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High-Speed Army Reference Vehicle

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14. ABSTRACT The US Army recently formulated a strategy regarding how the future Army will fight and the associated modernization and research priorities for achieving these military capabilities. Long-Range Precision Fires underpinned by hypersonic flight are critical to ensuring that the United States can enforce its will against any competitor. Many barriers must be overcome to realize an effective future US Army. Some of these gaps are in understanding hypersonic vehicle aerothermodynamics, thus motivating the need for foundational research. The goal of this report is to define a canonical, Army-relevant configuration suitable for foundational research to allow for focused collaboration with a critical mass of appropriate subject matter experts. Data and knowledge gained from studies on this open geometrical configuration may be subject to more restrictive distribution.					
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1. Introduction

The US Army recently formulated a strategy regarding how the future Army will fight and the associated modernization and research priorities for achieving these military capabilities.^{1,2} Long-Range Precision Fires underpinned by hypersonic flight are critical to ensuring that the United States can enforce its will against any competitor.

Many barriers must be overcome to realize an effective future US Army. Some of these gaps are in understanding hypersonic vehicle aerothermodynamics, thus motivating the need for foundational research. Lack of predictive knowledge of the complex physics and chemistry occurring around hypersonic vehicles inhibits timely, optimized multi-component design. Specific phenomena that are poorly understood include boundary layer transition and shock–boundary layer interactions. The inability to properly model phenomenon yields uncertainty in characteristics, such as the surface pressure distribution and heat flux, which negatively impact vehicle technologies including stability, control, and thermal load management.

Fortunately, a precedent exists for promoting community-wide scientific discourse through defining government reference vehicles that contain functionally relevant artifacts but are not sensitive to specific developmental programs (see Army-Navy Basic Finner missile,³⁻⁸ Air Force Modified Basic Finner missile,³⁻⁸ Army-Navy Spinner Rocket,⁸ National Aerospace Plane,⁹ and NASA studies^{10,11}). The goal of this report is to define a canonical, Army-relevant configuration suitable for foundational research to allow for focused collaboration with a critical mass of appropriate subject matter experts. Data and knowledge gained from studies on this open geometrical configuration may be subject to more restrictive distribution.

2. Vehicle Description

The High-Speed Army Reference Vehicle (HARV) is a symmetric flight vehicle that has an overall length-to-diameter of 10. The vehicle was initially shaped through a series of optimization analyses that identified design candidates with low drag and high lift-to-drag ratios. A more detailed description of the optimization process can be found in Vasile et al.^{12,13} Several design iterations to simplify model fabrication and wind tunnel experimentation resulted in the establishment of HARV. The flight vehicle was designed for a modular forebody as well as aftbody-fin shapes to allow researchers to study a wide variety of phenomena.

The body section was a constant diameter cylinder. The diameter of the cylindrical body section is defined as 1 cal. Two nose profiles were studied, a cone and a Von Kármán ogive. The profile shapes for both cone and ogive were described using generic power series (i.e., $n = 1$) and Haack series (i.e., $C = 0$), respectively, and computed as defined in Rosema.¹⁴ The equivalent half angle of the conical nose is approximately 5° . The fineness ratio of both forebodies is 5. The nose tips for both forebodies were modeled with a spherical tip defined by a bluntness radius that is 0.05 of the base diameter (i.e., 0.05 cal.). An iterative scheme was necessary to solve the transition point from spherical tip to each prescribed nose profile to ensure a smooth transition (i.e., slope matching). Further details on the profile formulation are provided in the Appendix. The cross section for each nose profile shape is presented in Fig. 1. The forebodies allowed for studying the difference between boundary layers formed in favorable pressure gradients versus those without a pressure gradient.

