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Methods of Measuring Lock-In Strength and their Application to the Case of Flow over a Cavity Locking into a Single Side Branch Resonator

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METHODS OF MEASURING LOCK-IN STRENGTH AND THEIR APPLICATION TO THE CASE OF FLOW OVER A CAVITY LOCKING INTO A SINGLE SIDE BRANCH RESONATOR

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ABSTRACT

Lock-in is a non-linear interaction between a flow induced noise source and a resonator when their respective frequencies are near each other. Lock-in has been reported under many different labels and for many different applications. There is a need however for a consistent community wide method to measure the strength of lock-in so that data from different tests and different source/resonator combinations can be compared. This paper discusses three methods for measuring lock-in strength. The first, Resonant Response Method, (RRM) subtracts (in the decibel scale) the linear modal response of the resonator to broadband (BB) flow noise from the resonant response when lock-in occurs. The second, Quality Factor Method (QFM) tracks the change in quality factor of the resonant response. The third defines the strength in terms of the difference between peak response and the local BB levels. The RRM is applied to a fundamental test in water of a weak source from grazing flow over a cavity locking into acoustic resonant modes of a single side branch resonator. The major velocity effects are captured in the resonant response to BB flow and not in lock-in strength. However, Strouhal stage number and modal damping is shown to have a significant impact on strength. For two modes, strength versus flow rate using the RRM is compared to strengths obtained using the QFM; on a decibel scale the results are shown to be within experimental uncertainty. However, the QFM is noticeably more difficult to apply. The author recommends the use of the Resonant Response Method as the most tractable measure of lock-in strength.

A. INTRODUCTION

Lock-in is a non-linear interaction between a flow induced noise (FIN) source and a resonator when their respective frequencies are near each other. There is a need for a consistent community wide method to measure the strength of lock-in so that data from different tests and different source/resonator combinations can be compared. It would be a useful tool in determining the effectiveness of active or passive lock-in inhibitors. Any method of measuring strength must be consistent with the concept of lock-in as an amplification of either separate source or resonance phenomena. This paper will discuss the lock-in process and three methods of measuring lock-in strength. The author will then apply the Resonant Response Method (RRM) of measuring strength to a fundamental lock-in test. Using the resultant strength curves lock-in behavior will be developed. A comparison will also be made of the RRM and Quality Factor Method (QFM) for two of the resonant modes.

Lock-in has been reported, under many different labels, even before the introduction of acoustic pressure transducers and documented for many different source/resonator pairs and scores of different applications. The phenomenon has at least been known since the invention of the first organ pipe, where the wind over the open end of a pipe (sidebranch resonator) produces a tone. Professor Rockwell refers to the phenomenon as lock-on[1]. Others refer to it as resonance excitation. The FIN sources known to result in lock-in include flow over cavities,[1,8] flow through orifices[2] and flow around protuberances (cylinders). Resonators include structural resonators, acoustic resonators sheltered from the flow (such as Helmholtz and sidebranch) and acoustic resonators in the flow (such as longitudinal).

In the de-coupled mode, there are many papers that have analyzed FIN sources. Naudascher and Rockwell[3], and Powell[4], present thorough surveys of the FIN literature. Fundamental acoustic and structural resonators are discussed in most textbooks on acoustics and modal analysis. There are fewer analyses addressing the lock-in phenomenon[1]. Howe[5] presents lock-in as an energy balance between generation and absorption. General approaches to the lock-in coupling are aimed at the inception when the phenomenon is in the linear range[6]. Maximum lock-in strength would be associated with a maximum non-linearity and any analysis would need to consider it from a limit standpoint.

A.1. De-coupled Flow Source:

A flow induced noise source (FIN) in a de-coupled mode has one or more narrow band features associated with it. Generally the frequency (f) is proportional to velocity (V) and inversely proportional to a length (L) associated with the source. The non-dimensional form of this frequency is a Strouhal number (S_L):

$$S_L = f\,L / V.$$

Most types of FIN source can have stages associated with them.

A.2. De-coupled Resonator:

When a resonator is excited only by broadband (BB) fluid generated turbulence flow noise, it produces a response amplitude peak in the spectrum whose peak amplitude follows a velocity (V) to a power (n) behavior. BB flow noise is known to act as a quadrapole[7], which radiates as velocity to a power. Experimentally it has been shown that the power can vary with frequency.
In linear units:
Response (linear units) = constant V^n
In decibels the response is given by:
Response (dB) = constant + 20 n log (V).
On a plot of response (in dB) versus log of velocity the above would appear as a straight line of slope 20 times "n". Experimental testing for de-coupled resonant response has shown this linear behavior within experimental uncertainty.

A.3. The Interactive Process

To facilitate understanding the lock-in process let us consider it as a set of black boxes, specifically from the point of view of a signal received at an acoustic transducer (Figure 1). Note, in this section and in the body of this report numbers in circles (⑩) will refer to the "boxes" included in Figure 1.

Any transducer in the test section will record, to varying degrees, effects from three exciters;
1) turbulence generated BB flow exciting the resonator, 2) local flow exciting the FIN source and 3) turbulence generated BB flow directly exciting the transducer ⑧.

① The BB noise directly exciting the resonator will be filtered through all the modal responses (including the modal damping) of the system ④ to the transducer's location. *Thus, a transducer located at the maximum value of the modal (Eigen) vector will record the strongest signal from the resonator mode.*

② The FIN source ⑤ would be excited by local (to the source) mean flow; that signal would be **fed forward** ⑥ through the appropriate modal coupling to excite the resonator, and further filtered through the appropriate modal response ④ to the transducer ⑧.

③ The BB noise directly exciting the transducer could mask either or both signals. *This is why a transducer located where the local flow is low, is a better one to measure strengths.*

When the source and resonant frequencies are far enough apart the system is de-coupled, and completely linear. When the source frequency is near a resonant frequency and only feed forward ⑥ is occurring the interactive process is generally **linear.** When a source and a resonant modal frequency are close enough to each other the modal response of the resonator can **feed back** ⑦ to amplify the FIN source. This **feed back** is the least understood component of lock-in; but is known to be impacted by source-resonator modal coupling, the modal damping, and the level of energy required to activate the coupling.

B. LOCK-IN STRENGTH

This paper discusses three methods for measuring lock-in strength. All three are based on tracking the resonant response.

The **Resonant Response Method** (RRM) tracks the peak amplitude for each resonant modal response during a flow sweep. It separates the interactive resonant response from the expected de-coupled resonant response; thus resulting in strength that measures the amplification effect of the lock-in process. This is achieved by subtracting (in the decibel scale) the modal response of the resonator to de-coupled turbulent generated BB flow noise from the resonant response when lock-in occurs. The author considers this the most consistent measure of lock-in strength as an amplification of the linear resonant response.

