Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

THE POTENTIAL FOR DISRUPTIVE TECHNICAL INNOVATION IN WIRELESS COMMUNICATION APPLICATIONS IN THE FREQUENCY CONTROL INDUSTRY

Bruce A. Vojak[1,2], William W. Ho[2]
[1]Department of General Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[2]Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Abstract – **Radically disruptive technical innovation offers a threat to, as well as an opportunity for, participants in any industry. This especially is the case in mature industries where product performance characteristic improvements and cost reductions typically are incremental over time. One example of such a relatively mature industry is the quartz-based frequency control device industry for wireless communication applications. We have studied perceptions of the potential for disruptive technical innovation in this industry by conducting two surveys, a "supply-side" survey of current industry participants and a "demand-side" survey of consumers who might purchase products enabled by such disruption. Our findings identify both where the industry anticipates and ignores the threat of disruption, as well as how the end-user market values products exhibiting radical reductions in size. Further, we have applied Christensen's theories to the results of our study of this industry in an attempt to identify the potential for disruptive innovation.**
Keywords – **Quartz crystals and oscillators, frequency control industry, disruptive technical innovation**

I. INTRODUCTION

Over the past sixty years, a relentless series of wireless communication applications have driven demand for new and improved products from the frequency control industry. From the early military communication applications in the 1940s through paging and modern cellular applications, the frequency control industry has repeatedly provided quartz-based solutions for wireless products that are smaller, less expensive, and displaying higher performance characteristics.

With this extended and successful history as a backdrop, as quartz technology continues to progress toward maturation, it is important for participants in the frequency control industry to periodically consider what the future might look like. That is, "will it be characterized by further incremental and sustaining developments in quartz-based technology?" or, on the other hand, "will it be characterized by radical and disruptive innovation from other technical sources?"

In the current work, we have studied perceptions of the potential for disruptive technical innovation in this industry by conducting two surveys, a "supply-side" survey of current industry participants and a "demand-side" survey of consumers who might purchase products enabled by such disruption. "Supply-side" survey responses were received from 37 industry participants from 36 companies. The "supply-side" survey results provide insight into the perceptions of the potential for the acceptance of disruption from current quartz industry participants. End-user market "demand-side" survey responses from 161 participants were obtained, indicating their willingness to pay for 10x and 100x size-reduced cell phones relative to the current industry standard cell phone products. The "demand-side" survey results provide the frequency control industry with an indication of the extent to which radically disruptive size reductions would be valued in the marketplace by cell phone users. Finally, we have applied Christensen's theories of innovation [1] to the results of our study of this industry in an attempt to identify the potential for disruption.

II. SUPPLY-SIDE SURVEY

A. Objective

The purpose of the "supply-side" survey was two-fold, (1) to understand the perceptions of frequency control industry participants regarding disruptive technical threats and opportunities and (2) to understand the propensity of frequency control industry participants to embrace disruptive alternatives.

B. Methodology

A cross-sectional survey design was employed in this study with a sampling frame consisting of the 117 quartz-based bulk acoustic wave device, surface acoustic wave device and oscillator manufacturers identified on the IEEE Ultrasonics, Ferroelectrics and Frequency Control (UFFC) web site as of November 2001 [2]. An open-ended, written-response survey instrument was used and the survey was administered via email during the first half of 2002. In order to reach survey participants in a position to respond knowledgeably, we networked into each organization to identify a willing participant at an appropriate level in an appropriate position. All responses were analyzed on an anonymous basis and are presented in aggregate form.

The survey instrument consisted of the following eleven questions:

1. What is your function? (e.g. applications engineer, research and development, marketing, sales, etc.)
2. What is your title?
3. What products does your company make and/or sell?
   - SAWs
   - Bulk acoustic wave resonators
   - Crystal oscillators
   - Other, please list
4. What is your impression of the future technical progression of the quartz crystal industry (both bulk and surface wave devices)?

