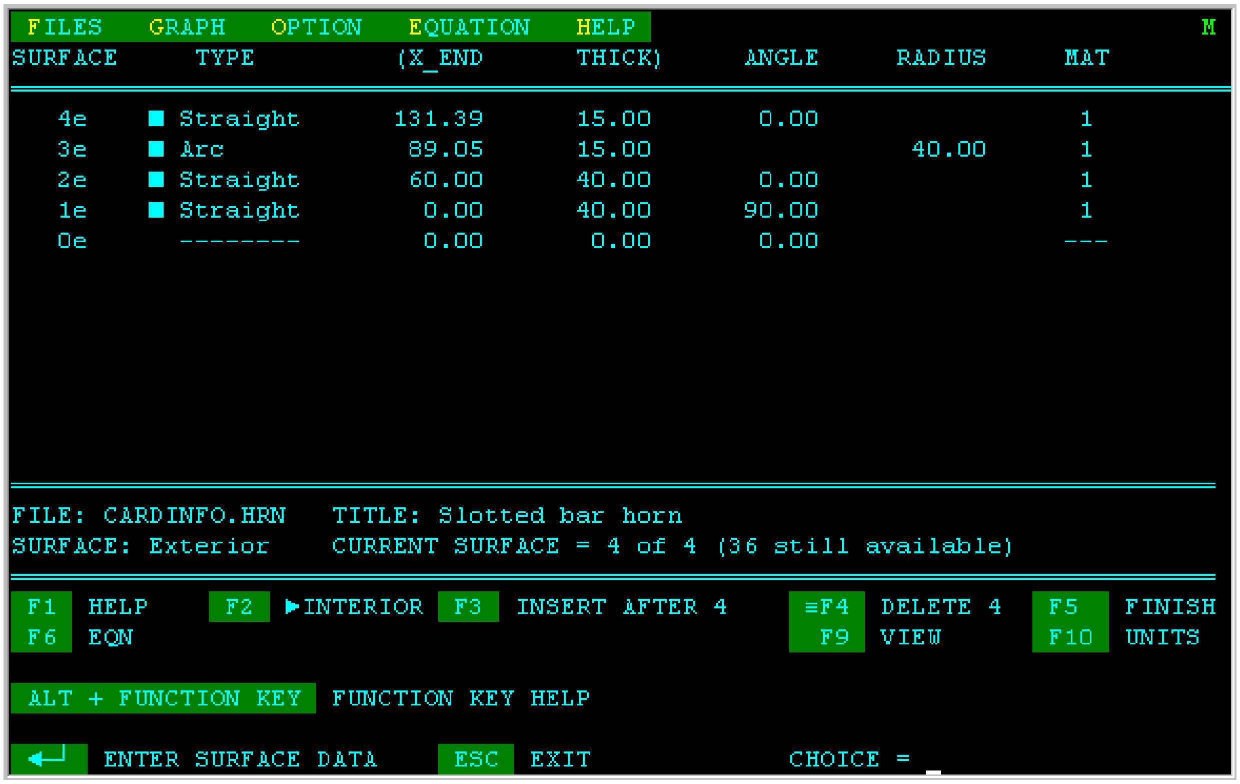

Figure 4. Spreadsheet for input of resonator shape.

The resonator shape can be graphically displayed to verify its correctness. The resonator can be composed of multiple, user-defined materials. The resonator can have a cavity in the face and can have studs, wrench flats, and spanner wrench holes.

CARD allows up to 10 different user-defined materials and ultrasonic equipment configurations. These defaults can be saved to disk.

CARD is very easy to learn and use, so that even those with minimum computer experience should have little difficulty. All user input is from menus; there are no commands to memorize. From any menu within CARD, a single keypress will change between metric and English units. Extensive hypertext help is available for each menu option. Also included with the help is a glossary of over 300 acoustic terms. (Note: although CARD is very easy to use, the user must have some understanding of resonator design in order to evaluate the computer-generated output.)

In addition to CARD's main analysis, CARD also has a section devoted to theoretical and empirical equations for longitudinal, flexural, torsional, and radial vibration. CARD also includes a database of metric and English bolt dimensions. Other sections include calculations for press-fits, bolt stresses, and piezoelectric ceramics.

Method of analysis

CARD analyzes the resonator by dividing it into a large number of thin slices. Each slice is perpendicular to the resonator's axis and extends entirely across the thickness (or diameter) of the resonator. (Figure 5 shows a typical resonator.) Starting from the back of the resonator, each successive slice is analyzed until the opposite end of the resonator is reached. This process is repeated several times until a specified convergence criterion is achieved.

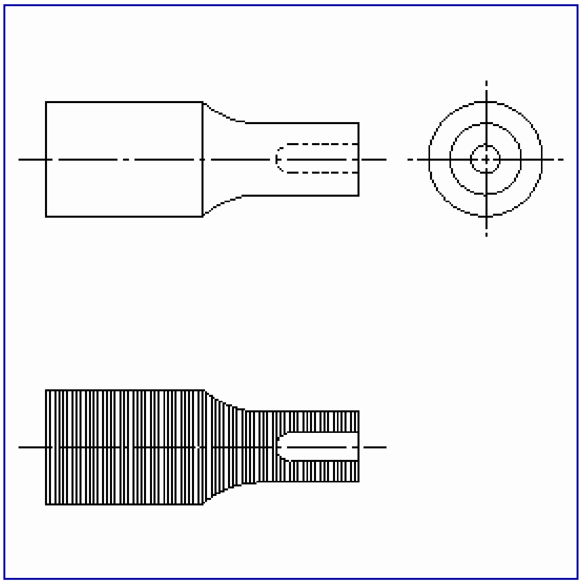

Figure 5. Slicing the resonator
Top view: resonator shape.
Bottom view: sliced resonator.

All acoustic parameters are assumed to be constant within each slice. Hence, such parameters as stress and amplitude cannot vary across the resonator thickness but can only vary along the resonator length. Thus, CARD gives a one-dimensional analysis of what is actually a three-dimensional acoustic phenomenon. In this respect, CARD is somewhat like one-dimensional finite element analysis.

CARD uses an equation to account for the decrease in wave speed that occurs as the resonator cross-sectional dimensions increase. Thus, "fat" resonators will have shorter tuned lengths than the equivalent "thin" resonators. This is consistent with theoretical and empirical studies.

Tuning methods

CARD operates in either of two modes:

1. Auto-tuning. If the resonator frequency is specified, then CARD will automatically change the dimensions of a user-specified resonator surface until the specified frequency is achieved. CARD can adjust a length dimension, a thickness dimension, or the location of a radius or step.

   While the resonator is being tuned, the gain can be automatically adjusted to a desired value. The stress can also be minimized automatically.

2. Manual tuning. If all of the resonator dimensions are specified, then CARD will calculate the resonant frequency. If desired, the resonator dimensions can then be manually adjusted to change the frequency. Auto-tuning is used most often. Manual tuning is used to adjust certain surfaces where auto-tuning is not appropriate.

Acceptable resonator shapes

Although all acoustic phenomena are actually three-dimensional, there are many resonators for which a one-dimensional analysis gives very satisfactory results. These include most unslotted cylindrical horns, bar horns (slotted or unslotted) up to about 250 mm wide by 75 mm thick at 20 kHz, boosters, and transducers (converters). Cylindrical horns can have a cavity, as long as the cavity is not excessive. CARD can analyze flatted-cylindrical horns (horns that have a cylindrical cross-section which is flatted toward the output end.)

CARD can analyze cross-slotted cylindrical or block horns, where the slots intersect at right angles. However, only the tuned length or frequency will be determined. Automatic gain and stress adjustments are not possible for these horns.

Resonators can be designed to any frequency between 5 kHz and 99 kHz. Resonators may be up to three half-wavelengths long. (5/99: This has been increased to 99 half-waves in the latest beta (test) version.)

Limitations

Because CARD uses a one-dimensional analysis, there are limitations on the parameters that can be calculated. Amplitude uniformity across the input and output surfaces cannot be calculated since the amplitude is not permitted to vary across each slice. Similarly, the frequencies of nonaxial resonances cannot be determined. However, this is not a severe limitation, since the majority of resonators for which CARD is suitable do not have problems with nonaxial resonances.

