Visualization of Unstable Regions in High PRF Doppler Using Baker Diagrams

Ahmed A. Morsy

Abstract — **This paper attempts to develop a better understanding of the high pulse repetition frequency (HPRF) mode used in ultrasound systems with pulsed wave Doppler capability. It provides both intuition and mathematical analysis to help answer the fundamental question of whether the HPRF mode is feasible at any given depth using a visualization tool called Baker diagrams. The tool provides a better understanding of many of the limitations associated with the HPRF Doppler mode.**

Keywords— **Doppler, medical ultrasound, pulse repetition frequency, high PRF.**

I. Introduction

The first practical Doppler velocimeter was produced by Baker in 1964 [1-3]. Shortly after, Doppler ultrasound has established itself as an essential mode for ultrasonic vascular diagnosis. Pulsed wave (PW) Doppler has the advantage, over continuous wave (CW) Doppler, of range gate localization. This localization is adjusted by controlling the depth of the Doppler gate along the Doppler line of sight. There are, however, two main inherent limitations associated with PW Doppler. The first limitation is the existence of an upper bound on the value of the pulse repetition frequency (PRF) used, set by the depth of the Doppler gate. This limitation is a direct result of the typical values of the speed of sound in tissue. Increasing the depth of the Doppler gate may force the system to switch to a lower PRF value. The second limitation is the existence of a lower bound on the value of PRF needed to adequately sample and correctly visualize the interrogated velocities within the Doppler range cell. This lower bound is dictated by the Nyquist limit, and its violation results in the phenomenon known as Doppler aliasing. The Nyquist limit dictates that the maximum Doppler frequency that can be detected without aliasing is one half the used PRF. Aliasing causes the aliased portion of the Doppler spectrum to appear with a reversed polarity and a wrong magnitude. While Doppler aliasing in color Doppler is sometimes used to the advantage of the user to identify the presence of high velocity jets, it is considered a severe disadvantage for PW Doppler as it compromises the usefulness of the Doppler spectrum. In particular, aliasing limits the user's ability to perform measurements on the Doppler spectrum. Since the quantitative capability of Doppler is what gives this mode its main strength, aliasing is considered an undesirable phenomenon in PW Doppler.

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The two fundamental limitations associated with PW Doppler interact if the depth of the Doppler gate is increased to an extent that would force the system to switch to a lower PRF value, and if this new PRF value causes aliasing of the Doppler spectrum. In this case, the user may choose to switch to the high PRF Doppler mode (if it is supported by the ultrasound system). In this mode, more than one ultrasonic pulse travel in tissue at the same time and hence more than one Doppler gate are active simultaneously. This means that the system transmits a new Doppler pulse before it is done with receiving echoes from the previous pulse. Thus, echoes from more than one consecutive pulse add together causing range ambiguity. The ambiguity is avoided if only the Doppler gate of interest (the deepest gate, which is referred to as the primary gate) lies on or within a blood vessel. The measured Doppler spectrum is attributed, in this case, to velocities within the primary Doppler gate. In reality, even if other (secondary or tertiary) Doppler gates do not interrogate any vessels, other issues may still arise from problems related to the dynamic range of the system. These problems are primarily seen if any of these gates interrogate a slowly-moving target in such a way that the return from this target may dominate the received signal. They also arise if one of the active Doppler gates is too close to the transducer face. The latter argument, as shall be explained later, causes the existence of a restricted zone adjacent to the probe where no Doppler gates are allowed to be present if the system is in the high PRF (HPRF) mode.

The activation of the high PRF mode, thus, has the advantage of avoiding aliasing despite the violation of the depth-dependent upper bound on the PRF value (Nyquist limit). Four main factors need to be taken into consideration for a successful implementation of the HPRF mode: the number of active range gates, the system's transmit/receive set-up time in the Doppler mode, the values of PRF available to the user, and the system's dynamic range. The first three factors and their effect on the performance of the HPRF mode are discussed in the next section. The last factor is beyond the scope of this paper, and shall be only discussed briefly wherever it is interrelated to the other factors. The fundamental questions that we shall try to answer are as follows: is the HPRF mode always feasible at any given depth? When is it not feasible? And why? This paper shall provide a mathematical analysis and a visualization tool that should provide the intuition needed to answer the above questions.