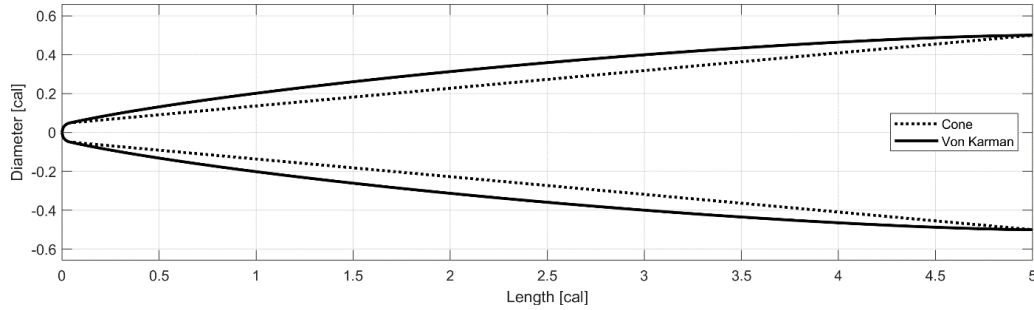


Fig. 1 HARV nose profile shapes

Two tail fin configurations were defined. The vehicle can be assembled using either three or four clipped-delta fins azimuthally separated 120° or 90° , respectively. The fin-body configurations allowed for investigating the effects of distance on fin-fin flow physics interactions. Each fin has a sweep angle of 80° and a root and tip chord length of 4.8 and 2.125 cal., respectively. Each fin has a uniform cross-sectional thickness of 0.07 cal. with a maximum tip semi-span of 0.95 cal. The leading edge was rounded using 0.03-cal. radii on either side of the fin with a flat section along the centerline with a width of 0.01 cal. Figure 2 shows additional details on the fin leading edge.

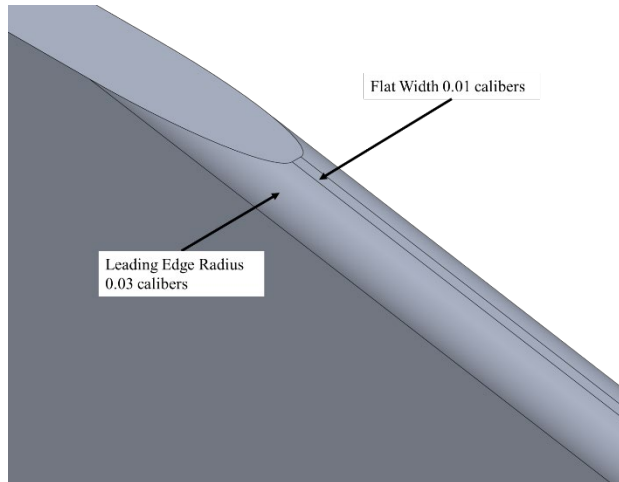


Fig. 2 HARV leading edge details common to all models. Zoomed view is where leading edge meets the fin tip.

The HARV for each unique configuration is illustrated in Figs. 3–6.

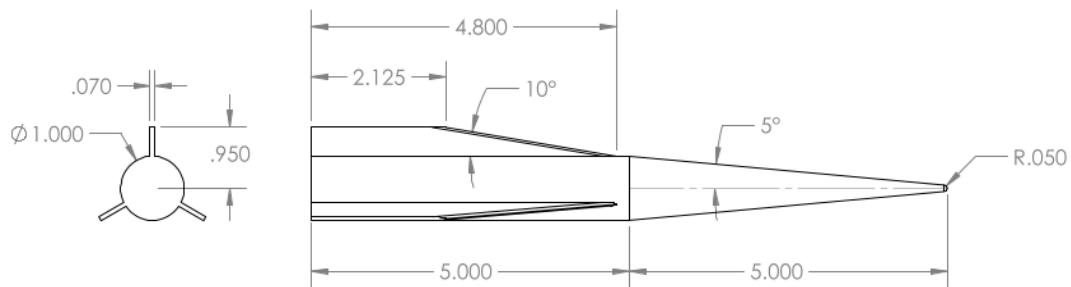


Fig. 3 HARV conical nose with three fins. All units are in calibers.

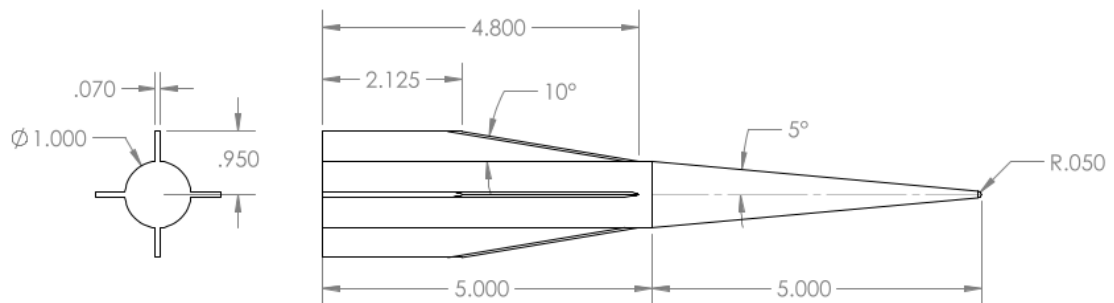


Fig. 4 HARV conical nose with four fins. All units are in calibers.