CARD designs resonators by looking at a side view of the resonator. (For slotted bar horns, this is the side view where the slots cannot be seen.) When looking at the resonator from the side, the resonator cross-section must be symmetric about the resonator axis (i.e., the cross-sectional shape on one side of the resonator axis must be the same as the shape on the other side of the resonator axis). Thus, CARD can not analyze resonators with asymmetric face contours, resonators with asymmetric face bevels, etc. unless these can be reduced to an equivalent symmetric design.

Except for flatted-cylindrical horns (above), CARD cannot be used for resonators whose cross-sectional *shape* changes along the length of the resonator. Thus, for example, if a resonator has a rectangular cross section, then this cross-sectional shape must continue along the entire resonator length. Although the cross-sectional shape cannot change, the cross-sectional dimensions can be adjusted as desired. (See the attached figures.) Note that certain nonsymmetric entities (e.g., wrench flats and spanner holes) are permitted.

CARD cannot be used on bar horns with risers on the back.

Calibration

If CARD is run without prior calibration, resonators of certain geometries or dimensions will give less accurate results. The following are listed approximately in order of decreasing accuracy:

1. Large thickness. Shaped resonators with large thickness (relative to the half-wavelength) generally give somewhat less reliable results than equivalent resonators with small thickness.

2. Large, abrupt area changes. Resonators with large, sharp steps in the area of the node give somewhat unreliable results. However, such designs would not normally be used because they have high stresses at the step.

3. Large cavities. Resonators with large cavities, such as bell resonators, usually have significant radial motion which tends to invalidate a one-dimensional analysis.

To correct for these limitations, a calibration mode has been provided. This mode allows CARD to be calibrated against a resonator of known design. For resonators that fall into the above categories, such a calibration can improve CARD's accuracy. Thus, CARD is intended to provide assistance with resonator design. It is not intended to replace the good judgment of the resonator designer. Neither is it intended to replace finite element analysis (or similar methods) as a final analysis tool.

Equations

The following tree diagram shows the equations section of CARD.

```
EQUATIONS
¦
¦-- INFORMATION
¦
¦-- AXIAL RESONANCE
¦     ¦
¦     ¦- Cylindrical Horns
```

```
¦    ¦   ¦-- Unshaped (*)
¦    ¦   ¦-- Conical (*)
¦    ¦   ¦-- Exponential (*)
¦    ¦   ¦-- Catenoidal (*)
¦    ¦   --- Spool (*)
¦    ¦
¦    -- Tip force (*)
¦
¦-- RADIAL RESONANCE
¦    ¦
¦    ¦-- Radial disk resonance (*)
¦    --- Radial ring resonance
¦
¦-- FLEXURE RESONANCE
¦    ¦
¦    ¦-- Rod --- (typical) --- Clamped-fixed plate (*)
¦    ¦-- Beam                ¦- Clamped-free plate (*)
¦    ¦-- Plate               -- Infinite plate (*)
¦    --- Disk
¦
¦-- TORSIONAL RESONANCE
¦
¦-- MATERIAL PROPERTIES
¦    ¦
¦    ¦-- Temperature effects (*)
¦    ¦-- Thin-wire parameters
¦    --- Q
¦
--- OTHER
     ¦
     ¦-- Bolt dimensions
     ¦-- Bolt calculations
     ¦-- Wrench flat equivalent diameter
     ¦-- Spanner hole equivalent diameter
     ¦-- Press-fit (*)
     ¦-- Von Mises stress
     ¦-- Piezo-ceramic calculations
         ¦-- Static performance
         --- Dynamic performance
```

(*) indicates that calculations can be graphed for the specified item.

Instruction manual

CARD is supplied with a comprehensive 300 page manual, with over 40 figures. The manual gives step-by-step instructions for using CARD. The manual includes numerous examples, with corresponding resonator designs on the distribution disk.

Copy protection

CARD is copy protected. The copy protection method allows CARD to be installed on multiple computers. However, CARD can only be operated from one computer at a time.

Newest beta version

The newest beta (test) version provides additional capabilities.

Demonstration version

A functional demonstration version is available for downloading.

Equipment requirements

Required equipment

Computer

IBM micro-computer (or true compatible) based on the Intel 80286 (or higher) microprocessor.

Operating system

Version 3.3 (or later) of Microsoft DOS. Version 5.0 (or later) is recommended for printing VGA graphics. (See below.)

Although CARD is a DOS program, it will run acceptably under Microsoft Windows. (Contact Krell Engineering for additional information.) Also, see known issues.

Memory

The computer must have approximately 480 KB of free conventional memory after any other memory-resident programs have been loaded.

Display

A VGA color display (640 x 480, or higher) is recommended. (The values in parentheses give the graphics resolution.) However, CARD will also run with any of the following displays: any video adapter and monitor capable of displaying IBM graphics (CGA, 320 x 200; MCGA, 320 x 200; EGA, 640 x 350).

Disk drives

A hard (fixed) disk with approximately 5 MBytes of free space is required. One 1.44 Mbyte floppy drive is required to load CARD onto the hard disk (not required for the demo version).

Optional equipment

Mouse

A two or three button mouse may be used. The mouse is only active when the on-line help is invoked.

Printer

CARD is configured to support any printer that is compatible with the IBM graphics printer (dot matrix) or Hewlett-Packard laser. CARD expects the printer to be connected to parallel port #1.

CARD does not support plotters.

Additional Information

Support

Krell Engineering will provide free support to registered users for one year from the date of the initial license agreement. During this time, Krell Engineering will answer questions about the use of CARD and will endeavor to fix any bugs that significantly affect the use of CARD.

Prices and delivery

Full version	$950.00
Upgrade from version 8.xx or earlier .... (includes several chapters from the CARD manual)	$200.00
Copy protection key, if required .... (see note 1 below)	$75.00

Shipping and handling

	U.S.A.	Elsewhere
With full manual	$20.00	$40.00
Without full manual .... (typically for upgrades)	$10.00	$30.00

Payment

1. All prices are US dollars.
2. Payment may be made by corporate check, personal check, purchase order, or any guaranteed negotiable instrument (cashiers check, money order, etc.). Purchase orders are subject to approval. Personal checks must clear before CARD is shipped.

Shipment -- two weeks (approximately) after receipt of payment.

Notes

1. CARD requires a diskette drive in order to access the copy protection diskette. If you intend to use CARD on a computer that does not have a diskette drive, then you will have to purchase a copy protection key that plugs into the computer's parallel printer port. Note that the copy protection key will not work under Windows 2000 or Windows XP.
2. The copy protection diskette or the copy protection key is your evidence of authorized use. If you have lost either of these, then you cannot upgrade directly. Instead, you must purchase a full version.

Return policy

Starting from the shipment date, CARD may be returned within sixty days. The purchase price will be refunded, less an evaluation fee of $150 and the shipping charge (above). (Prior to purchase, you may wish to download a functional demonstration version to insure that CARD meets your requirements.)

Defective diskettes or copy protection keys will be replaced at no charge within the first sixty days; after sixty days, a nominal fee will be charged. A lost copy protection diskette or copy protection key will not be replaced; a complete CARD purchase will be required.

Upgrades

Check out the current upgrades to older versions of CARD.

Frequently asked questions

See frequently asked questions.

Known Issues

The following are known issues as of 6/02. If you feel that these may be relevant, contact Krell Engineering.

1. Printing over a network may not work. Since network issues can be very complex, Krell Engineering can only give limited support for this issue.

2. The copy protection diskette can not be accessed over a network. It must be installed and accessed from the local computer (the computer on which the work is being performed).

3. For Windows NT:
   a. During printing, DOS programs (including CARD) may eject an extra sheet of paper before the actual printing begins.
   b. The print screen key may not send the graphics output to the printer. However, the graphics can be copied to the Windows clipboard and then pasted into a Windows application (e.g., Microsoft Word), from which they can be printed. This procedure is explained by CARD's online help.

4. CARD's manual has been written for CARD version 6.xx. It has only been partially updated for the newest version of CARD. However, CARD's extensive on-line hypertext help is up-to-date.

Top | Home | Site Map | What's New | Company Information | Contact Us

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Home | Site Map | What's New | Company Info | Contact Us

Upgrades

[Up]

This page describes features that have been added or improved from previous versions of CARD. This page also describes features of the latest beta (preproduction) version. If you need any of these features, then you should consider upgrading.