5. What disruptive or radical technical changes are you aware of that threaten to replace conventional quartz bulk and surface acoustic wave devices in frequency control and selectivity applications?
6. What qualities do you look for to benchmark potential disruptive changes against conventional quartz technology?
7. What can you tell me about the strengths and limitations of the potential competitive threats that you are aware of? What performance characteristics of these new technologies need to be improved to meet customer requirements?
8. Where have you learned about these technologies? Can you provide references (technical journal or conference proceedings) where you seen this information?
9. What types of applications might these potential competitive threats be most appropriately applied to? e.g. low-end devices (tuning forks for wrist watches, clock oscillators for computers) or high-end devices (cell phones)?
10. What technical societies do you belong to? What technical journals do you read? What technical conferences do you attend?
11. Other related comments not addressed by above questions.

C. Results

Responses were received from 37 participants representing 36 companies. As shown in Table I, these responses were obtained from a relatively high organizational level and a relatively broad base of organizational functions. Note, however, that the responses were relatively focused by geographic location, with most coming from companies located in North America. Responses to survey Questions 4 through 9 are shown in Tables II through VII, respectively.

TABLE I
"Supply-side" survey response profile

Organizational level of respondents		
	President / CEO	8
	Vice President	8
	Director	2
	Manager	13
	Non-management	6
Organizational function of respondents		
	Engineering	13
	Sales and Marketing	11
	President / CEO	8
	Applications Engineering	4
	Production / Quality	1
Geographic location of respondents		
	North America	30
	Europe	4
	Asia	3

TABLE II
Frequency of responses to Question 4 (frequency of 2 or greater)

Respondent's impression of the future technical progression of the quartz crystal industry	
Smaller packages	21
Higher frequencies	13
Lower cost	11
Integration into more complex subassemblies	8
Improved electrical performance	6
Incremental progression	5
Innovation primarily from Europe and Asia	3
Manufacturing moving to Asia	3
Increased automation	2
Inverted mesa / strip mesa	2

TABLE III
Frequency of responses to Question 5 (frequency of 2 or greater)

Respondent's impression of disruptive technical threats to the quartz crystal industry			
Digital techniques in silicon			19
	Silicon-based oscillators	6	
	Direct conversion / ZIF	5	
	DSP filtering and processing	2	
	Semiconductor synthesizers	2	
None			10
Synchronization			7
New materials			6
Atomic clocks			5
Micro-electro-mechanical systems (MEMS)			5
Film bulk acoustic resonators (FBARs)			2
Photonic devices			2

TABLE IV
Frequency of responses to Question 6 (frequency of 2 or greater)

Respondent's impression of what to look for to benchmark potential disruptive threats to quartz technology			
Performance			24
	Temperature stability	9	
	Stability over time	8	
	High Q	5	
	General electrical performance	3	
	Maximum frequency	3	
	Operating temperature	3	
	Phase noise	2	
Cost			21
Size			6
Application dependence			6
Atomic clocks			3
Ease of design			3
Ease of manufacture			3
Power consumption			2

TABLE V
Responses to Question 7

Respondent's impression of strengths (labeled with "+") and limitations (labeled with "-") of potential disruptive threats to quartz technology		
Digital techniques in silicon		
	Smaller than quartz	+
	Potentially less expensive than quartz	+
	More capital available in silicon industry to support this threat	+
	More rugged than quartz	+
	Performance not yet there	-
Synchronization		
	Better stability than quartz	+
	GPS signals too weak to be used in-doors	-
	Neither GPS or digital TV signals globally available at this time	-
New materials		
	Typically poorer temperature stability than quartz	-
Atomic clocks		
	Better stability than quartz	+
	Higher cost than quartz	-
	Questionable reliability relative to quartz	-
MEMS		
	Smaller than quartz	+
	Potentially less expensive than quartz	+
	Performance not yet there	-

TABLE VI

Frequency of responses to Question 8 (frequency of 2 or greater)