II. Problem Formulation

To obtain a range gate at depth r = R, the returning signal is sampled at time lag Tr given by:

$$Tr = \frac{2R}{c} \quad (1)$$

where c is the speed of sound in tissue. Tr is measured relative to the pulse transmission time. After a time interval Ts, the next pulse is transmitted and another sample of the signal is taken after the same time lag, Tr. The time lag of the second sample is thus Tr+Ts, and it corresponds to a second range gate at depth Rs, given by

$$Rs = \frac{cTs}{2} \quad (2)$$

The collected Doppler samples are the result of superposition of returns from the ranges R, R+Rs, and in general from R+n.Rs, where n is a positive integer. Signals from more distant range gates are, in general, attenuated beyond the noise level. This is especially true if the gain of the system in the Doppler mode is optimized relative to the shallowest range gate, as is the case for the “regular” PRF mode (normal PW Doppler operation). In the HPRF mode, the range gate of interest is the deepest range gate, and the system’s Doppler gain needs to be adjusted accordingly. Another practical issue is related to the set-up time required by the system to be ready to receive a new sample after it is done with transmitting a given pulse. The time length of the pulse repetition period (PRI) cannot be fully budgeted to account for the round trip time of Doppler pulses, as the systems set-up time consumes a portion of this budget.

$$PRI = RTT + Tsu \quad (3)$$

$$PRF = \frac{1}{PRI} \quad (4)$$

where RTT is the round trip time of the pulse and Tsu is the set-up time of the system. Based on this notation, we shall discuss three separate cases. First is the case where there is only one range gate (the primary range gate). This is the known regular PRF mode. We then discuss the cases where HPRF is used with two, three, and more than three active range gates.

1. Regular PRF

This case is illustrated in Fig.1. Only the primary range gate is active and is located at depth r. According to Eq.3, the minimum possible PRI (which corresponds to the maximum allowable PRF at depth r) is given by:

$$PRI_{min} = \frac{2r}{c} + Tsu \quad (5)$$

This relationship represents a straight line in the PRI-Depth plane, with a slope of 2/c and an intercept that equals Tsu as shown by the dashed line in Fig. 1. In this case, and referring to the above analysis, one can see that Tr = Ts.

In practice, only a finite set of PRF values are available to the user and the curve for PRImin is shown by the staircase line in Fig1. The number of available PRF’s in this case is 8 with values shown on the left hand side of Fig1. It can be seen that there is a minimum depth below which no Doppler gates are allowed to be present. It must be noted that the depths shown exceed those typically used in medical ultrasound. This illustrates that the presence of low PRF values in the system is not dictated by the depth limitation,

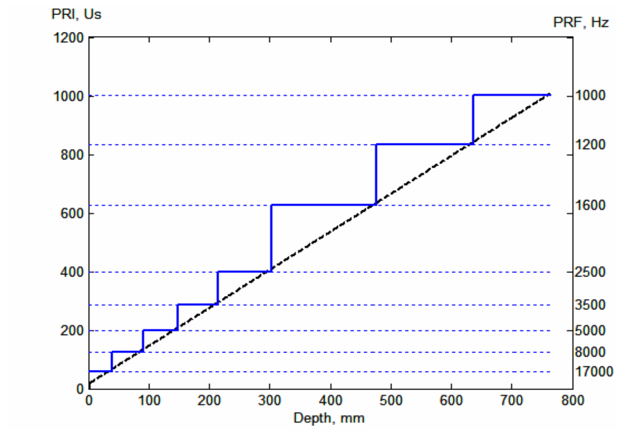

Figure 1. Regular PRF mode.

but rather by the need to monitor slow flow conditions with better resolution. The PRI-Depth diagram as shown in Fig. 1 shall be called Baker diagram in honor of Donald W. Baker for his pioneering work on PW Doppler [2].

2. High PRF with two active range gates

An example of this case is shown in Fig. 2. In this case, the shallow range gate is governed by Tr as indicated by Eq. 1, while the deeper (primary) range gate is separated from the first by Ts. The returning echo is from both gates, but this mode works well only under the assumption that most of the signal is coming from the primary range gate.

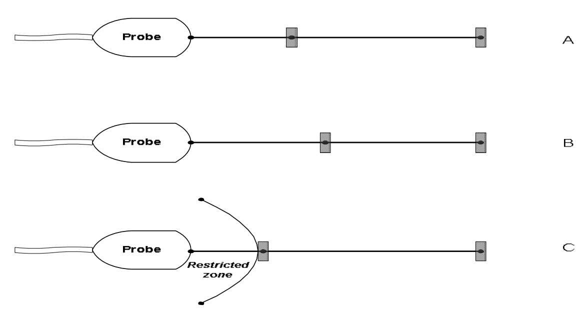

Figure 2. High PRF mode with two active range gates. (A) general case, (B) case of minimum possible PRI, and (C) case of maximum possible PRI.