CARD receives continuous upgrades. You should check here periodically for the latest information.

Table of Contents

Version 9.00 (Current Version)

CARD 9.00 is the current official version. It is a major upgrade to version 8.26c. (For a general description of the CARD's capabilities, click here.)

The improvements fall into four major categories: 1) easier to use, 2) greater functionality, 3) improved accuracy, and 4) other changes.

Easier to use

The user interface now acts more like Windows, while retaining the flexibility of operating under either DOS or Windows. These interface changes make CARD considerably easier to use.

1. Bar menu. A bar menu is positioned at the top of the screen. You can access any of the bar menu options by pressing the Alt key plus the associated hot key. For example, to access the File option, press Alt+F. The bar menu may be accessed up to five layers deep. (The depth of the bar menu is indicated at the upper right corner of the screen.)

2. Hot keys. Some submenus or options can be called directly by pressing an option hot key. These hot keys are shown in [ ] following menu option description. For example, to save a file from within any menu, press S.

3. Input checklist. Rather than using multiple sequential input menus, CARD now has a main menu checklist. This allows you to access only those menus that are relevant to your particular resonator design. If you are unsure of which menus are required, you should use the "Step through Checklist" options.

4. On-line help. The on-line help has been significantly improved and expanded. The help text now pops up in a full-screen window, which can be scrolled by using a mouse on the scroll bar or with any of the cursor keys.

   The on-line help now includes all of the CARD manual except the examples and the figures. In many cases, the on-line help is more current and extensive than the manual. There are 1000+ help topics, 3800+ cross-references, and 250+ pages. The help now contains all of the previous *.err files.

   The help text is extensively cross-referenced. For a particular help window, just click the left mouse button on any of the highlighted topics that appear.

   For CARD's menus that display results below the input section (e.g., many of the Equation's menus), you can now use Insert key to make the cursor jump to the results section. You can then get information about each result by pressing Enter or F1.

   For help that corresponds to a menu option, the path to the corresponding menu is shown at the end of the help information. For example, the path to the file menu's Save File option would be shown as \Files\Save file \.

   If desired, CARD's help can be directly accessed by running CARDhelp.exe, for which CARD itself does not need to be running. This can be useful if you are running under Windows and want to run CARD in one window and CARDhelp in another.

5. Scrolling lists. Files, directories, and drives can now be selected from scrolling lists. When a search window is open, you can type in a search string and the cursor will jump to the closest match.

6. Paged selection. You can now Page-up or Page-down through the materials and equipment lists.

7. Material changes. After you have entered the resonator shape in the spreadsheet, you can easily change the material that is assigned to a particular surface. For the exterior resonator shape (F2 key) and any surface other than surface 0, pressing M (a hot key) will display the current material for that surface. Then Page-up or Page-down to the desired material and press Esc to changed to the displayed material. (Note: for surface 0, pressing M displays a list of all available materials where you can adjust the material properties, if desired.)

8. Menu indicators. For some menu options, pressing the Ctrl+Enter keys together has a special effect. For example, in the material properties menu, pressing Ctrl+Enter will automatically calculate the particular material property. To identify these special menu options, a "=" precedes the option description. The on-line help for the particular menu option describes the special effect.

9. Setup options. Additional setup options have been added. The most important are:

   Checklist menu options
   Override numeric limits
   Default tuning mode

   See the online help for more information.
10. Flip resonator. You can use the "|" key to flip the resonator end-for-end when you are in the spreadsheet. This is useful for resonators with pointed ends, for which CARD may have difficulty converging. CAUTION: this is still experimental.

Greater functionality

1. Equations. An Equation section has been added. This allows you to access various theoretical and empirical equations (and associated graphs) which are useful in designing ultrasonic resonators. These include equations for theoretical resonator shapes (exponential, catenoidal, conical, radial, flexural, etc.), the effect

of temperature on resonator performance, amplitude uniformity of unslotted cylindrical resonators, press fits, thread dimensions and stresses, material properties, etc. A tree diagram is shown below.

```
EQUATIONS
¦
¦-- INFORMATION
¦
¦-- AXIAL RESONANCE
¦    ¦
¦    ¦- Cylindrical Horns
¦    ¦   ¦-- Unshaped (*)
¦    ¦   ¦-- Conical (*)
¦    ¦   ¦-- Exponential (*)
¦    ¦   ¦-- Catenoidal (*)
¦    ¦   --- Spool (*)
¦    ¦
¦    -- Tip force (*)
¦
¦-- RADIAL RESONANCE
¦    ¦
¦    ¦-- Radial disk resonance (*)
¦    --- Radial ring resonance
¦
¦-- FLEXURE RESONANCE
¦    ¦
¦    ¦-- Rod --- (typical) --- Clamped-fixed plate (*)
¦    ¦-- Beam                 ¦- Clamped-free plate (*)
¦    ¦-- Plate                -- Infinite plate (*)
¦    --- Disk
¦
¦-- TORSIONAL RESONANCE
¦
¦-- MATERIAL PROPERTIES
¦    ¦
¦    ¦-- Temperature effects (*)
¦    ¦-- Thin-wire parameters
¦    --- Q
¦
--- OTHER
     ¦
     ¦-- Bolt dimensions
     ¦-- Bolt calculations
     ¦-- Wrench flat equivalent diameter
     ¦-- Spanner hole equivalent diameter
     ¦-- Press-fit (*)
     ¦-- Von Mises stress
     ¦-- Piezo-ceramic calculations
         ¦-- Static performance
         --- Dynamic performance
```

(*) indicates that calculations can be graphed for the specified item.

2. Temperature dependent wave speed. The thin-wire wave speed can now be temperature dependent. See the "Wave speed coefficients" option in the material properties menu. The actual resonator temperatures are set in the general requirements menu.

   Note that the current implementation assumes a linear temperature distribution from the front to the back of the resonator, which will only be true for an unshaped resonator. See the on-line help for further discussion.

3. Square block horn. A square block horn has been added to the available horn types. For this horn, all dimensions (bevels, banding, etc.) are completely symmetric on both the thickness and width.

4. Cylindrical cross-slotted horn. A cylindrical cross-slotted horn has been added to the available horn types. This is a cylindrical horn where the slots intersect at 90°, rather than intersecting radially at the center of the horn. This horn does not have a face cavity or interior.

5. More slots. For bar and block horns, the maximum number of slots has been increased from four to six.

6. Hollow studs. Studs can now have a through hole that overrides any overlapping resonator material.

7. Additional results. After slicing, CARD now also calculates the strain energy, loss, overall Q (quality factor), and the resonator's weight.

8. More complex resonators. To allow for the design of more complex resonators, the maximum number of exterior and interior surfaces has been increased from 20 to 40. The number of surfaces that have been used in the current resonator is shown in the spreadsheet.

9. Improved output. When you output the text results, you can now output to either a printer or to a file (either formatted for subsequent printing or unformatted). The file output is useful if you don't have immediate access to an appropriate printer (e.g., if working from a laptop computer), or if you want to use the results in a word processing document (unformatted).

   For a formatted output file, you can send the file to the printer by typing "type filename.ext > lpt1".

   You can now print a list of all resonator materials from the Files menu.
10. Greater control. You now have greater control over the slicing process by specifying values for the calibration gain error, the auto-tune gain error, and the auto-tune stress angle increment. (\Checklist\Set tuning parameters\)
11. Improved graphics. To clarify the shapes of slender resonators, the surface numbers can be temporarily hidden. Also, autotune surfaces now have a distinctive dashed pattern.

    For printing, the graphics background color can be selected.
12. Graphics menu. The resonator's input or output amplitude can now be specified. All graphs that are available from the graphics menu are then scaled to this amplitude.
13. Loss and strain energy graphs. The graphics menus now display loss and strain energy graphs. These graphs are useful when designing a resonator for minimum loss or where the loss must be distributed over the length of the resonator.

Improved accuracy

CARD's accuracy has improved for the following conditions:

1. Block horns. In a comparison of 52 rectangular and square block horns, the average frequency predicted by CARD was within 0.03% of the corresponding frequencies predicted by finite element analysis (versus -1.4% for CARD 7.12c).

2. Resonators with a stud. When the resonator has a stud, CARD is now more accurate.

3. Full-wave resonators. CARD now gives correct results for full-wave resonators. (Previously, CARD's predicted frequency was too low.)