Where respondents have learned about potential disruptive threats to quartz technology		
IEEE		24
Frequency Control Symposium	8	
UFFC web site	5	
Other IEEE conferences and journals	3	
Web sites (including 5 for the IEEE UFFC site)		11
Customers		8
Others in the technical community		7
Trade magazines (various)		7
University research publications		3
PTTI		2
Suppliers		2
Trade shows		2

TABLE VII

Responses to Question 9

Respondent's dominant impression of types of applications addressed by disruptive technical threats to the quartz crystal industry (high-end applications such as cell phones labeled "H" and low-end applications such as tuning forks and clocks labeled "L")	
Digital techniques in silicon	H, L
None	
Synchronization	H
New materials	H
Atomic clocks	H
MEMS	H, L
FBARs	H, L
Photonic devices	H

D. Observations

Seven summary observations can be drawn from the results displayed in Tables II through VII. First, it is clear from Table II that "smaller, better and less expensive" continues to be the perceived theme of future technical progression of quartz technology. Second, as shown in Table III, digital techniques in silicon are perceived to pose the greatest disruptive technical threat to quartz-based solutions. Further, it is interesting to note that the second most frequent response in Table III was that there is no disruptive threat to quartz-based frequency control solutions. Fourth, from Table IV, it is clear that the stringent performance criteria of frequency control applications are viewed as the primary consideration when benchmarking potential disruptive threats to quartz-based solutions. Fifth, from Table V, we see that the power of invested capital in the much larger silicon industry underlies much of the threat of this technology. Sixth, from Table VI, the dominant role of the IEEE (especially the IEEE Frequency Control Symposium) is shown in alerting current industry participants to potential disruptive technical threats. Finally, Table VII indicates the relative emphasis placed by industry participants on high-end applications.

III. DEMAND-SIDE SURVEY

A. Objective

The purpose of the "demand-side" survey was to determine the propensity (quantitatively) of consumers to purchase cell phones with disruptive size reductions as compared with those products currently available commercially.

B. Methodology

Many methods for predicting customer value appear in the literature of market research, including conjoint analysis, contingent valuation, choice theory, and prospect theory. Shortcomings of these approaches vary, but include their inability to predict cardinal values, rather than ordinal values, and their complexity of implementation. Since we sought a simple and inexpensive means of predicting value, we employed the Direct Value (DV) method [3]. The DV method combines key elements of conjoint analysis and choice theory with findings from prospect theory to arrive at a cardinal measure of customer value in dollars.

It can be shown [3] that the price difference between two competing options, at the same quantity of demand, is equal to the value difference, or

$$P_N - P_0 = \delta V, \tag{1}$$

where P_0 is the price of a baseline product and P_N is the price at which customers are neutral in preference between the baseline product and an alternative product with a change in attribute. This is also seen graphically in Fig. 1. The focus of the DV method, then, is to determine differences in the price customers are willing to pay for the change of a single attribute relative to a baseline product. Obtaining the difference in price is then interpreted as being equal to the difference in value.

In the DV method, survey participants are explicitly asked to compare the price they are willing to pay for the attribute change relative to the baseline product. They are probed with a series of price comparisons with the baseline price fixed and the price for the alternate product with a changed attribute varied. At each price point the researcher notes whether the participant prefers the baseline product or the alternative product at the specified price. The neutral price, P_N, is determined by calculating

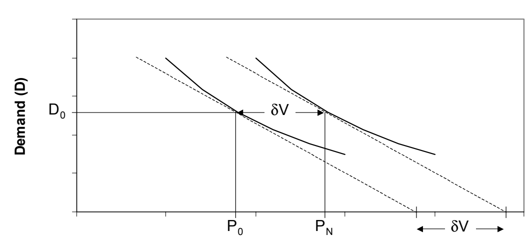

Fig. 1. Demand curves of baseline and alternative products showing the definitions of baseline price, P_0, neutral price, P_N, and value difference, δV.

the price that the sample population is indifferent between the baseline and the alternative product with the changed attribute.