The second **Quality Factor Method**[*] (QFM) tracks the change in Quality factor of the resonant response during a flow sweep. The hypothesis is that the increase (and subsequent decrease) in Quality factor is a measure of the lock-in process strength.

Both of the latter two methods are consistent with an interpretation of lock-in as a non-linear feed forward/feed back process and both are considered relatively independent of transducer locations.

The **third measure** defines the strength in terms of the difference (in dB) between peak response and the local spectral broadband levels.

B.1. Resonant Response Method (RRM)

The measure of interactive strength for the RRM is based on separating the effects due to the BB flow ① exciting the resonant mode ④ from the effect of the interaction. On a plot of response amplitude, in dB versus log of pump speed (or velocity) this response behavior to only BB flow, without any interaction, would look like a straight line whose slope would equal

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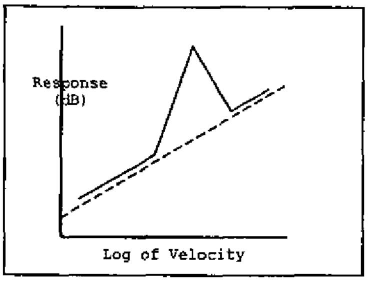
[*] This method as well as others were presented in Reference 1.

the "n" value introduced in section A.2. Any interaction would appear as a set of higher data points above the straight line fit. (See sketch below.)

If the interaction were due only to a linear feed forward ⑥ phenomenon (Figure 1) then one would expect that the measured amplitude would have resulted from a vector sum of the BB flow and the FIN source ⑤ exciting the resonator (as represented by Equation 2). This linear effect of the FIN source on the interaction would be obtainable from a subtraction (in dB). If, on the other hand, the interaction results from a non-linear feed forward / feed back ⑦ phenomenon (i.e. lock-in) then the modal response and the FIN would be amplifying (multiplying) each other. In this case also, the amplification measure of the lock-in strength would be the difference (in dB) between the measured value and the straight line fit to the de-coupled data. In both cases, the measure of interactive strength is the difference (in decibels) between the response curve and the straight line fit to only the BB flow excitation; as noted on the sketch. This strength method produces amplification factors of the original resonant signal, where 20 dB would represent an amplification factor of 10, and 40 dB an amplification factor of 100. It should be noted that this method must utilize spectral data with an unchanging frequency resolution so as not to introduce resolution effects in the response amplitude.



The author considers this the most consistent measure of lock-in strength as an amplification of the linear resonant response.

B1.1 Linear versus non-linear interaction:
An issue is at what strength does the interaction show non-linearity. General representation of a resonant response signal P(f) can be written in the form:

$$P(f) = T_R(f)\, S_{BB}(f)$$

where $T_R(f)$ is the transfer or impedance function containing resonant modal information and location effects, and

$S_{BB}(f)$ is the BB flow turbulent source driving the response.

A narrow band FIN source would have a similar response function to the pressure field of the form:

$$P(f) = T_s(f)\, S_s(f),$$

where $S_S(f)$ is the FIN source strength, and

T_S denotes the transfer function from the source to the pressure field.

Assume for this analysis that: $T_S = T_R = T$. Thus, the combined effect on the pressure field would be:

(Eq. 1) $P(f) = T(f)\,\{S_{BB}(f) + S_S(f)\exp[i\Phi(f)]\}$

where $\Phi(f)$ is the relative phase angle between the BB excitation and the signal from the source.

In terms of an autospectrum, $\hat{P}(f)$:

$$\hat{P}(f) = \sqrt{P(f)\tilde{P}(f)}$$

$$\hat{P}(f) = |T(f)\, S_{BB}(f)| * \sqrt{1 + g^2 + 2g\cos[(\Phi(f))]},$$

where $\tilde{P}(f)$ is the complex conjugate of P(f),

and $g = |S_S(f)/S_{BB}(f)|$.

When evaluated at the resonant frequency (f_r) and converted into decibels, $\hat{p}(f_r)$ results in:

(Eq. 2) $$\hat{p}(f_r) - \hat{p}_{BB}(f_r) = 10 * \log_{10}[\,(1+g)^2 - 2*g\{1-\cos\Phi(f)\}]$$

where $\hat{p}_{BB}(f_r) = 20 * \log_{10}(\,|T_R(f_r)S_{BB}(f_r)|\,)$ is the predicted de-coupled response in decibels, and the term on the right side of equation 2 is what has been defined as interactive strength.

The maximum value for the strength term would be when the two sources are in phase; i.e. the relative phase angle, $\Phi = 0$. Thus a value for the maximum linear response (MLR) would be:

$$\text{MLR} = 20 * \log_{10}[1 + |S_S(f_r)/S_{BB}(f_r)|]$$

A strong enough FIN source to impact the spectrum at lower or higher flow conditions away from interaction will result in data to evaluate the above MLR. If the FIN source is too weak to appear away from an interaction, one can assume its strength must be less than the BB signal.

Once a strength curve has been developed it can be applied to designs and compared to other cases of lock-in.

B.2. Quality Factor Method (QFM):

Professor Rockwell in Reference 1 examines using the Quality factor as a measure of lock-in strength. In the reference, the Quality (Q) factor of the resonant response is tracked during flow sweeps. The hypothesis is that the increase (and subsequent decrease) in Q factor is a measure of the lock-in process strength.

The Q factor is calculated based on the ½ power point formulae of: $Q = f_{peak} / \Delta f$

where f_{peak} is the frequency of the peak amplitude,

Δf is the difference in the two frequencies,

and where the amplitude value is equal to $\sqrt{2}$ of the peak linear amplitude.

For this method to be effective the spectral resolution has to be fine enough to capture the rapidly increasing Q factor. If the resolution is not fine enough the high values of Q will be truncated. Thus finer and finer resolution data points need to be taken where lock-in is suspected until the calculated Q values cease to increase.

B.3. Third Method

The third measure defines the strength in terms of the difference (in dB) between peak response and the local spectral BB levels. The weakness of using this method is that local BB spectral response ③ is largely governed by the location of the transducer and not anything related to the lock-in process. The modal response signal at a transducer is a function of the location of the transducer with respect to the mode shape and changes with the BB ①and FIN excitation ⑥of the mode. However the BB local spectrum is independently driven by the BB flow about the transducer location ③.

Consider the test to be discussed in the next section: Due to the location of the P1 transducer (see Figure 2), it will measure high modal response, but low BB levels since it is sheltered from the flow; thus a high difference in "strength" value. On the other hand, the location of transducer P8 is such that its response to ¼ wave type modes is low, but it is in a high flow region; thus it will measure high levels of BB flow noise. For P8 there would be small differences and the "strength" by this method would be low. The difference of strength as measured by this method for these two transducers would be significantly different. Thus showing that this method is not a valid measure of lock-in strength, as a valid measure of strength should be independent of transducer location.