Other changes

1. In order to make the mouse work with CARD's help, the mouse has been disabled for CARD's menus.

2. Monochrome monitors are no longer directly supported.

3. CARD's file format is not compatible with 7.xx. No conversion utility is available or planned.

4. CARD's installation program CARDinst.bat has been renamed to Setup.bat to be consistent with Windows.

5. A laser printer is now the default printer.

6. English density units are now correct (i.e., not divided by the acceleration of gravity).

7. You now exit CARD from the Files menu. You can also press X to exit. You can no longer abort CARD by pressing Ctrl+C.

8. CARD should now work with Windows NT, although some potential problems remain.

9. The following menus will not be accessible in this version, but may be implemented in future versions:

   \Checklist\Resonator type\Transducer\
   \Option\Setup\Help messages\
   \Option\Setup\Mouse sensitivity\
   \Equation\Axial resonance\Bar horns\
   \Equation\Axial resonance\Block horns\
   \Equation\Material properties\Materials database\
   \Equation\Other\Stress concentration\
   \Equation\Other\Piezo-ceramic calculations\Dynamic performance\

Version 8.5x (Beta)

CARD 8.5x is the most current version. It has not yet been officially released but is currently undergoing testing. This version is available under the same conditions as the official version. You should consider this version if you need any of the following added features. However, because it is still undergoing testing, it may have bugs that are not present in the official version.

1. 99 half-waves. The maximum number of half-waves for unslotted horns has been increased from three to 99. This is particularly useful for long medical probes. Note: most of the added half-waves must be prismatic (constant cross-sectional area), since CARD stores the prismatic data in a special compressed format. Since this is the usual condition, this imposes only a mild limitation for designing very long resonators.

2. Added equations. The following have been added to the Equations section:

   \Equation\Other\Linear estimate\ -- This option allows linear interpolation/extrapolation between two known data points in order to provide an estimate of acoustic parameters (node location, frequency change, etc.).

   \Equation\Other\Lissajou diagram\ -- Resonators sometimes have odd amplitude patterns (ovals, figure-8', arrowheads, etc.). These patterns occur when the resonator vibrates simultaneously at two or more frequencies. The Lissajou diagram option allows you to adjust frequency and amplitude parameters in order to duplicate these amplitude patterns. This can provide insight into the cause of these patterns.

   \Equation\Acoustic radiation\ -- This option predicts the power that can be delivered by a flat circular piston to an infinite fluid (i.e., no energy is reflected back to the piston). This may be used to estimate the power that will be delivered by a horn, excluding cavitation.

3. Wrench flat calculations. CARD now correctly calculates the area for wrench flats that have been machined into a sloping surface.

The file format for this version is currently compatible with version 9.00. However, this compatibility is not guaranteed for future releases.

Important Notes

1. For versions 9.xx, CARD's file format is not compatible earlier versions (6.xx and 7.xx). No conversion utility is available or planned.

Price and Delivery

Full version	$950.00
Upgrade from version 8.xx or earlier .... (includes several chapters from the CARD manual)	$200.00
Copy protection key, if required .... (see note 1 below)	$75.00

Shipping and handling

	U.S.A.	Elsewhere
With full manual	$20.00	$40.00
Without full manual .... (typically for upgrades)	$10.00	$30.00

Payment

1. All prices are US dollars.
2. Payment may be made by corporate check, personal check, purchase order, or any guaranteed negotiable instrument (cashiers check, money order, etc.). Purchase orders are subject to approval. Personal checks must clear before CARD is shipped.

Shipment -- two weeks (approximately) after receipt of payment.

Notes

1. CARD requires a diskette drive in order to access the copy protection diskette. If you intend to use CARD on a computer that does not have a diskette drive, then you will have to purchase a copy protection key that plugs into the computer's parallel printer port. Note that the copy protection key will not work under Windows 2000 or Windows XP.
2. The copy protection diskette or the copy protection key is your evidence of authorized use. If you have lost either of these, then you cannot upgrade directly. Instead, you must purchase a full version.

Top | Home | Site Map | What's New | Company Information | Contact Us

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Home | Site Map | What's New | Company Info | Contact Us

Frequent Questions

[Up]

This page answers frequently asked questions about Computer Aided Resonator Design (CARD).

Language

- Is CARD available in any language other than English? No. All menus and on-line help are in English only.

Capabilities

- Can CARD analyze resonators that vibrate in flexure (bending), radial, or torsional modes? Generally, CARD cannot analyze flexural, radial, or torsional resonators that have an arbitrary shape; CARD can only analyze resonators that vibrate longitudinally (parallel to the axis of the resonator). However, CARD has an Equations section that allows some calculations for simple flexural, radial, and torsional resonators (beams, plates, disks, rings). These simple resonators are those that can be described by classic differential equations.

- Can CARD analyze transducers (converters)? Yes. CARD can determine the longitudinal resonant frequency and the relative stresses, amplitudes, and losses (with the same accuracy and limitations as with any other resonator analysis). CARD works best for relatively slender transducers, such as handheld transducers used in medical applications. CARD is not well suited for analyzing "fat" transducers (e.g., those used for cleaning tanks).
Note: CARD cannot currently determine the actual output amplitude for a specified electrical input, since CARD does not have the piezoelectric transformations. This capability may be included in a future release if there is sufficient demand.

- Can CARD determine higher harmonic resonances? Yes. This works well for relatively slender resonators. As the frequency of the harmonic resonance increases (i.e., the resonator becomes fatter in relation to the half wavelength), the accuracy decreases.

Equipment requirements

- Will CARD run on an Apple computer? No. CARD will only run on an IBM-compatible computer. The operating system must be either Windows or DOS. For other equipment requirements, click here.

Setup

- I receive the following error message when attempting to start CARD: "The copy protection key must be plugged into the printer port" (or similar). CARD has failed to recognize the copy protection key. Try each of the following, in turn:
a. Make sure the copy protection key is plugged into the parallel printer port, not the serial port.
b. If a printer is attached to the copy protection key, make sure it is turned on and ready to print. (Try printing a page from another application, such as a word processor.)
c. Turn the printer off and disconnect the printer cable from the copy protection key. If this corrects the problem, then the printer is probably interfering with the copy protection key. This is especially likely if the printer is a Hewlett-Packard with bi-directional capabilities. To resolve this

problem:
i. Install HP's newest drivers.
ii. If the newest drivers don't solve the problem, then install a second printer port that is dedicated solely to the copy protection key. This is relatively easy and should cost about $20.
iii. Use a different printer.
d. Turn the printer off and disconnect the printer cable from the copy protection key. Run Keshow.exe. This will show the status of the copy protection key.

- Can CARD be used on multiple computers? Yes. However, CARD can only be used on the computer that has the copy protection key attached. If you want to use CARD on another computer, then you must transfer the copy protection key to that computer.

- Will CARD operate on a networked computer? Yes. However, the user must run CARD from the computer where CARD has been installed and where the copy protection key is attached. Also, although CARD may print satisfactorily to a networked printer, this will depend on the particular network and is, therefore, not guaranteed. For additional information, see CARD's online help at <Alt+H>\Setup and starting procedures \Printer setup\Printing on a network\.

- Is CARD Y2K compliant? Yes. CARD does not use any function that manipulates or depends on the date.

- How should CARD be uninstalled? If you find that CARD does not meet your requirements, then you can simply delete the directory (folder) in which CARD has been installed. (Note: since CARD is not a Windows program, it would not have made any changes to the Windows' Registry.)

Analysis

- After I machine a resonator, the tuned length (or frequency or gain) is not the same as predicted by CARD. Card gives approximate results based on a one-dimensional analysis. These results are intended to assist with design, not to give absolutely correct values. (See method of analysis. Also see chapter 6 "Impedance Matching" in the CARD manual.) Where CARD's internal accuracy is not sufficient, a calibration mode has been provided.

- How can I print CARD's graphics? See CARD's online help at <Alt+H>\Setup and starting procedures\Printer setup\. Then select either "Printing graphics under DOS" or "Printing graphics under Microsoft Windows".

Maintenance

- How do I replace the battery in the copy protection key? The copy protection key has a button that contains two components:
  a. the copy protection integrated circuit.
  b. a ten-year battery.
  It is unlikely that the battery will ever need to be replaced. If required, the button can only be replaced by Krell Engineering.