This process is best illustrated with an example. Consider cell phone number storage capacity as the attribute under study. Baseline and alternative products are defined as having differing phone number storage capacity. The number storage capacity and price for the baseline phone are simply selected as the capacity and price at which a standard phone is offered to the market. A range of alternative prices for the alternative phone number storage capacities are selected based on a preliminary survey. The survey instrument is constructed as shown schematically in Fig. 2. For each phone number storage capacity comparison, each survey respondent selects between two options (baseline and alternative) at a series of price points for the alternative.

A frequency of choosing the alternative option, f, is then calculated for each price of the alternative. The neutral price is then determined by the relationship

$$f(P_N) = 50\%. \quad (2)$$

Alternate product values are determined by

$$V(g) = V_0 + \delta V(g), \quad (3)$$

where g is the attribute value.

For the purposes of the current study of radically smaller cell phone sizes, the baseline phone was chosen to be the size of the Motorola VT10 cell phone. The two alternative phones were roughly the size of a pen (10x size reduction) and roughly the size of an ear-plug (100x size reduction).

The sampling frame consisted of three geographically distinct pools. 68 responses were obtained at a regional shopping mall in Champaign, IL, 57 responses were obtained from executives working in downtown Chicago, Il, and 36 responses were obtained from engineers and managers employed by Ford Motor Company in Dearborn, MI. Note that this clearly does not represent a random sample. It does, however, provide some indication of value from multiple response pools. The survey was administered in the first half of 2002. All responses were analyzed, and are presented, in anonymous and aggregate form.

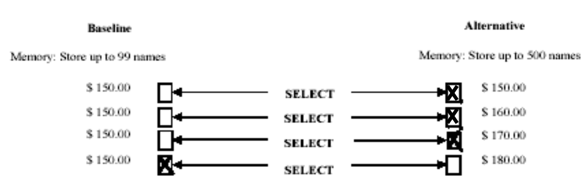

Fig. 2. Sample survey instrument used to employ the direct value (DV) method.

C. Results

Figs. 3 through 6 show the value responses, as a function of cell phone size, of the Champaign, IL (Fig. 3), Chicago, IL (Fig. 4), Dearborn, MI (Fig. 5) and total response (Fig. 6) pools, respectively.

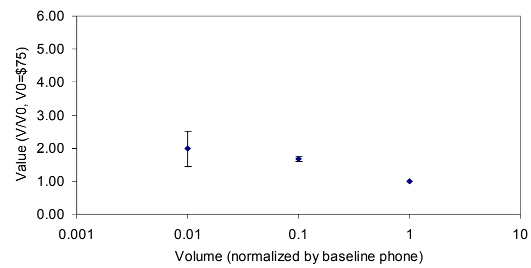

Fig. 3. Normalized value as a function of normalized cell phone volume for the Champaign, IL response pool.

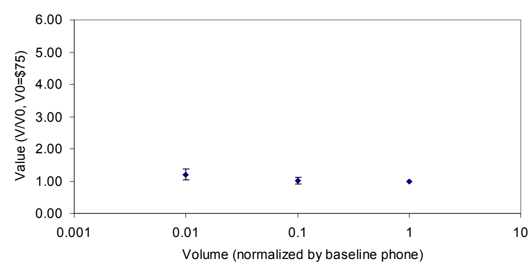

Fig. 4. Normalized value as a function of normalized cell phone volume for the Chicago, IL response pool.

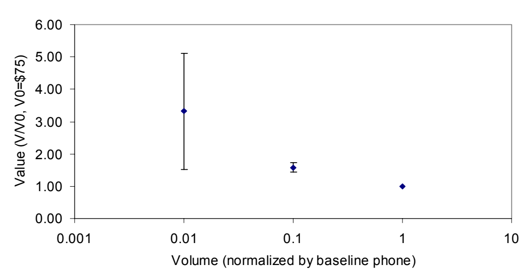

Fig. 5. Normalized value as a function of normalized cell phone volume for the Dearborn, MI response pool.