The author does not consider this a valid measure of lock-in and there will be no application of this method.

C. EXPERIMENTAL TEST

A test was performed to examine measures of lock-in strength and develop insight into the lock-in process. It was a fundamental test of a flow-induced noise (FIN) from flow over a rectangular cavity locking into a single side branch resonator.

C.1. Facility

The lock-in facility is shown as Figure 2. The facility was designed to have low damping values. Thus, soft aluminum seals rather than rubber was used at critical junctions. The test section cross section was a 2" by 2" square cylinder with a rectangular slot ½" long by 2" along the floor. The sidebranch was mounted directly below the slot. The modal damping of this sidebranch was measured from 0.2% to 0.7% of critical damping. The test sequence requires that a gas extraction system be in the loop at all times. Data were taken only when there were no visual signs of air in a vertical acrylic pipe in the return loop piping, and no audible indications of air could be noticed when listening at the downstream cone of the test section. A static pressure of 20 psig was maintained in the area of the cavity until the pump head forced the pressure higher; above 70% pump speed.

Pressure transducers were positioned to measure the response of each mode and the mode's ability to propagate through the system ④. P8 was located on the floor of the square test section just downstream of the cavity. Transducer P1 is located near the bottom of the resonator and was expected to have the highest modal response ④ of all the transducers (it has the highest Eigen vector value) for all the 1/4 modes.

C.2. Test Results

It is known that damping is one of the significant parameters controlling lock-in and for these tests was carefully measured every day data was taken; before the start of a test sequence and at the end of the sequence. The damping for each sweep was the average of that taken at the start and end of the sequence.

It was determined that a resolution of 0.5 Hertz and 40 averages was necessary to obtain repeatable calculations. The half-power point method was used to calculate damping and Q factors.

C.2.1 FIN Source Behavior ⑤

The source in all of the testing is flow over a rectangular cavity slot, ½" in the flow direction by the width of the test section (2"), located in the floor of the test section. This cavity flow source generates a set of Strouhal stages. However, none of the pressure transducers in the test facility showed any signs of the source in the de-coupled mode; i.e. when the stage source frequencies are not near any of the resonant standing modal frequencies.

The only way of obtaining the source frequencies of the de-coupled signals was by using a Coherence Technique. This technique is based on measuring the coherence between two transducers. It was applied to the transducer near the bottom of the resonator (P1) and the transducer located just downstream of the slot (P8). The number of averages used was greater than 100. Coherence data was taken at 5 different low flow rates. Four Strouhal values were fitted to the source frequency data. The stage lines designated by "first" to "fourth" fit close to a standard recursive Strouhal (S) representation of: $S_n = 0.6 * (n - \frac{1}{4})$, with n = 1 to 4. Included on Table 2 is the experimentally determined and analytical representation of the Strouhal numbers. The above descriptors will be used throughout the rest of this report.

C.2.2 Resonator ④

The resonator is a sidebranch resonator whose inside cross section matches the cavity dimensions. The resonator was fabricated of aluminum and had a rectangular cross-section of internal dimension of 0.5" x 2.0" and wall thickness of 0.25". The resonator is constructed of soft thin aluminum so as to take advantage of compliance on the effective speed of sound; this effect reduced the speed of sound by about 40%. The installed resonator inside length is 4 1/2 feet long. Lock-in was achieved with this single sidebranch resonant modes of ¾, 5/4, 7/4, and 9/4 standing modes (open-closed). Table 1 lists the modal frequencies and modal damping for the resonator modes. The experimental modal damping values that are shown are averages of the damping data for eight days of testing (with the pump running at the reference speed). The standard deviation of that data is well within the expected experimental uncertainty. Theoretical damping values based on viscous shear are also included in the table, these are based on the formula for percent of critical damping (ζ): $\zeta = 100\,(2\,\nu / \omega)^{1/2}$
where ν is the dynamic viscosity (0.00144 in^2 /sec),
and ω is the frequency in radians per second.
The predicted damping does not include effects of end effects, radiation and structural damping and may explain some of the differences shown on the table.

Table 1 - Modal Frequencies & Damping

Mode Type	Freq. (Hz)	Modal Damping (per cent of critical)		
		Meas-ured	Stand. Dev.	Predicted
¾ mode	270	0.40	0.05	0.16
5/4 mode	455	0.28	0.04	0.13
7/4 mode	640	0.60	0.08	0.11
9/4 mode	840	0.52	0.06	0.09

All the modes (except for the 1/4) were well isolated from longitudinal and structural resonant modes. The contamination of the 1/4 mode by other nearby resonators was similar to that observed for resonators that was previously tested. Consequently there are no measured damping values and no interaction data.

The measured damping is at least a factor of 2 higher than predicted. The crossing of the source and resonant lines are noted as potential interaction points on subsequent figures.

C.2.3 Modal Response Plots

Modal response, for each mode, is the peak magnitude from autospectrum about each modal frequency. The modal response plots are in pressure amplitude in decibels (reference to one psi) versus log of pump speed. Response plots were generated for the first five modes from the transducer located at the bottom of the resonator (P1); the data was taken on 8 separate days. Most of the data was obtained as the flow rate was increased so as to avoid any hysteresis effects. The response plot for the 3/ 4 to 9/4 modes are shown as Figure 3 to 6. Included on the figures are the mean velocity and the velocity where the source stages would intersect that resonant mode. The straight dashed line and n values on each figure represent the predicted uncoupled BB response. On each of the figures (Figure 3 to 6) a straight line was fitted to the data believed to not have any interaction occurring. The straight line and its "n" value are included on each figure. The response data are repeatable within ±2 dB except where the strong interaction with the first stage occurs.

The plot for the ¾ mode (Figure 3) clearly shows an interaction beginning at where the second stage crosses the modal resonant frequency at about 11 ft/sec and a strong interaction of at least 20 dB beginning just before where the first stage crosses the modal frequency. The maximum interaction strength with the first stage shows very large variation with time. There is no sign of interaction with the third stage. The falloff above 60% pump speed may be due to additional radiation damping affecting this mode or the BB energy affecting this mode being absorbed into the higher (5/4) mode locking into the first stage. There is no sign of interaction with the third stage. The 5/4 response (Figure 4) shows the same pattern as the 3/4 mode with an interaction beginning where the second stage intersection occurs, and a strong interaction, stronger than with the 3/4 mode, beginning just before the first stage intersects the modal frequency. The large variation of first stage interaction, as with the 3/4 mode response, may be due to structural interaction. The 7/4 mode (Figure 5) has a damping more than twice that of the 5/4 mode, but repeatable, modal damping. Both the

7/4 and 9/4 (Figure 6) modal responses show an interaction starting about the second stage intersection point. The 9/4 mode is showing a weak interaction with the third source stage.