- What should I do if the copy protection key becomes damaged? Contact Krell Engineering. If required, the key will be repaired or exchanged for a fee.

- What should I do if the copy protection key is lost? The copy protection key is an indicator of authorized use. Therefore, if you lose the copy protection key, you must purchase an entire CARD.

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Demo Download

You can download the CARD demonstration version from this page.

Description

The CARD demo is the same as the standard version of CARD (currently version 9.00) except:

1. The following functions have been disabled:
   a. Saving the resonator design file or modified CARD defaults
   b. Printing the resonator dimensions, materials, or results

2. A diskette drive is not required for installing CARD.

3. A copy protection diskette or key is not required.

4. Only an abbreviated CARD manual is available, which is included in the download.

Before downloading

Before downloading you may want to check on the following.

- Required equipment -- generally, most PCs (not Apple) will meet the requirements.
- General CARD information -- also includes a description of the required equipment.
- Frequently asked questions

Download procedure

To download the CARD demo (CARDzip.exe, approximately 1 MB) and read the Quick-Start manual:

1. Create a directory (folder) on your hard drive that will contain the downloaded file. The directory name is not important since it is a temporary directory that is only used for installation. Suggested name: "CARDdemo".

2. Download CARDzip.exe (below). When a dialog box appears, make sure that "Save this program to disk" is indicated (this should be the default). Then click OK and download to the directory of step 1. When the download is complete, close the download dialog box.

3. After CARDzip.exe has downloaded, *run* it to extract (unzip) all of the enclosed files. Note: this does not install CARD; it only extracts the required files.

4. Type "CARDinfo" to read/print the quick-start manual. This manual gives information on installation, starting and exiting, help, an example horn tutorial, a list of example horns, support, upgrading, and other matters. You may wish to preview the installation procedure before downloading.

Begin download of CARD demo. This will take about 10 minutes with a 28.8 modem.

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Quick-Start Manual

Computer Aided Resonator Design (CARD)

Quick-Start Manual

Version 1.4, revised 6/20/02

Notice

If this document is reproduced for further distribution, this title page must be included.

Table of Contents

Introduction

About Krell Engineering

Krell Engineering consults in the design of ultrasonic resonators (horns/sonotrodes/probes, boosters, transducers/converters) for frequencies between 10 kHz and 100 kHz. These resonators are designed using finite element analysis (FEA) simulation software. These resonators are used for industrial and medical applications.

- Industrial applications -- welding of plastics and nonferrous metals, cleaning, abrasive machining of hard materials, cutting, enhancement of chemical reactions (sonochemistry), liquid processing, atomization, etc.
- Medical applications -- surgical devices for cutting, cauterizing, scraping, and cavitating, dental descalers, etc.

Krell Engineering also provides Computer Aided Resonator Design (CARD) software which facilitates the design of ultrasonic resonators.

About this document

This document is an abbreviated users manual for the demonstration version of CARD (Computer Aided Resonator Design).

To assure that you have the latest demo version of CARD (which also includes the latest version of this document) and to obtain additional information about CARD, visit Krell Engineering's web site at http://www.krell-engineering.com. For other ways to contact Krell Engineering, see the Support section below.

CARD overview

"Computer Aided Resonator Design" (CARD) applies quantitative techniques to the design of acoustic resonators (horns/ sonotrodes/probes, boosters). Its goal is to provide assistance in the design of resonators of low-to-moderate complexity. It should be especially useful for designing low-stress resonators.

CARD will aid in designing new resonators or analyzing existing resonators. Resonator dimensions can be selected for automatic tuning, or the resonator can be manually tuned. Resonators up to three half-waves long can be analyzed (99 half-waves will be available in an upcoming version). CARD calculates numerous acoustic parameters, including tuned length, tuned frequency, gain, node location, maximum stress, stored energy, loss, overall quality factor (Q), and weight. When calculating the stress, CARD considers the effect of stress concentrations at radii and slot ends. CARD graphically displays the calculated amplitude, stress, and loss distributions at each point along the length of the resonator.

CARD has been designed for maximum ease of use, so that even those with minimum computer experience should have little difficulty. However, the user must have some understanding of resonator design in order to evaluate the computer-generated output.

CARD demo

The CARD demo is the same as the standard version of CARD (currently version 9.00) except:

1. The following functions have been disabled:
   a. Saving the resonator design file or modified CARD defaults
   b. Printing the resonator dimensions, materials, or results

2. A diskette drive is not required for installing CARD.

3. A copy protection diskette or key is not required.

4. Only an abbreviated CARD manual is available, which is included in the download.

Disclaimer

CARD is designed to assist with resonator design. It is not meant to replace the good judgment of the resonator designer. Therefore, the user assumes full responsibility for the proper use of CARD and any consequences that may result. (See the license agreement.)

License agreement

If you use this demonstration version of CARD (Computer Aided Resonator Design), you must abide by the following conditions.

1. CARD (comprising both software and manual) is copyrighted by United States Copyright Law to Donald R. Culp, to whom all rights are reserved.

2. You are free to distribute this **demonstration version** of CARD to others, provided that you include all of the original files in the original form and that none of these files has been modified in any way. You may not distribute the **standard version** in any form.

3. This license may be revoked if you fail to comply with any provisions of this license agreement.

4. CARD provides only approximate solutions to resonator design problems. (See CARD's online help at \Master topic index \CARD overview\Impedance matching.) Therefore, you assume all responsibility for using CARD within its limitations and for proper interpretation of the results produced by CARD.

Except for replacement of defective diskettes, the author and distributors of CARD specifically disclaim all other warranties, expressed or otherwise implied, including but not limited to implied warranties of merchantability and fitness for a particular purpose, use, or application. In no event shall the author, distributors, their employees or heirs be liable for any loss of profit or any other commercial damage, including but not limited to special, incidental, consequential, or other damages.

No oral or written information or advice given by the author, distributor, or their employees shall create additional warranty or in any way increase the scope of this warranty.

Distribution files

The download file is named CARDzip.exe. This is a self-extracting file that contains the remainder of the CARD files. To extract the files, simply run (execute) this file. Note: some of the following files may not be evident until CARD has been completely installed.

1. CARDinfo.bat: type "CARDinfo" to view the quick-start manual. CARDinfo will display either:
   a. QSmanual.hlp: a Windows help file.
   b. QSmanual.txt: a short text file for DOS users.

2. Setup.bat: the file for installing CARD.

3. CARDxxx.exe: the main CARD program (the executable file), where xxx refers to the version number. For example, CARD900.exe is version 9.00 of CARD.

4. CARD.bat: the file for running CARD.

5. CARD*.cfg: configuration files.

6. CARD1.hlp: CARD's online help file. This file is also viewable by typing "Showhelp" at a DOS prompt in the directory where CARD1.hlp exists. This file is displayed during setup. Note: CARD1.hlp is not a standard Windows help file.

7. Examples.exe: a self-extracting file that contains the resonator example files. This will automatically be installed by Setup.bat

8. Readme.doc and other doc files: any last-minute information that is not contained in the manual. Please read these files before installing or using CARD.

9. Other miscellaneous files, mainly for installation.

Note: all CARD files have been checked for computer viruses using Symantec's AntiVirus software.

Installation

This section will explain how to install CARD to a hard drive.

The download file is named CARDzip.exe. This is a self-extracting file that contains the remainder of the CARD files. To extract the files required for installation, simply run (execute) this file.

Automatic installation

CARD comes with an automatic installation program (Setup.bat). Setup will guide you through the installation process. You should not attempt a manual installation of CARD because some of the files may be compressed and therefore will not work properly.

A complete installation (including the original CARDzip.exe file and the extracted setup files) requires about 5 MBytes of disk space. If you have limited disk space, then Setup allows a limited installation (without the example resonators). You will be prompted during the installation process.

To use Setup, do the following:

1. If you are installing from Windows, open a DOS window.

   a. Press *Ctrl+Esc* together to bring up the Windows task bar.
   b. Click on "Programs".
   c. Find and click on "MS-DOS Prompt".
   d. If the DOS window is not full-screen (i.e., if it has a title bar and border), then press *Alt+Enter* to produce a full-screen window.