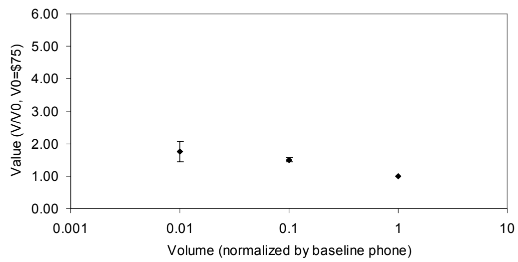

Fig. 6. Normalized value as a function of normalized cell phone volume for the total response pool.

D. Observations

It is informative to use the data of Figs. 3 through 6 to gain insight into the maximum price premium that cell phone customers might be induced to pay for size reductions. This premium can also be inferred to be the maximum sustainable price premium that cell phone producers might be induced to pay for size reductions of the components that comprise a cell phone [4].

In Fig. 5, we see that the maximum price premium of any of the geographic pools is roughly 5x for a 100x size reduction. Similarly, in Fig. 6, we see that the average price premium of all respondents is slightly less than 2x for a 100x size reduction. These two observations can be translated into an estimate that cell phone producers will be willing to pay no more than a 10% to 25% price premium for each halving of component volume (i.e. a $100x \sim 2^7$ size reduction yielding a $2x \sim 1.10^7$ to $5x \sim 1.25^7$ price premium). Further, in practice, such premiums typically only have been realized in the early stages of new product launches and have not been sustained at full volume. As such, it can be concluded that current cell phone users represent a relatively weak economic driver for component size reductions.

IV. Insight from Disruptive Innovation Theory

In summary, the "supply-side" and "demand-side" surveys reveal:

- "smaller, better and less expensive" continues to be the perceived theme of future technical progression of quartz technology;
- digital techniques in silicon are perceived to pose the greatest disruptive technical threat to quartz-based solutions;
- "nothing" is the second most frequently identified disruptive threat to quartz-based frequency control solutions;
- the stringent performance criteria of frequency control applications are viewed as the primary consideration when benchmarking potential disruptive threats to quartz-based solutions;
- the power of invested capital in the much larger silicon industry underlies much of the threat of silicon technology;
- significant emphasis is placed by industry participants on high-end applications; and
- current cell phone users represent a weak economic driver for component size reductions.

Taken collectively, these conclusions can be interpreted in light of Clayton Christensen's insights into disruptive innovation [1]. In *The Innovator's Dilemma*, Christensen describes the progression of customer demand and industry supply for product performance due to sustaining technologies, as shown schematically in Fig. 7.

In summary, Christensen's thesis is that industry progression is described by a series of sustaining technology improvements, defined as those improvements that satisfy the existing customer base. Over time, successive sustaining improvements outpace demand for performance at the high end of the market, resulting in cost-based competition and a gradual retreating to supply customer demand that is defined by higher and higher performance products. It is when this occurs that the potential exists for a disruptive change in the industry. Disruptive change involves the satisfying of non-current customer needs. These non-current customer needs often are characterized by demand for lower performance products in smaller markets and by smaller margins, neither of which are as attractive as current customer needs to most competitors in the industry. As such, only the truly innovative firms will risk leaving the comfort of the high-end markets for these new markets. Ironically, as demonstrated through several case studies in *The Innovator's Dilemma*, it is often precisely those firms, that abandon the comfort of current customer demand, that ultimately succeed in the marketplace.

There are some striking similarities between Christensen's theories of innovation and the current behavior of the portion of the frequency control industry that supplies products for wireless communication applications (see Fig. 8). While competition on performance and size continues, competition on the basis of cost is significant. This is supported by the relatively low premium that cell phone customers are willing to pay for size reductions. The emphasis of current industry competitors on high-end products and stringent performance criteria (i.e. the high end of the market) also is consistent with Christensen's views. The fact that only silicon-based solutions, many of which address low-end applications, are perceived as a threat is particularly interesting. The financial support of the silicon industry by non-communication-industry customers is an important driver in its ability to compete with quartz-based solutions. Also, while not dominant on the list of perceived potential threats, MEMS frequency control solutions are driven by federal funding for non-communications MEMS. Again, financial support from an industry outside the wireless communication industry is driving disruptive threats.