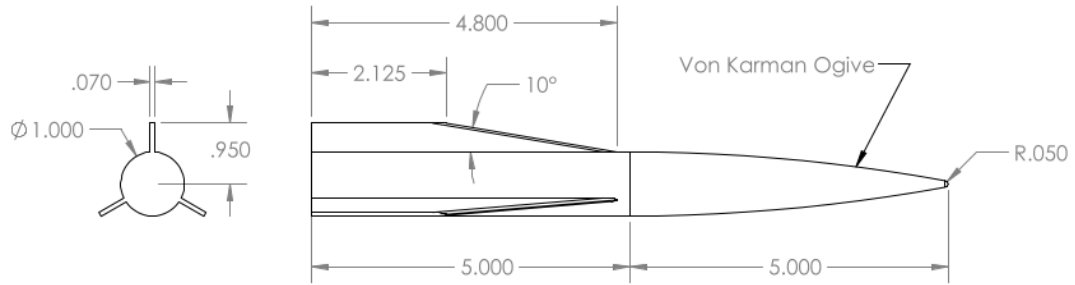


Fig. 5 HARV ogival nose with three fins. All units are in calibers.

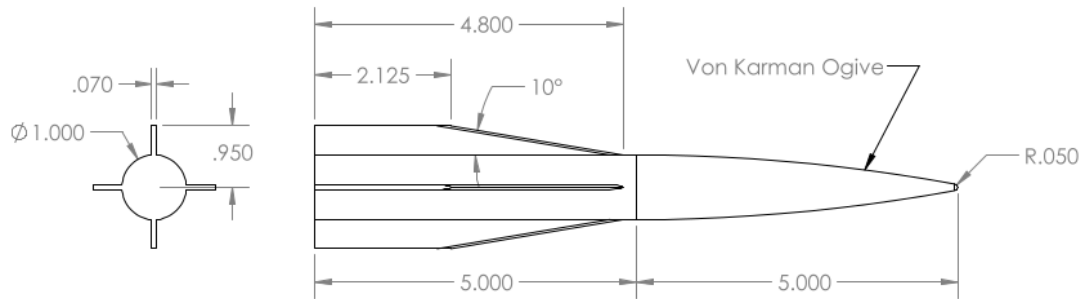


Fig. 6 HARV ogival nose with four fins. All units are in calibers.

The solid model rendering of the HARV for each unique configuration is presented in Figs. 7–10.