C.2.4 Measuring Interaction Strength

Figures 7 to 10 present the resulting interactive strength for each mode versus pump speed, with the equivalent velocity included on each graph. The strength was obtained by subtracting in dB the predicted BB response from the measure response data. As with the response plots, flags were positioned at the pump speeds where the Strouhal stage frequencies intersect the modal frequency. The symbols represent the interactive strength data taken on the eight days with the curve drawn through the average values except where some smoothing was necessary. Arrows were positioned at maximum strength values; one for each interaction noted. The dashed horizontal lines on Figures 5 to 8 are to help denote where the strength curve reaches the 3 dB, 6 dB (2 times), 12 dB (4 times), and 24 dB (24 times) values.

The 3/4 mode interactive strength curve (Figure 7) shows interaction with the second and first source stages. The data is repeatable within the expected error band except for where the first stage interaction becomes strong. The strong interactive strength with the first stage varies from about 17 to 37 dB. The negative strength values above 60% pump speed may be due to additional radiation damping or energy being absorbed into the higher (5/4) mode locking into the first stage. The 5/4 mode interactive strength curve (Figure 8) shows interaction with the third, second and first stages. The peak strength of the third stage interaction was 5dB and occurred at 15 ft/sec (27% pump speed). Data repeatability was reasonable, except for the first stage strong interactive peak which varied from 22 to 38 dB. Both the ¾ and 5/4 strength curves show a region of negative strength after the second interaction "ends" and before the first stage interaction "begins". What may be occurring is that both stages may still be interacting with the mode but mutually interfering with each other. The 7/4 mode interactive strength curve (Figure 9) shows interaction with the third and second stages. The top pump speed was not high enough to excite first stage interaction. The higher damping for this mode explains the weaker interaction strength as compared to the 5/4 and 9/4 modal responses. The 9/4 interactive strength curve is shown on Figure 10, this curve shows clear interaction with the third (6 dB) and second stages (9 dB). The interactive strength curve is weak for the 9/4 mode, but stronger than the 7/4 mode curve. This is due to its lower damping. There was definitely no interaction of the fourth stage with any of the modes.

The interactive strength data for all the modes were cross-plotted on a source resonant plot so as to obtain a complete picture of all the interactions (Figure 11). Symbols were used to position the peak interaction "location" on the graph and a straight dashed line through the origin was fitted to those points. The Strouhal numbers representing those three lines were calculated and included on the figure (also on Table 2). The width and colors of the horizontal lines on the graph represent the strength of the interaction. The thin green line represents strengths between 3 and 6 dB, the thicker green between 6 and 12 dB, blue for strengths between 12 and 24 dB, and the thickest yellow line for strengths greater than 24 dB. Figure 11 shows that there is frequency pulling (non-linear behavior) with strengths down as low as 3 dB; due, not to the interaction strength, but that the interaction distorted the Strouhal frequency. The first stage lock-in strength is more than 20 dB higher than the second stage. The third stage interaction is believed to be only a linear combination of source and resonant response. It should be noted that compared to the stage effects on strength, the strength variation in velocity is negligible.

Effect on Source Frequency

Table 2 presents the Strouhal numbers at peak interactive strength and comparison to the values obtained for the source stages in the uncoupled mode using the coherence approach and the analytic recursive formula. The table also shows percent difference. It is clear that the interaction has introduced lowering of the Strouhal numbers as compared to the de-coupled Strouhal source values.

Table 2 - Strouhal Values

Stage No.	Analytic Value	Based on Coherence	Based on Interactive Strength	Difference
1	0.45	0.47	0.41	13%
2	1.05	1.05	0.90	14%
3	1.65	1.75	1.31	25%

Observations

a) The source stages are all too weak to appear above the broadband (due to turbulence) noise spectrum.

b) The BB response shows strong velocity variation; at least velocity raised to the second power. The impact of velocity on interactive strength is much less.

c) Interactive strength:

- Interactive strength varies significantly with Strouhal stage number. The first stage is quite strong - 30 to 40 dB. The second stage is significantly weaker but still showing lock-in; the third stage may only be showing linear interaction-strength - less than 6 dB.

- Interactive strength varied with modal damping. The interactive strength with the 7/4 mode with higher modal damping is measurable lower than the interaction with the 5/4 mode, which has half the modal damping.

d) None of the interaction caused resonant frequencies to be pulled to match Strouhal frequencies.

e) The P1 response curves show a variation of less than 5 dB except when strong interaction occurs.

f) The scatter of the data points about the first stage interaction peak may be due to several things:

- The expected limit cycle that most likely occurs for the strong interaction / lock-in may contain a missing component, for instance, a fluid-structure interaction.
- The tightness of the curve suggests that a small uncertainty of the measured velocity of ±5% would cover the variation in strength noted on the graph.

C.2.5 Q factor as a measure of interactive strength
A separate sweep was performed to develop comparison between the Resonant Response and the Q Factor Methods. For the initial sweep the spectra were taken at the same resolution of 1/2 Hertz. This resolution was fine enough to calculate the Q factor (and damping) at low or linear interaction; however it is not fine enough for calculating Q factors when significant interaction occurs. Signal processing manuals suggest at least six bins between Δf points for calculating Q or damping, but the author was able to get repeatable results with Δf containing a lower number of bins. Hence, those speed points with high Q factors were repeated at finer resolution.

Figures 11 and 12 present the comparison of the two methods of calculating interactive strength for the 3/4 mode and 5/4 mode. The Q values are presented in dB referenced to a Q=1. The Q factors are presented in this form because of the order of magnitude change in Q and so as to directly compare the two methods of measuring strength. The scale on the right applies to the Resonant Response Method of calculating interactive strength (resolution of ½ Hertz- triangles). The scale on the left applies to the Q factor calculations; both scales have the same full-scale range of 40 dB. The 1/2 Hz resolution Q factor data are shown as diamonds with dashed lines connecting them. This resolution, as expected, was not adequate for calculating high Q factors. Additional data was taken when there was appreciable interaction with the resolution finer by a factor of 4 (1/8 Hz resolution - square symbols), and at the strongest interactive flow points the data was taken with an even finer resolution of 1/16 Hz (circle symbols). The solid orange line represents the curve joining the Q factors with adequate resolution. For both the 3/4 and 5/4 modes the Q factor curve and the curve based on amplitude agree within experimental uncertainty for most of the flow range.

To obtain agreement on the strength as a measure of amplification, a reference Q factor representing one without any interaction would need to be applied to calculating the Q values in dB, rather than the value of 1 used herein. Based on the figures, a reference Q value of 40 would be necessary for both methods to be in agreement.