2. From the DOS prompt, type the following, with an *Enter* key after each line:

   X:
   CD\Xdirectory
   Setup X: Y: Ydirectory

where X = letter of the drive where CARD's setup files reside
Xdirectory = directory on X where CARD's setup files reside
Y = letter of the drive where CARD will be installed
Ydirectory = directory on Y where CARD will be installed.
(Ydirectory will be directly beneath the root directory.)

Ydirectory can have any name. However, the recommended name is CARDxxx, where CARDxxx is the name of CARD's executable file. (See "Distribution Files" above.) For example, if CARD's executable file is CARD900.exe, then you should name Ydirectory "CARD900".

Caution: Ydirectory should not be the same Xdirectory.

After you enter the above information, Setup automatically creates Ydirectory and copies all of the CARD files to Ydirectory. Any compressed files will be automatically expanded to their full size.

Example 1

To install CARD version 9.00 from directory CARDdemo of drive C: to directory CARD900 on hard drive D:, open a DOS window and type the following:

```
C:
CD\CARDdemo
Setup C: D: CARD900
```

Example 2

To install CARD version 9.00 from the root directory of floppy drive A: to directory CARD900 on hard drive C:, open a DOS window and type the following:

```
A:
CD\
Setup A: C: CARD900
```

Uninstalling

If you find that CARD does not meet your requirements, then you can simply delete the directory (folder) in which CARD has been installed. (Note: since CARD is not a Windows program, it would not have made any changes to the Windows' Registry.)

Starting CARD

After CARD has been installed, you can run CARD from a DOS prompt. (If you are running under Windows, first open a DOS prompt window. If the DOS window is not full-screen (i.e., if it has a title bar and border), then press *Alt+Enter* to produce a full-screen window.) Then enter the following, with a Enter key after every entry.

Y:
CD\Ydirectory
CARD

where: Y = the disk drive letter where CARD has been installed by Setup.bat.
Ydirectory = the directory where CARD has been installed by Setup.bat.

Loading sequence

As CARD begins loading, it first checks for the copy protection diskette or key. (This doesn't apply to the demo version.)

CARD then resets the printer if the printer is properly connected. This permits proper CARD printouts (not available in the demo version). Note: CARD also resets the printer before quitting so that printouts by subsequent programs will not be affected.

Next, CARD's title page (with copyright notice) appears and remains on-screen for approximately seven seconds. For the demo version, a short explanation appears.

CARD then performs some general hardware/software error-checking. If needed, status messages will be displayed before CARD proceeds.

CARD then loads several configuration (.cfg) files which contain user-definable defaults. These defaults can be adjusted from CARD's "Option" menu (*Alt+O*).

Main program

After the above process, the Main Menu Checklist will be displayed:

```
Files   Graph   Option   Equation   Help

MAIN MENU CHECKLIST
   Information
   Step through input checklist [1]
```

```
      Resonator type
      Tuning mode
      General requirements
      Resonator parameters
      Face cavity
   Equipment [E]
   Material [M]
-----------------------------------------
Enter resonator shape (spreadsheet) [v]
-----------------------------------------
Step through tuning checklist [2]
   Choose calibration material
   Choose auto-tune surfaces [A]
Set tuning parameters [T]
-----------------------------------------
Set slice parameters
Slice [z]
```

Access "Information" to learn the general procedure for using CARD.

How to quit

You can quit (leave CARD) from most menus by pressing *X* or from the Exit option of the File menu. At this point you will see the prompt:

Save current file before quitting? Y/N

If you want to quit, then press *N*. If you would rather continue with the current session of CARD, then press *Y*. (Note: for the demo version, the resonator file cannot be saved.)

Help

Overview

CARD provides two sources of help: the CARD manual and CARD's online help. The manual provides an overview and also examples of resonator design. CARD's online help provides detailed information about each of the menu options. It may also provide additional help that is not available in the manual.

General help

From anywhere within CARD, you can obtain general help information by pressing *Alt+H*. This will bring up the master list of topics.

From the master list, you should access "Using the help system" to understand how to use the help system. (To access a help topic, simply move the cursor to the desired topic or highlighted cross-reference and press the *Enter* key or double-click.) Note: unlike the rest of CARD, the mouse is active within the help system.

You can exit from CARD's help by pressing *Esc* until the CARD menu reappears.

Keyboard help

CARD uses certain keys for special purposes. From within CARD, press *K* for keyboard help. See below for a list of these keys.

Menu help

For many menus, the first option is "Information". This option gives general information about the purpose of the menu. If you are unfamiliar with a menu, you should read this information first.

If you need help about a particular menu option, first move the cursor to that option. Then press *F1* to obtain help.

Results help

Some menus have both an input section and a results section (located below the input section) where the calculated values appear. For example, the "Bolt calculations menu" appears as:

```
BOLT CALCULATIONS MENU
   Bolt dimensions ..................... M10-1.25
   Bolt force .......................... 50000 N
   Bolt thread coeff of friction ....... 0.15
   Bolt head coeff of friction ......... 0.15

   Torque coefficient K ................ 0.20
   Tensile stress diameter ............. 8.72 mm
   Tensile stress area ................. 59.7 mm²
   Tensile stress ...................... 837.62 MPa
```

```
Torque ............................. 101.0 N-m
```

To make the cursor jump between the input section (blue text) and the results section (green text), press the *Ins* (Insert) key. After the cursor jumps to the results section, you can move the cursor to the desired result and press *F1* to get more information about a particular result (e.g., if you need help with the "Torque coefficient K" result). When you have finished in the results section, use the *Ins* key to return to the input section.

Spreadsheet help

In the spreadsheet, you can use the *F1* key to get general information about entering the resonator shape. In addition, you can get more specific help about the indicated keys by holding down the *Alt* key and pressing the desired key. For instance, for help with the *F2* function key, hold down the *Alt* key and press the *F2* key. This only works in the spreadsheet.

Keys

This section describes the keys that are used within CARD.

From within CARD, press *K* for keyboard help. This may provide additional information.

In the columns below labeled Key, the equivalent mouse button is given in parentheses (L = left button, M = middle button, R = right button).

Bar menu keys

The bar menu appears at the top of each menu screen. To access one of the listed options, press *Alt* and the highlighted key together. For example, to access the File option, press *Alt+F*.

Menu keys

The following keys are used in CARD's menus.

Key	Location	Description

F1 or ?	All menus	Calls help information.
Esc	All menus	Cancel an entry, or escape from the current menu.
↵ (Enter)	All menus	Accept the current value or option.
↓ or Space	All menus	Moves the cursor down to the next menu option. If the cursor is at the last option, then it will jump to the top menu option.
Up arrow	All menus	Moves the cursor up to the next menu option. If the cursor is at the first option, then it will jump to the last menu option.
Space	Spreadsheet	Changes the active surface to the previous or next surface.
Home	All menus	Moves the cursor to the top (first) option.
End	All menus	Moves the cursor to the bottom (last) option.
F9	All menus	Displays the resonator shape.
F10	All menus	Changes the current units (from metric to English, or from English to metric).
Alt + Num	Spreadsheet	Help with the surface type associated with Num.
Alt + Fn	Spreadsheet	Help with function key Fn, where n is the function key number.

Menu quick-access (hot) keys

The following letter keys ("hot" keys) give quick access to certain menu options.

Notes:

1. In CARD's menus, the hot keys are shown in brackets at the right of the associated option (e.g., [*E*] -- the Equipment menu).

2. The quick keys respond to either upper or lower case keys. However:
   a. Keys shown as upper case can be accessed from any menu, even if the key is not visible from that menu (e.g., [*E*] -- the Equipment menu).
   b. Keys shown as lower case can be accessed from the menu where they are visible (e.g., [*z*] -- Slice (available only from the Checklist menu.)).

3. In the table, the menu path to the option that is associated with the hot key is shown in brackets (see the example).

Example: to access the printer setup [\Option\Setup\Printer], either:

1. Use the hot key *P* (quick method):
   a. Press *P* (either upper case or lower case).
   b. After adjusting the required options, press *Esc* to exit the printer setup and return directly to your previous location in CARD.

2. Use conventional menus (slow method):
   a. Press *Alt+O* (to access the bar-menu "Option" option).
   b. Access the "Setup" option.
   c. Access the "Printer" option.
   d. After adjusting the required options, press *Esc* three times to exit the above menus and return to your previous location in CARD.