Given the geometry and the constraint posed by Tsu, it is possible to calculate a minimum and a maximum value for the possible PRI. The case for minimum PRI ($PRI_{2G\,min}$) is shown in Fig. 2B and is given by Eq. 6. The primary range gate is placed at the required depth (the deeper gate in the case.) The other active gate is placed such that its distance from the probe is just not enough to squeeze in a third gate with the same PRI. Equation 6 is illustrated by the lower green line line in the Baker diagram shown in Fig. 3.

$$PRI_{2G\min} = \frac{RTT + Tsu}{2} = \frac{r}{c} + \frac{Tsu}{2} \quad (6)$$

The value for the longest allowable PRI in this case ($PRI_{2G\max}$) is shown in Fig. 2C. The shallower range gate may pose a problem to the dynamic range of the system if it gets too close to the transducer. In this case, the echo from this range gate shall be of large signal amplitudeand may dominate the signal from the primary range gate, giving rise to a wrong Doppler spectrum. It is thus important to prevent the shallower range gate from getting too close to the transducer face by adding an appropriate idle time, Tidle to the value of Tsu. The addition of this time period creates a “restricted zone” next to the probe where range gates are not allowed to be present if the system is in the HPRF mode.

$$PRI_{2G\max} = RTT - (Tsu + Tidle) = \frac{2r}{c} - (Tsu + Tidle) \quad (7)$$

Eq. 7 is illustrated by the upper green line in Baker diagram shown in Fig. 3. This straight line is parallel to that represented by Eq. 5. The gap between the two lines represents an unstable region in Baker diagram. A point in this gap means that this particular PRI is not allowed at this particular depth. The system must get out of this unstable region by switching to a lower PRI or get out of the HPRF mode by switching to the maximum possible PRF (i.e. a higher PRI value). Baker diagrams, thus, provides a tool for illustrating the locations of the unstable regions and the dynamics of what happens when changing the depth as it is interrelated to the allowable PRI values. The importance of Baker diagrams in this regard shall be even clearer when the case of 3 active range gates is discussed.

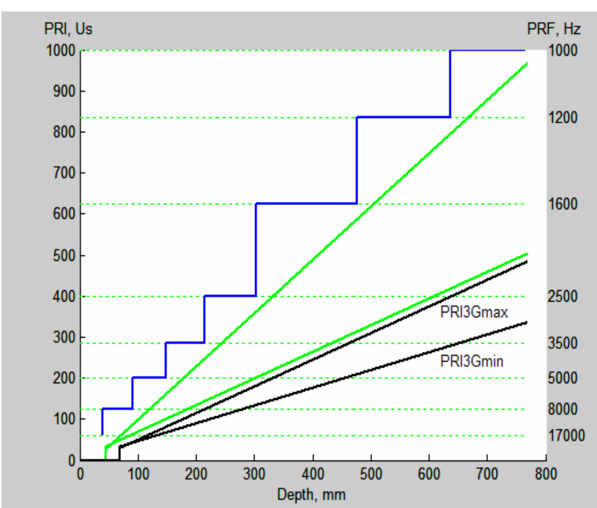

Figure 3. Baker Diagram for High PRF mode for 2 active range gates (green lines) and 3 active range gates (black lines).

3. High PRF with three active range gates

Using a similar geometric analysis for the case of three range gates and the constraint posed by Tsu, it is possible to calculate a minimum and a maximum value for the possible PRI. The case for minimum PRI is given by Eq. 8. This is also a straight line in Baker diagram as represented by the lower black line in Fig. 3.

$$PRI_{3G\min} = \frac{RTT + Tsu}{3} = \frac{2r}{3c} + \frac{Tsu}{3} \quad (8)$$

The value for the longest allowable PRI in this case is illustrated by the upper black line in Fig. 3. The closer range gate is again constrained by Tidle to ensure staying out of the restricted zone.

$$PRI_{3G\max} = \frac{RTT - (Tsu + Tidle)}{2} = \frac{r}{c} - \frac{(Tsu + Tidle)}{2} \quad (9)$$

Eq. 9 is also shown in Fig. 3 as a straight line parallel to that represented by Eq. 6. Also, there is a gap between these two straight lines that represents another part of the unstable region.

The cases for more than three range gates can be analyzed using the same approach. The next section shall provide examples to illustrate how Baker diagrams can be used to develop insight into the behavior of an ultrasound system in the HPRF Doppler mode.

III. EXAMPLES

The first example, whose Baker diagram is shown in Fig. 4, illustrates a case where the system only permits a finite set of values for the PRF. These values are selected in such a way that allows for a good HPRF performance. The horizontal straight lines are used to identify and annotate the locations of the available PRF values as marked on the right side of the diagram. Many of the PRF values provide a good coverage of region G2 (which supports HPRF with two range gates) and region G3 (which supports HPRF with three range gates). Figure 4 also shows a trajectory that simulates increasing the depth of the Doppler range gate from 50 mm with an initial PRF of 4000 Hz to a depth of 200 mm. This new locus corresponds to an unstable point and the system switches to HPRF mode with two range gates and a PRF value of 6000 Hz. When the user tries to switch to the next higher PRF value of 8000 Hz, the new locus also corresponds to an unstable point and the system swtitches to HPRF with three range gates and a PRF value of 10000 Hz.