Observations
The Q factor Method can be used to calculate interactive strength if one is careful to use fine enough resolution to capture the high Q values. It is also necessary to develop a reference Q value for each mode in order to convert Q values to strength values. The drop off of the strength at speeds above which the first stage interaction occurs with the ¾ mode is noticed using both methods, but not as steep when using the QFM.

It is interesting to consider both methods as a valid measure of the lock-in process. The lock-in process is expected to initially utilize only the energy in the spectral neighborhood of the resonant feature. Consequently, for unchanged spectral energy balance, during lock-in the higher feature amplitude must arise from the feature narrowing (higher Q factors). Thus, both the amplitude and Q factor would be expected to increase almost in lock step. Only when the non-linear process is obtaining additional energy from other resonant features (harmonics or sub-harmonics), or other frequency ranges, should it be expected that both methods would not produce the same results.

However, QFM is not as tractable as the RRM because of the need to repeat with finer resolution those flow points with higher Q values until the Q value stops increasing.

D. CONCLUSIONS

Two valid measures are presented of lock-in strength as an amplification of resonant response; the Resonant Response Method (RRM) and Q Factor Method (QFM). The RRM was successfully applied to a fundamental test of a single sidebranch resonator locking into a weak source due to flow over a rectangular cavity. It was shown that the major velocity effects are captured in the resonant response to BB flow and not in lock-in strength. However, Strouhal stage number and modal damping was shown to have a significant impact on strength. Lock-in occurred between four resonant modes and three-source stages. Interaction starts about a flow where the first, second, and third stage de-coupled frequencies equal the modal frequencies. The interaction is strongest for the first stage (20 dB and higher), noticeably weaker for the second (10 to 15 dB), and quite weak for the third stage (3 to 5 dB). Variation in damping between modes results in measurable variation in strengths. Variation of strength with velocity is much less significant. There is no sign of interaction with the fourth stage. Similar stage lock-in behavior has been noted in testing of slots and Helmholtz resonator pairs in air[9], but does not necessarily agree with interactions noted in other tests.

The QFM, while a valid method, is not as tractable and more difficult to implement than the RRM. It is recommended that the Resonant Response Method be used to calculate lock-in strength in the fluid acoustic community so that data from different tests and different source/resonator combinations can be compared.

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7) Modern Methods in Analytic Acoustics: Lecture Notes; by G.C. Lauchle; Springer-Verlag; copyright 1992.
8) Fluid Dynamics of a Flow Excited Resonance, Part II: Fluid Acoustic Interaction; By P.A. Nelson, N.A. Halliwell, and P.E. Doak; J. Sound & Vibration; February 1983.
9) Experimental Investigation of Flow-Induced Cavity Resonance; by P.J. Zoccola; NSWCCD-TR-2000/010; June 2000

Figure 1

Source - Resonator Lock-in

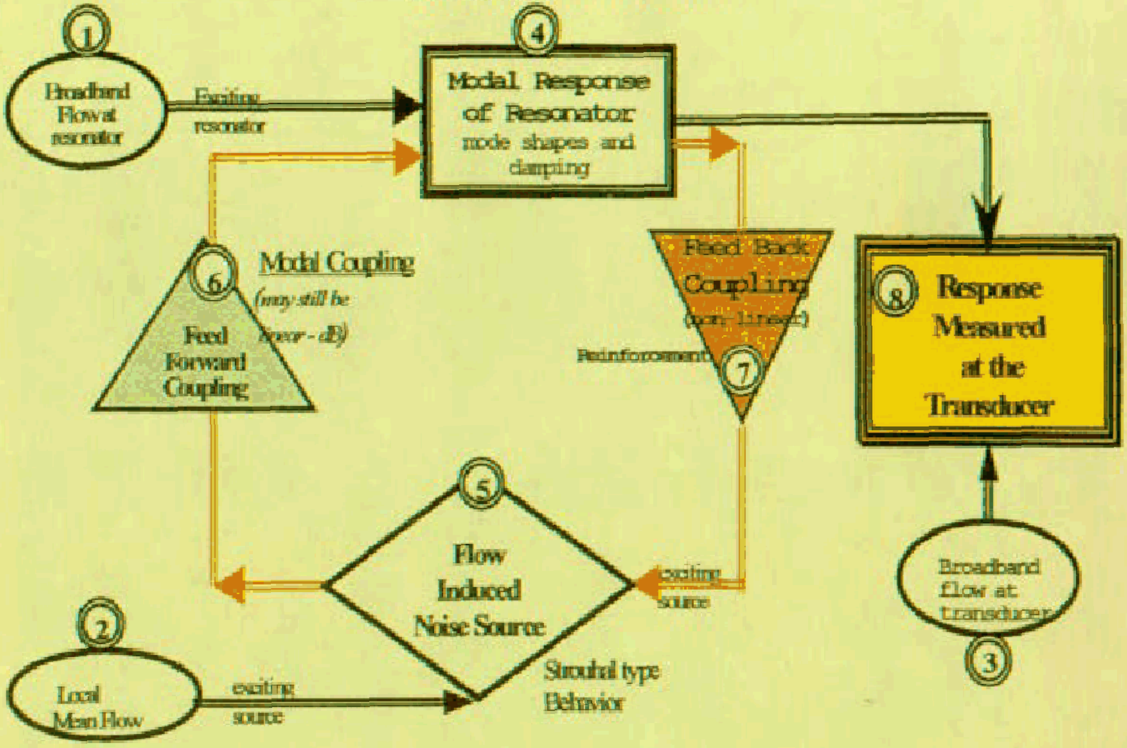
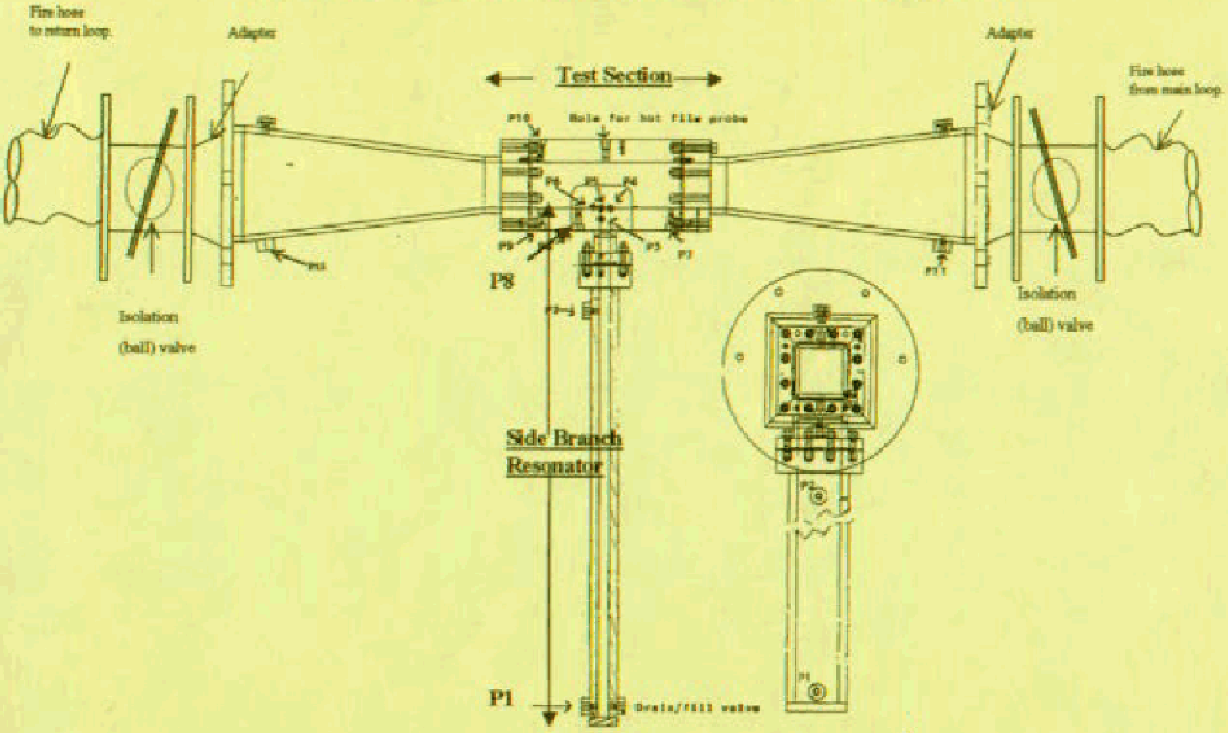