Key	**Description**
A	Set Auto-tune parameters. [\Checklist]
B	A menu of standard bolt sizes. [\Equation\Other\Bolt dimensions]
E	A menu of available equipment. [\Options\Configuration\Equipment]
G	A menu for adjusting how the graphics are displayed. [\Option\Setup\Graphics]
K	Displays keyboard help.
M	A menu of available materials. [\Options\Configuration\Materials] For the spreadsheet, this displays the material corresponding the currently active surface. The material properties for this surface can be changed.
O	Open (load) a resonator file from disk. [\File\Open]
P	A menu for adjusting the printer parameters. [\Option\Setup\Printer]
S	Save the current resonator design to disk. [\File\Save]
T	Set tuning parameters. [\Checklist]
v	Enter the resonator shape (spreadsheet). (Available only from the checklist menu.)

X	Exit CARD. [\File\Exit]
Y	Equivalent geometry [\Equations\Other\Equivalent geometry]
z	Slice. (Available only from the Checklist menu.)

Help window keys

The following keys can be used when CARD's help window is displayed.

Key	Description
F1	Displays the master topic index.
Alt+F1	Displays the previous topic window.
Esc (R)	Closes the current topic window and returns to the master topic index. If currently in the master topic index, then closes all help.
Tab	Moves to next highlighted cross-reference item.
Shift+Tab	Moves to previous highlighted cross-reference item.
↵ (L)	Accesses the help topic at the cursor.
Up arrow	Moves 1 line toward the beginning of the help.
↓	Moves 1 line toward the end of the help.
PgUp (Page Up)	Moves 1 screen toward the beginning of the help.
PgDn (Page Down)	Moves 1 screen toward the end of the help.
Home	Moves to the left of the current window.
End	Moves to the right of the current window.
Ctrl+Home	Moves to the top of the current window.

Ctrl+End	Moves to the bottom of the current window.
Ctrl+PgUp	Moves to the last line of the help.
Ctrl+PgDn	Moves to the first line of the help.

Example resonator

This section will explain how to load and analyze a simple resonator. Editing the resonator shape in the spreadsheet will not be explained.

Auto-tune length example

The resonator for this example (At-leng1.hrn) is a cylindrical unslotted 20 kHz horn with a .375" diameter stud. This horn will be analyzed in the auto-tune length mode, where CARD will automatically adjust the horn's length to tune from the initial frequency (19228 Hz) to the desired frequency (20000 Hz).

Follow these steps:

1. Start CARD.

2. Normally, the first time that you start CARD you should access Options on the bar menu (*Alt+O*) and make any required changes. This is not necessary for this example but you may wish to do this the next time you start CARD.

3. You should access the Information option to get an overview of CARD.
    a. Move the cursor down to the "Information" option using the arrow keys or the space bar. Press *Enter*.
    b. Press *Esc* to exit from the help.

4. Load the horn At-leng1.hrn.
    a. Press *Alt+F* to access the File menu on the menu bar.
    b. Load the horn At-leng1.hrn:
        i. Access the "Open [O]" option or press *O* (the hot-key to open a file).
        ii. Type "At-leng1.hrn" and press *Enter* or
        iii. Obtain a list of horns:
            1. Type "*.hrn" and press *Enter*. This will list all of the hrn files.
            2. Scroll through the list until you find At-leng1.hrn. Press *Enter*.
        iv. The status section at the middle of the screen will show that At-leng1.hrn has been loaded. The title will show

a description of this horn.

c. Press F10 as required to change between English and metric units. The units will be indicated in the upper right corner of the screen as "E" or "M". *F10* will change the units throughout CARD and can be used from any menu.
d. You will be asked if you want to view this horn. You should generally view the horn to verify that it is the desired horn. To view the horn, press *Y*. (Note: you can also press *Enter*, since the *Y* is highlighted to indicate that it is the default response.) Whichever response you choose (*Y* or *N*), this will become the default (highlighted) the next time you load a resonator. If you choose to view the horn:
    i. Wait for the horn shape to be displayed.
    ii. Press any key to return to the Files menu.
    iii. Note: you can also view the horn from any menu by pressing *F9*.
e. Press *Esc* to return to the Main Menu. (For all menus, pressing *Esc* will exit the menu and either:
    i. return you to the previous menu.
    ii. take you to the next menu in the menu sequence.)
f. Note: in the following, you should assume that the *Enter* key is used to access a menu option or after setting an option value.

5. Access "Step through input checklist [1]" from the Main Menu. For this example, all of the checklist items have been correctly configured. However, you should look at the available options as you move through the menus. To leave each menu and move to the next menu, press *Esc*. After several menus, you will return to the Main Menu.

6. At this point you might normally adjust the resonator's dimensions in the spreadsheet (the "Enter resonator shape (spreadsheet) [v]" option from the Main Menu). You might also adjust the material properties or set the equipment parameters (e.g., the stud dimensions, wrench flats, spanner holes, etc.). For this example, we will assume that these are already correct. Therefore, you are ready to analyze (Slice) the resonator to determine its performance.

7. At this point you would normally access "Step through tuning checklist [2]" from the Main Menu. For this example, all of the checklist items have been correctly configured. If you access this option, choose surface 5 (the last surface) as the auto-tune length surface. For the next menu ("Tuning parameters menu"), just *Esc* to return to the Main Menu.

8. Set the slice options:
    a. From the Main Menu, access "Set slice parameters". (Note: you can quickly get to this option from the Main Menu by pressing *End* and then the *Up* arrow.)
    b. Access "Slice speed" and set the value to "1" (slowest). This is done so that you can see the details of the slicing process; otherwise, you can set the speed to any available value (1 = slowest; 10 = highest).
    c. Access "Pause after each iteration". This will automatically change from "No" to "Yes". This will cause the slicing to pause when the slicing reaches the end of the resonator. At that point, you can then press any key to begin the next slicing iteration. (Note: after you have finished with this example horn, you can reset this to "No" for faster execution.)

9. From the Main Menu, access the "Slice [z]" option to begin slicing. Notes:
    a. During slicing, don't press any key except when the slicing pauses. Otherwise, the slicing will be aborted.
    b. Observe that each slice conforms to the shape of the resonator. For each slice, CARD calculates numerous

parameters associated with that cross-section.

c. At the end of each iteration, following will be displayed:
    i. The top panel displays a text status box. The contents of this box will depend on the chosen tuning method.
    ii. The horn shape will be displayed in the bottom panel. Initially, the slices will not stop at the end of the horn; this indicates that the horn is not yet tuned. After each iteration, the slices should be closer to the end of the horn as CARD adjusts the length of surface 5; this indicates that the tuning is converging to a solution.
    iii. The calculated stress curve will be displayed in the middle panel. For this horn, an approximate radius stress is also displayed. (If preferred, you could have chosen to display other parameters (such as the amplitude) from the "Main menu\Set slice parameters\Slice graphics" option.)

d. After you have studied the results at the end of each iteration, press any key to begin the next iteration. For this horn, four iterations will be needed for the results to converge (i.e., for the resonator to be tuned to 20 kHz). Other resonators may require a different number of iterations.

10. View the results:
    a. When slicing is complete, you will see a text summary of the results. If you press *F1* at this point, you will receive a description of each result.
    b. When you have finished viewing the text summary, press *Esc* to view the graphical results. Note: you can only return to the text summary screen by slicing the resonator again.
    c. Graphical results: view each of the desired results.
        i. If this is a standard version (not a demo version), then you can print the Summary and Detailed results.
    d. When you have finished viewing the graphical results, press *Esc* to return to the Main Menu. Note: after you return to the Main menu, you will only be able to print out the results by slicing the resonator again. However, you will be able to view the graphical results by accessing the bar menu Graphics option (*Alt+G*).

11. Make any required changes in order to improve the horn's performance:
    a. The horn's shape can be adjusted in the Spreadsheet. In the spreadsheet, press *F1* for information on how to enter or edit the horn's shape.

12. You should explore CARD's Equation section (*Alt+E*), which has many theoretical and empirical equations dealing with resonator design. In the Equation menu, access "Information" to see a tree diagram of all options. You can click on any of these options to see a detailed description.

Other examples

The following table describes all of the example resonators. The file name for each example resonator ends with a "hrn" extension. These horns are listed in the order in which they appear in the full CARD manual.