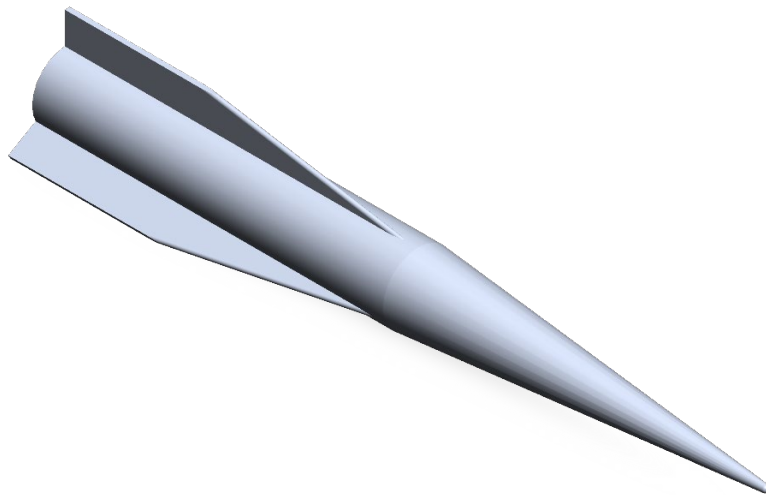


Fig. 7 HARV conical nose with three fins solid model rendering

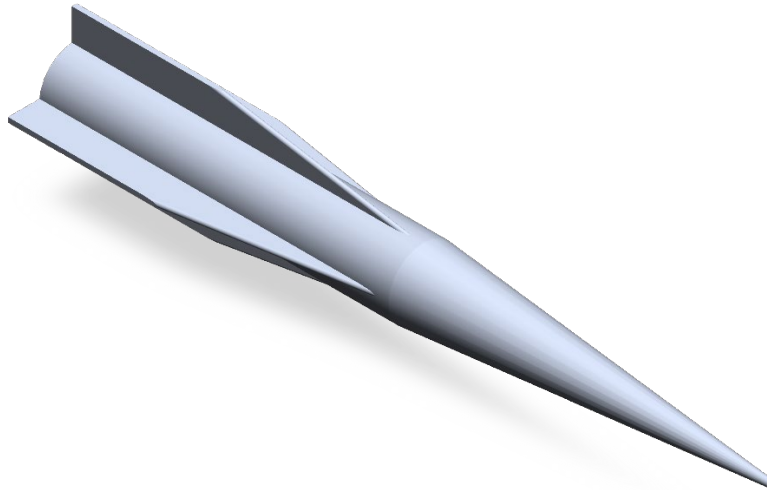


Fig. 8 HARV conical nose with four fins solid model rendering

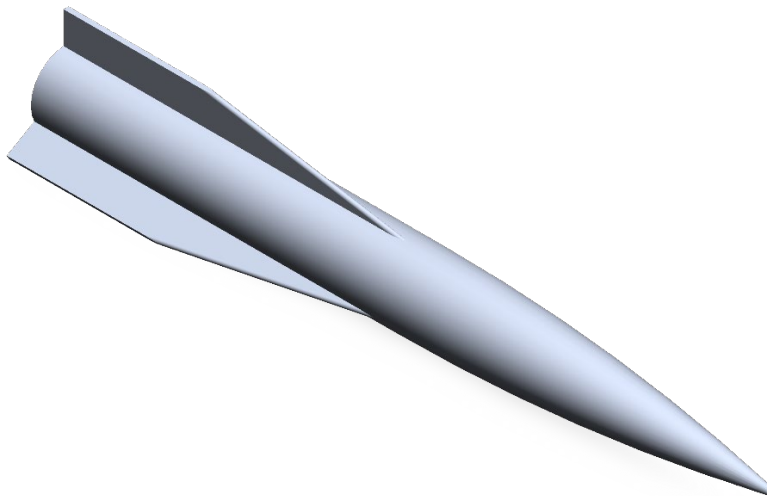


Fig. 9 HARV ogival nose with three fins solid model rendering

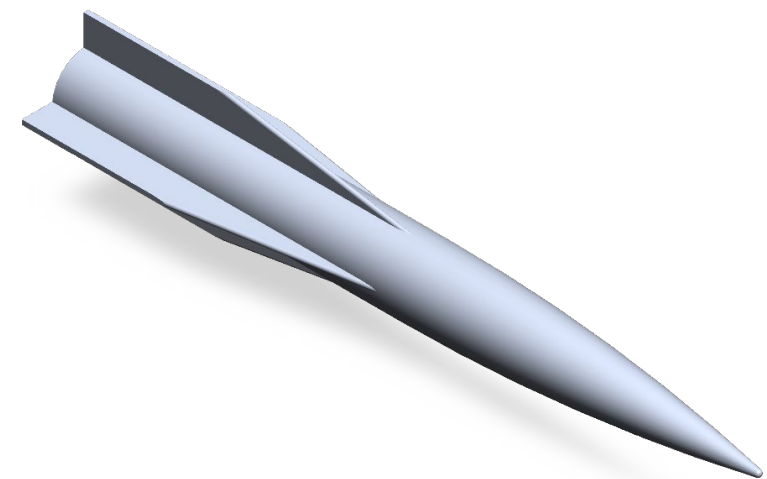


Fig. 10 HARV ogival nose with four fins solid model rendering

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Appendix. Nose Profile Definition

A-1. Power Series Nose Profile

The blunted power series nose profile can be calculated through Fig. A-1 and subsequent content. (Figure and equations formulated from Rosema.¹)

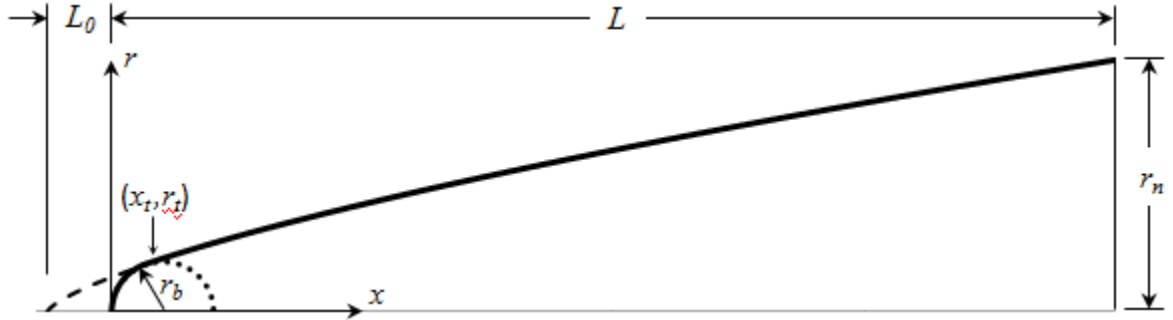


Fig. A-1 Definition of power series nose profile parameters

Basic power series relationship:

$$r(x) = r_n \left(\frac{x}{L} \right)^n$$

The equation for cone noses is formed by setting $n = 1$.