Figure 2
Lock-in Test Facility with Sidebranch Resonator



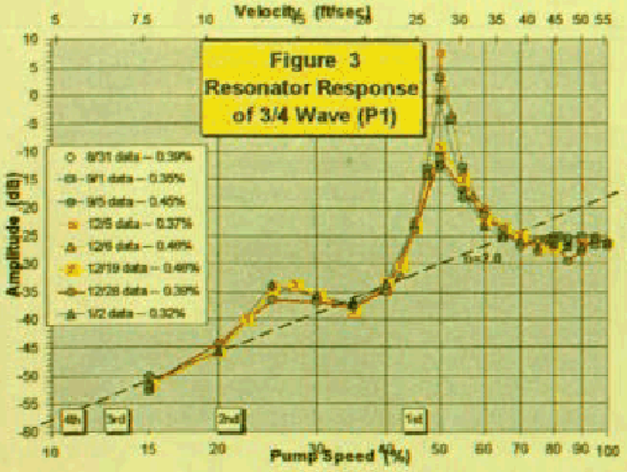


Figure 3
Resonator Response
of 3/4 Wave (P1)

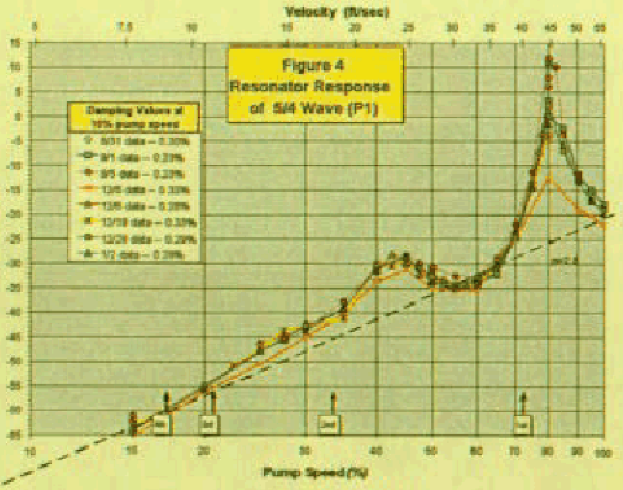


Figure 4
Resonator Response
of 5/4 Wave (P1)

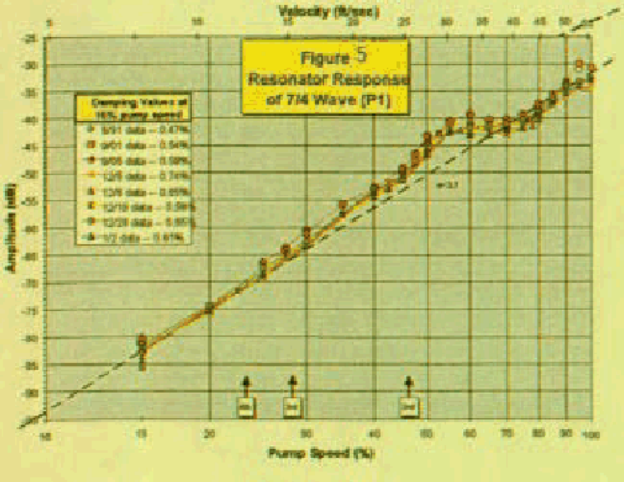


Figure 5
Resonator Response
of 7/4 Wave (P1)

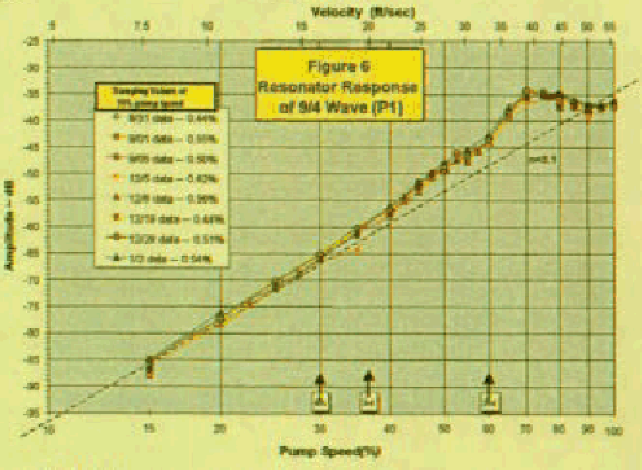


Figure 6
Resonator Response
of 9/4 Wave (P1)

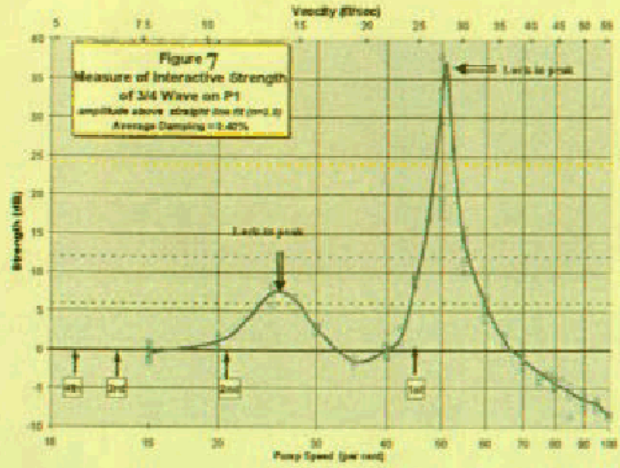


Figure 7
Measure of Interactive Strength
of 3/4 Wave on P1
amplitude above straight line fit (n=2.5)
Average Damping = 0.40%