The second example shows a Baker Diagram as illustrated in Fig. 5, demonstrating a trajectory of increasing the PRF value by the user at a depth of 160 mm. The initial value of PRF is 4000 Hz. When the user requested an increase in the PRF, the trajectory was caused to fall within an unstable region and the system switched to HPRF with two active range gates and a PRF value of 12000 Hz. When the user reduced the depth to 140 mm, the system had to get out of this new unstable locus and switched to a lower PRF value of 10000 Hz. While it is counter intuitive that reducing the

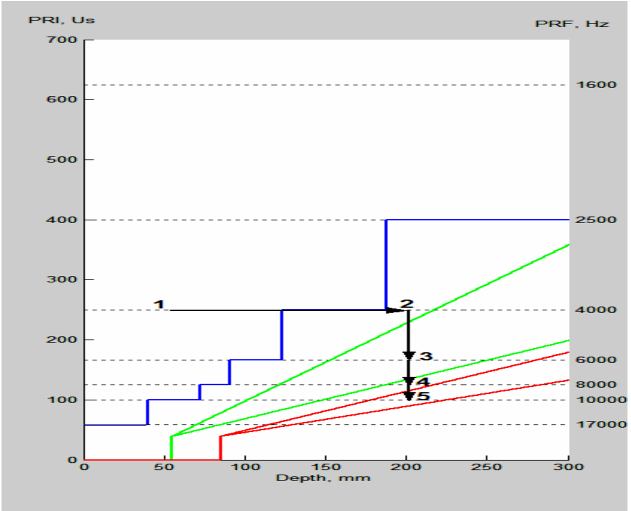

Figure 4. Illustration of Example 1.

depth would cause reduction of the PRF value, this situation is possible to occur in the HPRF mode.

IV. Discussion

Baker diagrams are easy to construct given the available PRF values and the values of the system parameters Tsu and Tidle. These diagrams present a valuable visual tool that describes the behavior of the system in the PW Doppler mode. The examples in the previous section show that it is easy to construct trajectories that describe the behavior of the system when changing the PRF and/or the depth of the primary Doppler range gate.

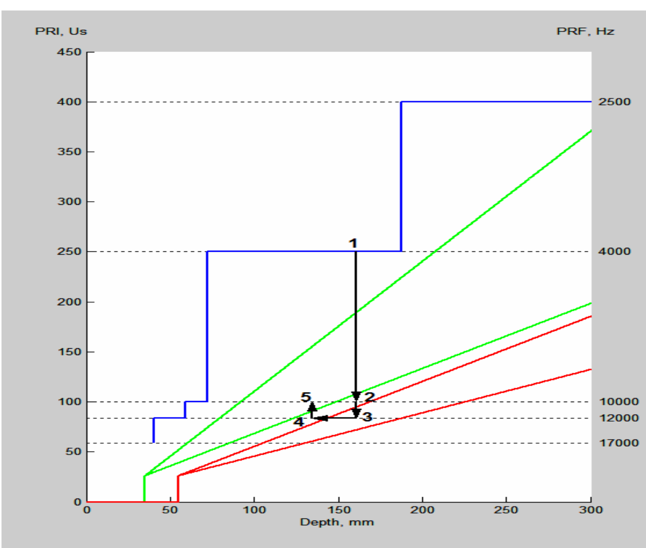

Figure 5. Illustration of Example 2.

The fundamental factors affecting the performance of the system in the HPRF mode can also be studied using Baker diagrams. It is important to discuss some of these factors here.

First, while the selection of the number and the values of the available PRFs are influenced by the applications supported by the system, it is important to provide a good coverage of regions G2 and G3 to help avoid the unstable regions and a counter intuitive behavior of the system.

Second, the slopes of the lines defining various regions in Baker diagram are functions of the values of Tsu and Tidle. Reducing both values increases the areas of the stable regions.

Third, region G3 is considerably smaller than region G2. It is possible to write equations corresponding to region G4, region G5, and so on. However, it is already clear that the areas of those regions shall not be large enough to justify the extra logic and the increased risk of unstable behaviors. Another important factor is that the intersection point of the two straight lines representing each region moves deeper and deeper as we increase the number of range gates. This limits, further, the usefulness of the cases of four and more active range gates.

Finally, for the simplicity of the analysis, the actual length of the Doppler gate was not accounted for in the equations. This modification, however, is straight forward and does not change the applicability of the concepts discussed here.

V. Conclusion

We have presented a visual tool, called Baker diagram, for the analysis of the HPRF mode in ultrasound systems with PW Doppler capability. While this paper did not discuss any design or implementation details, the concepts discussed may provide valuable insights that can aid in the understanding of this design problem.

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