For the blunted tip,

$$r(x) = \sqrt{2xr_b - x^2}$$

For blunted cases, an iterative scheme is necessary to solve for the transition point, x_t .

Set an initial value for $r_t \approx 0.99r_b$ and let

$$t_1 = nr_t^2$$

$$t_2 = 1 - \left(\frac{r_t}{r_n} \right)^{1/n}$$

$$t_3 = \left(\frac{r_t}{r_n} \right)^{1/n}$$

$$t_4 = \sqrt{r_b^2 - r_t^2} + L - r_b$$

¹ Rosema C. Analysis of supersonic nose pressure drag using computational fluid dynamics. Army RDECOM AMRDEC (US); 2014. Report No.: RDMR-SS-13-14.

$$t_5 = \sqrt{r_b^2 - r_t^2}$$

and

$$\frac{dt_1}{dr_t} = 2nr_t$$

$$\frac{dt_2}{dr_t} = \frac{-1}{nr_n} \left(\frac{r_t}{r_n} \right)^{1/n-1}$$

$$\frac{dt_3}{dr_t} = -\frac{dt_2}{dr_t}$$

$$\frac{dt_4}{dr_t} = \frac{-r_t}{\sqrt{r_b^2 - r_t^2}}$$

$$\frac{dt_5}{dr_t} = \frac{dt_4}{dr_t}$$

then

$$f(r_t) = t_1 t_2 - t_3 t_4 t_5$$

and

$$f'(r_t) = t_1 \frac{dt_2}{dr_t} + t_2 \frac{dt_1}{dr_t} - t_3 t_4 \frac{dt_5}{dr_t} - t_3 t_5 \frac{dt_4}{dr_t} - t_4 t_5 \frac{dt_3}{dr_t}$$

The Newton-Raphson method may be used to solve for r_t :

$$r_t(i+1) = r_t(i) - n \frac{f(r_t(i))}{f'(r_t(i))}$$

where n is the relaxation factor and is usually set to a value of 0.1 for this case for stability.

Once r_t is known, x_t and L_0 can be solved for

$$x_t = r_b - \sqrt{r_b^2 - r_t^2}$$

$$L_0 = \frac{L \left(\frac{r_t}{r_n} \right)^{1/n} - x_t}{1 - \left(\frac{r_t}{r_n} \right)^{1/n}}$$

For $x \leq x_t$,

$$r(x) = \sqrt{2xr_b - x^2}$$

and for $x > x_t$,

$$r(x) = r_n \left(\frac{x + L_0}{L + L_0} \right)^n$$

A-2. Von Karman Nose Profile

The blunted Von Karman nose profile can be calculated through Fig. A-2 and subsequent content. (Figure and equations formulated from Rosema.¹⁾)

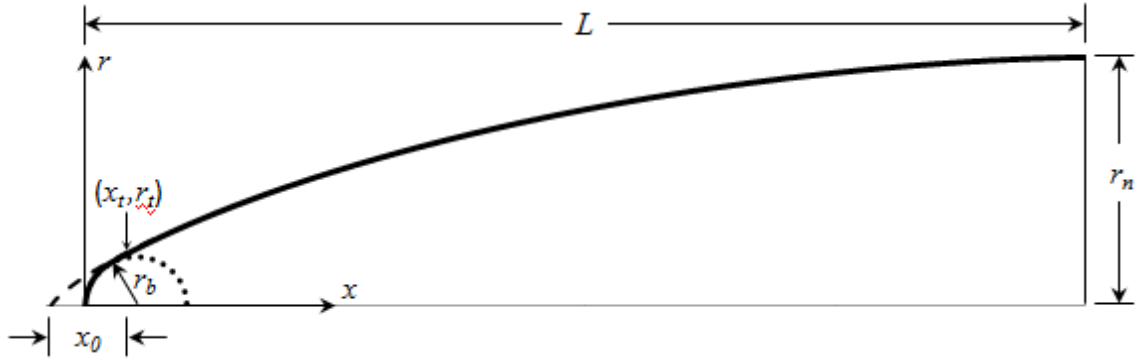


Fig. A-2 Definition of Von Karman nose profile parameters

The Von Karman profile is derived from the Sears–Haack series profile (i.e., $C = 0$):