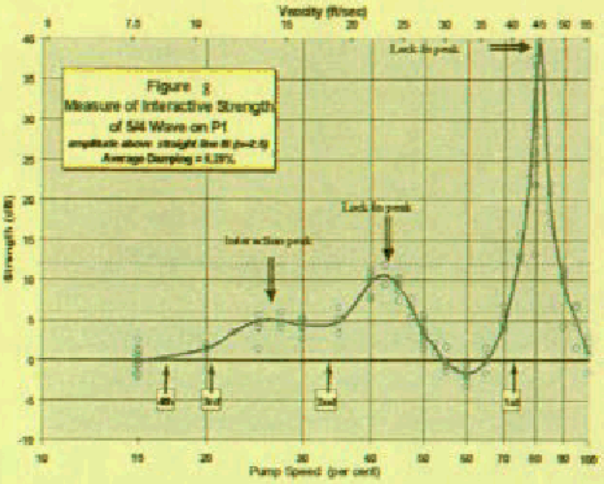


Figure 8
Measure of Interactive Strength
of 5/4 Wave on P1
amplitude above straight line fit (n=2.5)
Average Damping = 0.28%

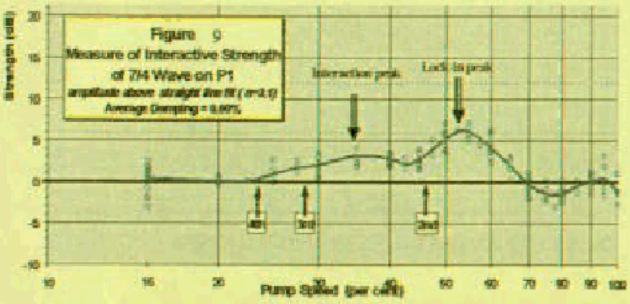


Figure 9
Measure of Interactive Strength
of 7/4 Wave on P1
amplitude above straight line fit (n=3.5)
Average Damping = 0.60%

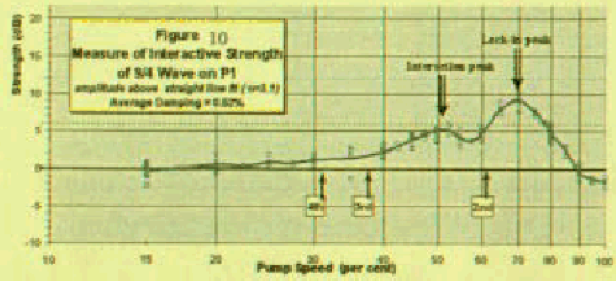


Figure 10
Measure of Interactive Strength
of 9/4 Wave on P1
amplitude above straight line fit (n=3.5)
Average Damping = 0.52%

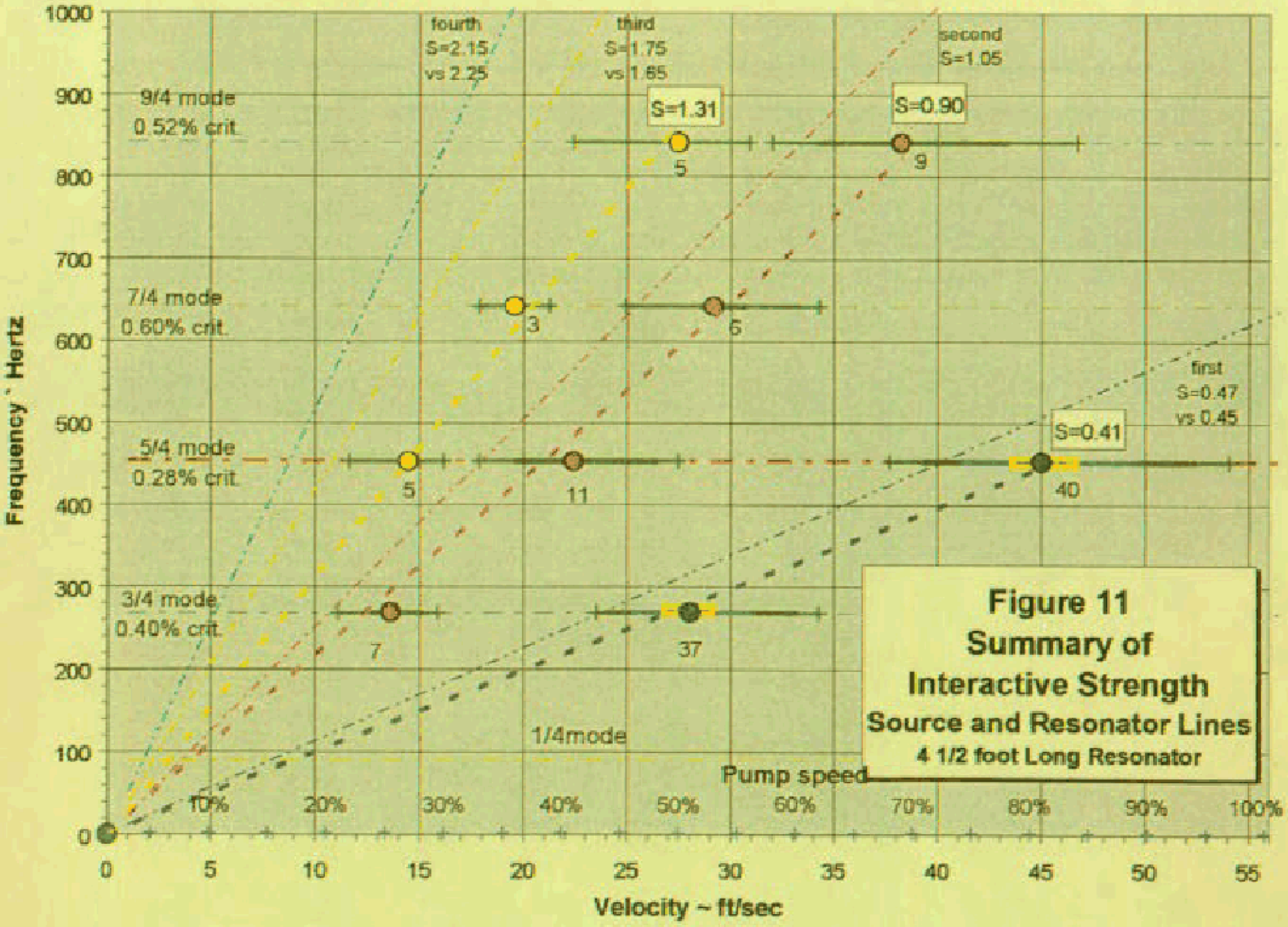


Figure 11
Summary of
Interactive Strength
Source and Resonator Lines
4 1/2 foot Long Resonator