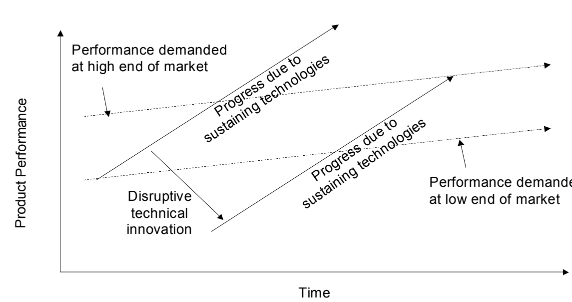

Fig. 7. The progression of customer demand and industry supply for product performance as discussed by Christensen in The Innovator's Dilemma [1].

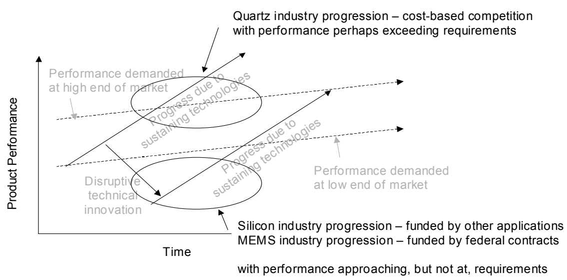

Fig. 8. The progression of customer demand and industry supply for product performance in wireless applications in the frequency control industry.

Thus, the quartz-based frequency control industry is following its existing customer base to higher performance niches and competition based increasingly on cost, while producers of potentially disruptive products are exploring potentially new customers in small markets at the low end of the market.

Taken collectively, the results of the present work indicate that the quartz-based frequency control industry is positioned to be the target of disruptive threats. Whether these threats materialize will depend on several factors. These factors include: the level and duration of funding for competitive threats, the ability of these potentially disruptive technologies to address the performance demanded by the market, and actions taken on the part of wireless systems designers to take advantage products with lower performance but potentially smaller size and lower cost, such as silicon and MEMS solutions.

The question thus arises: "How might a quartz-based frequency control solution supplier respond to this situation in the market?" Possible actions might include proactively establishing a small independent operation to address silicon-based or MEMS-based frequency control solutions and working with cell phone providers to identify applications that can employ components with the reduced performance characteristics currently displayed by these potentially disruptive devices. Note that such a move need not require investment in the technology but, rather, might involve teaming with firms possessing technical strength in these areas. The capability of existing quartz-based frequency control industry firms to supply product to cell phone producers (e.g. applications understanding, sales and marketing infrastructure, customer qualified manufacturing operations, etc.) should not be minimized. The challenge to quartz-based solution providers, however, is to position themselves to both claim a market presence in these new solutions and be able to abandon the portion of the existing market likely to succumb to these threats should disruption occur.

V. SUMMARY

We have studied perceptions of the potential for disruptive technical innovation in this industry by conducting two surveys, a "supply-side" survey of current industry participants and a "demand-side" survey of consumers who might purchase products enabled by such disruption. Our findings identify both where the industry anticipates and ignores the threat of disruption, as well as how the end-user market values products exhibiting radical reductions in size. Further, we have applied Christensen's theories to the results of our study of this industry in an attempt to identify the potential for disruptive innovation.

With the current producers of quartz-based components, we look forward to monitoring the future progression of competition in wireless communication applications in the frequency control industry.

ACKNOWLEDGMENT

The authors gratefully acknowledge Professor Harry Cook (University of Illinois at Urbana-Champaign) for many helpful discussions.

REFERENCES

[1] C. M. Christensen, *The Innovator's Dilemma*, Boston: Harvard Business School Press, 1997.

[2] http://www.ieee-uffc.org/freqcontrol/piezo.html

[3] H. E. Cook, *Product Management: Value, Quality, Cost, Price, Profits, and Organization*, New York: Chapman and Hall, 1997.

[4] B. A. Vojak and C. A. Suarez, "Improving product attribute forecasts at the component and subsystem levels of the value chain," unpublished.