$$r(x) = \frac{r_n \sqrt{\phi - \frac{\sin(2\phi)}{2}}}{\sqrt{\pi}}$$

where

$$\phi = \cos^{-1} \left(1 - \frac{2x}{L} \right)$$

For the blunted tip,

$$r(x) = \sqrt{2xr_b - x^2}$$

For blunted cases, a two-layer nested iterative scheme is necessary to solve for the transition point, x_t , and the offset length, x_0 :

Set an initial value for $x_t \approx 0.97r_b$,

thus

$$r_t = \sqrt{2x_tr_b - x_t^2} = \frac{r_n \sqrt{\phi_t - \frac{\sin(2\phi_t)}{2}}}{\sqrt{\pi}}$$

Now iterate to solve for ϕ_t using the Newton–Raphson method where

$$f(\phi_t) = \frac{r_n \sqrt{\phi_t - \frac{\sin(2\phi_t)}{2}}}{\sqrt{\pi}} - r_t$$

and

$$f'(\phi_t) = \frac{r_n}{2\sqrt{\pi}} \frac{1 - \cos(2\phi_t)}{\sqrt{\phi_t - \frac{\sin(2\phi_t)}{2}}}$$

$$\phi_t(i+1) = \phi_t(i) - \frac{f(\phi_t(i))}{f'(\phi_t(i))}$$

The outer loop iterates on x_t to match the slopes at the transition point.

Let

$$L_h = L - x_t + x_0$$

where

$$x_0 = (L - x_t) \frac{1 - \cos(\phi_t)}{1 + \cos(\phi_t)}$$

Now let $f(x_t)$ equal the difference in the slopes of the two curves:

$$f(x_t) = \left. \frac{dr}{d\phi} \right|_{\phi=\phi_t} \left. \frac{d\phi}{dx} \right|_{x=x_0} - \frac{r_b - x_t}{r_t}$$

$$f'(x_t) = \left. \frac{dr}{d\phi} \right|_{\phi=\phi_t} \left. \frac{d^2\phi}{dx^2} \right|_{x=x_0} + \left(\left. \frac{d\phi}{dx} \right|_{x=x_0} \right)^2 \left. \frac{d^2r}{d\phi^2} \right|_{\phi=\phi_t} + \frac{1}{r_t} + \frac{(r_b - x_t)^2}{r_t^3}$$

where

$$\left. \frac{dr}{d\phi} \right|_{\phi=\phi_t} = \frac{r_n}{2\sqrt{\pi}} \frac{1 - \cos(2\phi_t)}{\sqrt{\phi_t - \frac{\sin(2\phi_t)}{2}}}$$

$$\left. \frac{d\phi}{dx} \right|_{x=x_0} = \frac{1}{\sqrt{x_0 L_h - x_0^2}}$$

$$\left. \frac{d^2r}{d\phi^2} \right|_{\phi=\phi_t} = \frac{r_n}{2\sqrt{\pi}} \left(\frac{2 \sin(2\phi_t)}{\sqrt{\phi_t - \frac{\sin(2\phi_t)}{2}}} - \frac{(1 - \cos(2\phi_t))^2}{2 \left(\phi_t - \frac{\sin(2\phi_t)}{2} \right)^{3/2}} \right)$$

$$\left. \frac{d^2\phi}{dx^2} \right|_{x=x_0} = \frac{2x_0 - L_h}{2(x_0 L_h - x_0^2)^{3/2}}$$

And finally

$$x_t(i+1) = x_t(i) - n \frac{f(x_t(i))}{f'(x_t(i))}$$

where $0 < n \leq 1$, but $n = 0.01$ is recommended

For $x \leq x_t$,

$$r(x) = \sqrt{2xr_b - x^2}$$

and for $x > x_t$,

$$r(x) = \frac{r_n \sqrt{\phi - \frac{\sin(2\phi)}{2}}}{\sqrt{\pi}}$$

where

$$\phi = \cos^{-1} \left(1 - \frac{2(x - x_t + x_0)}{L_h} \right)$$

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