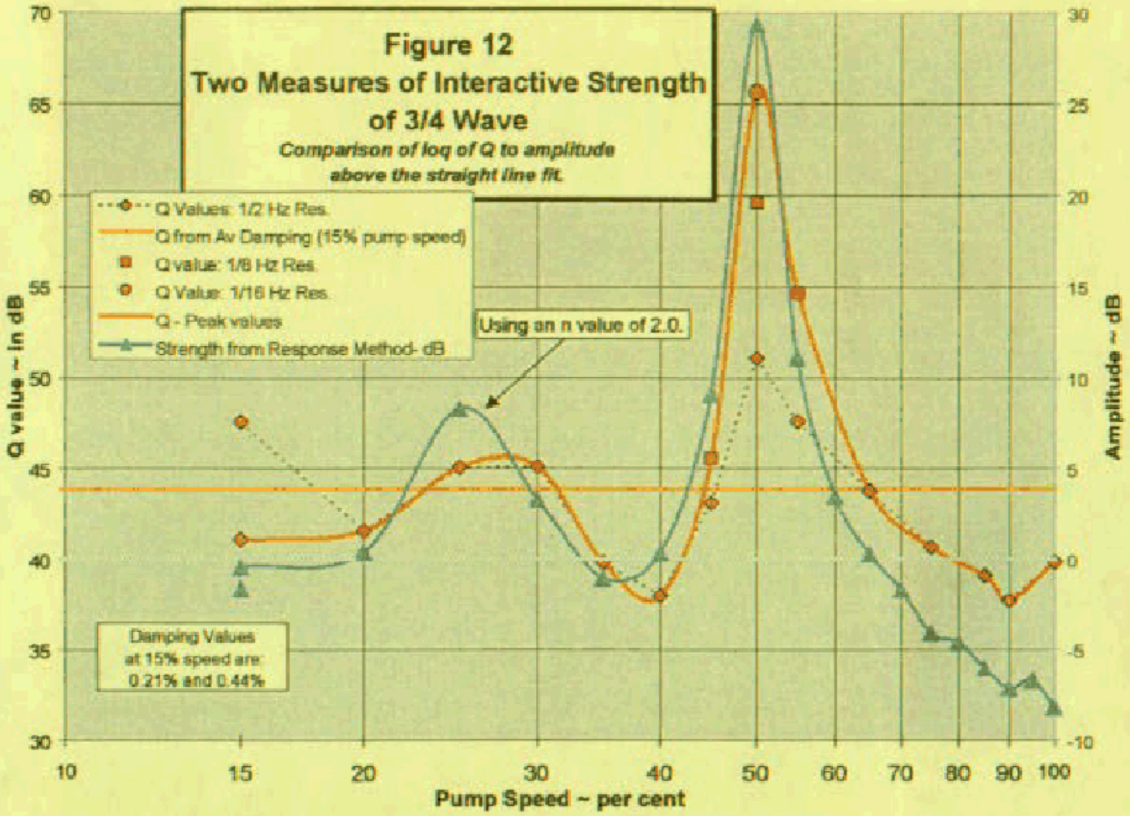


Figure 12
Two Measures of Interactive Strength of 3/4 Wave
Comparison of loq of Q to amplitude above the straight line fit.

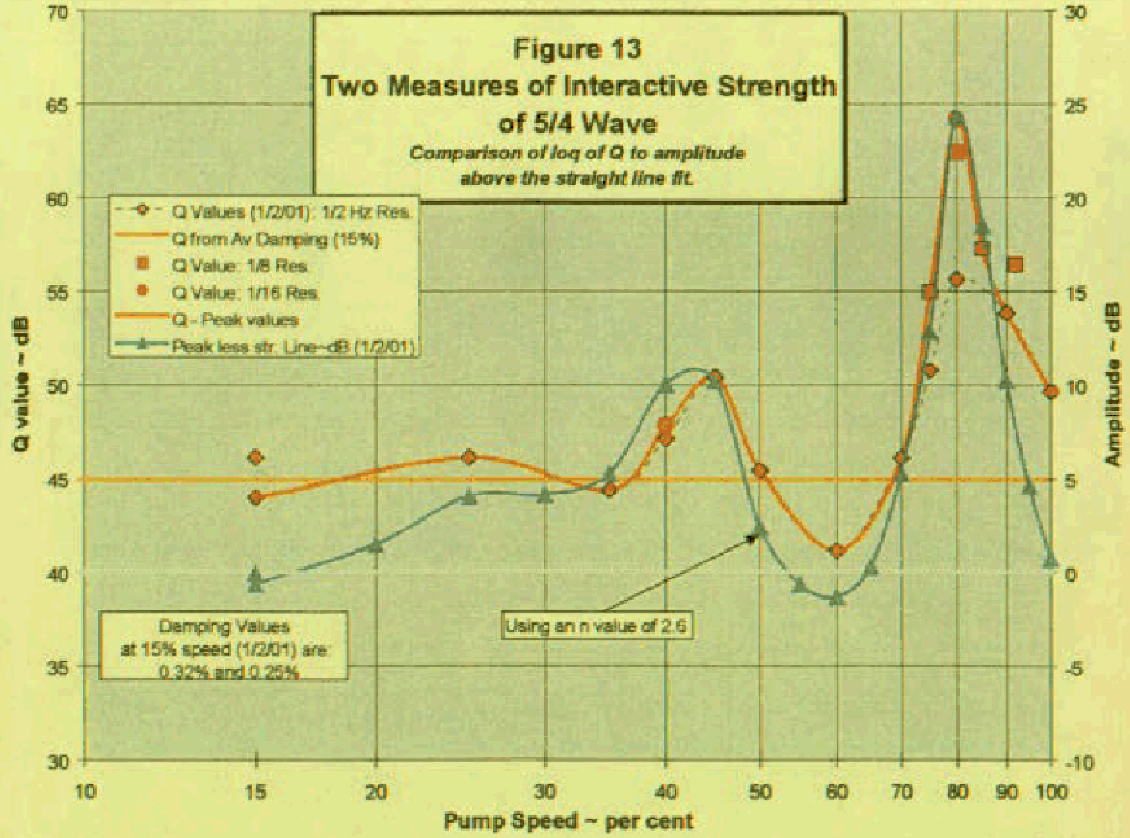


Figure 13
Two Measures of Interactive Strength of 5/4 Wave
Comparison of loq of Q to amplitude above the straight line fit.