Horn	Description

Example1.hrn .. Example6.hrn	Various example horns that show how the horn shape is entered and modified in the spreadsheet. These are explained thoroughly in the full CARD manual.
Cal1.hrn	Calibrate mode: A cylindrical horn with known dimensions, frequency (19877 Hz), and gain (2.47). The thin wire wave speed and gain correction factor will be adjusted until the known parameters have been achieved.
Cal2.hrn	The same as Cal1.hrn, but after completion of calibration.
At-leng1.hrn	Auto-tune length mode: A 20 kHz tapered cylindrical horn, frequency = 19887 Hz (per Cal2. hrn). The length of surface 5 will be adjusted in order tune to 20 kHz. This is the example that is detailed above.
At-leng2.hrn	The same as At-leng1.hrn, but after completion of auto-tuning to 20 kHz.
At-thic1.hrn	Auto-tune thickness mode: A 20 kHz slotted unshaped bar horn, frequency = 20435 Hz. The material has been calibrated and the menus remain as they appear at the end of calibration.
At-thic2.hrn	The same as At-thic1.hrn, but the menus have been set for the desired auto-tune thickness mode. The thickness of surface 4 will be adjusted toward the middle of the slots (banding) in order tune to 20 kHz.
At-thic3.hrn	The same as At-thic2.hrn, but after completion of auto-tuning to 20 kHz.
At-step1.hrn	Auto-tune step mode: A 20 kHz cylindrical horn, frequency = 20222 Hz. The position of the nodal radius-step (surface 3) will be adjusted in order tune to 20 kHz.
At-step2.hrn	The same as At-step1.hrn, but after completion of auto-tuning to 20 kHz.
At-gain1.hrn	Auto-tune gain mode (variable resonator length): A 20 kHz tapered cylindrical horn. The thickness (diameter) of surface 2 will be adjusted in order to increase the gain to 3.63. Simultaneously, the length of surface 5 will be adjusted to maintain a frequency of 20 kHz.
At-gain2.hrn	The same as At-gain1.hrn, but after completion of auto-tuning.
At-strs1.hrn	Auto-tune stress mode: A 20 kHz cylindrical horn. The angle of surface 4 will be adjusted in order to minimize the stress. Simultaneously, the length of surface 5 will be adjusted to maintain a frequency of 20 kHz.
At-strs2.hrn	The same as At-strs1.hrn, but after completion of auto-tuning.
Matcolor.hrn	This horn simply shows each of the color-hatch pattern combinations for each of the 10 available materials. This horn should not be analyzed.

Upgrading

If you decide to upgrade from the demo version to the standard version, you will receive the following:

1. A diskette containing the current standard version with all functions enabled.
2. A copy protection diskette or key.
3. A complete manual (300+ pages and over 40 figures) with tutorial examples.
4. One year of free support.

To upgrade, contact Krell Engineering (see the Support section below).

Support

You may use the following options for support.

Krell Engineering
212 E. Medwick Garth
Baltimore, MD 21228
USA

tel/fax: 410-747-5731
e-mail: CARD@krell-engineering.com
http://www.krell-engineering.com

For the standard version of CARD, free support will be provided for one year from the initial license date. For the demo version, free support will be provided for one month from the initial support inquiry.

Problem resolution

If you encounter a problem, you will receive the best support via telephone. If appropriate, you should consider e-mailing a copy of the resonator file on which you were working when the problem occurred. Printouts of your monitor screen (by fax or e-mail) can also be useful in diagnosing the problem. Please note the version of CARD that you are using and the operating system (DOS , Windows, or Windows NT version).

If you write, please include as much relevant information as possible. This will permit the quickest resolution of the problem. If you have questions about the manual, just photocopy the desired sections and write your questions in the margins. (Please write legibly.) Also, please include a telephone number and convenient time when you can be reached.

You may also want to log onto Krell Engineering's web site (above) to see if there are any suggestions related to your problem. You can also e-mail from that location.

>> All suggestions for improving CARD are appreciated. <<

Equipment requirements

Required equipment

Computer

IBM micro-computer (or true compatible) based on the Intel 80286 (or higher) microprocessor.

Operating system

Version 3.3 (or later) of Microsoft DOS. Version 5.0 (or later) is recommended for printing VGA graphics. (See below.)

Although CARD is a DOS program, it will run acceptably under Microsoft Windows. (Contact Krell Engineering for additional information.) Also, see known issues.

Memory

The computer must have approximately 480 KB of free conventional memory after any other memory-resident programs have been loaded.

Display

A VGA color display (640 x 480, or higher) is recommended. (The values in parentheses give the graphics resolution.) However, CARD will also run with any of the following displays: any video adapter and monitor capable of displaying IBM graphics (CGA, 320 x 200; MCGA, 320 x 200; EGA, 640 x 350).

Disk drives

A hard (fixed) disk with approximately 5 MBytes of free space is required. One 1.44 Mbyte floppy drive is required to load CARD onto the hard disk (not required for the demo version).

Optional equipment

Mouse

A two or three button mouse may be used. The mouse is only active when the on-line help is invoked.

Printer

CARD is configured to support any printer that is compatible with the IBM graphics printer (dot matrix) or Hewlett-Packard laser. CARD expects the printer to be connected to parallel port #1.

CARD does not support plotters.

Top | Home | Site Map | What's New | Company Information | Contact Us

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Home | Site Map | What's New | Company Info | Contact Us

Price and Delivery

[Up]

Prices

Full version	$950.00
Upgrade from version 8.xx or earlier .... (includes several chapters from the CARD manual)	$200.00
Copy protection key, if required .... (see note 1 below)	$75.00

Shipping and handling

	U.S.A.	Elsewhere
With full manual	$20.00	$40.00
Without full manual .... (typically for upgrades)	$10.00	$30.00

Payment

1. All prices are US dollars.

2. Payment may be made by corporate check, personal check, purchase order, or any guaranteed negotiable instrument (cashiers check, money order, etc.). Purchase orders are subject to approval. Personal checks must clear before CARD is shipped.

Shipment -- two weeks (approximately) after receipt of payment.

Notes

1. CARD requires a diskette drive in order to access the copy protection diskette. If you intend to use CARD on a computer that does not have a diskette drive, then you will have to purchase a copy protection key that plugs into the computer's parallel printer port. Note that the copy protection key will not work under Windows 2000 or Windows XP.

2. The copy protection diskette or the copy protection key is your evidence of authorized use. If you have lost either of these, then you cannot upgrade directly. Instead, you must purchase a full version.

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Management

[Up]

Donald R. Culp, Owner

Ultrasonic background

Owner, Krell Engineering (1985 - present)

- Design and optimization of ultrasonic resonators (horns, boosters, transducers) using finite element analysis. Design parameters include static, dynamic, and thermal stress, power loss, resonant frequency separation, input and output amplitude uniformity, materials specifications, and manufacturability.
- Computer Aided Resonator Design (CARD) software.

Senior Research Engineer (1980 - 1985)
Acoustics Research Group
Branson Sonic Power Company

- Development of advanced ultrasonic resonators, including solid-mount boosters and transducers. Optimum designs were achieved through finite element analysis and empirical testing.
- Development of materials with improved fatigue strength for use in ultrasonic resonators.

Chief Ultrasonic Engineer (1978 - 1979)
Energy and Minerals Research Company
(Private and government research in ultrasonics)

- Directed the ultrasonic research laboratory for this start-up company. Research projects included ultrasonic apparatus to determine integrity of coal mine roof rock and roof bolts, and ultrasonic coal grinding for use in coal-oil mixtures. Two patents were awarded.

Research Engineer (1972 - 1977)
Research and Development
Branson Sonic Power Company

- Development of equipment for ultrasonic metal welding, resulting in two patents.
- Research of advanced projects, including ultrasonic drying of fabrics, metal pickling, wave soldering, wire cleaning, and particle de-agglomeration.
- Support of customers for advanced applications.

Membership

- Ultrasonic Industry Association (UIA)
- Ultrasonic and Acoustic Transducer Group (UATG)

Education

Master of Science in Management of Engineering, 1985
University of Bridgeport

Master of Science in Mechanical Engineering, 1972
West Virginia University
Thesis: "Metal Deformation with Ultrasound"

Bachelor of Science in Mechanical Engineering, 1970
West Virginia University

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