Chapter 4

Excavator Computational Model

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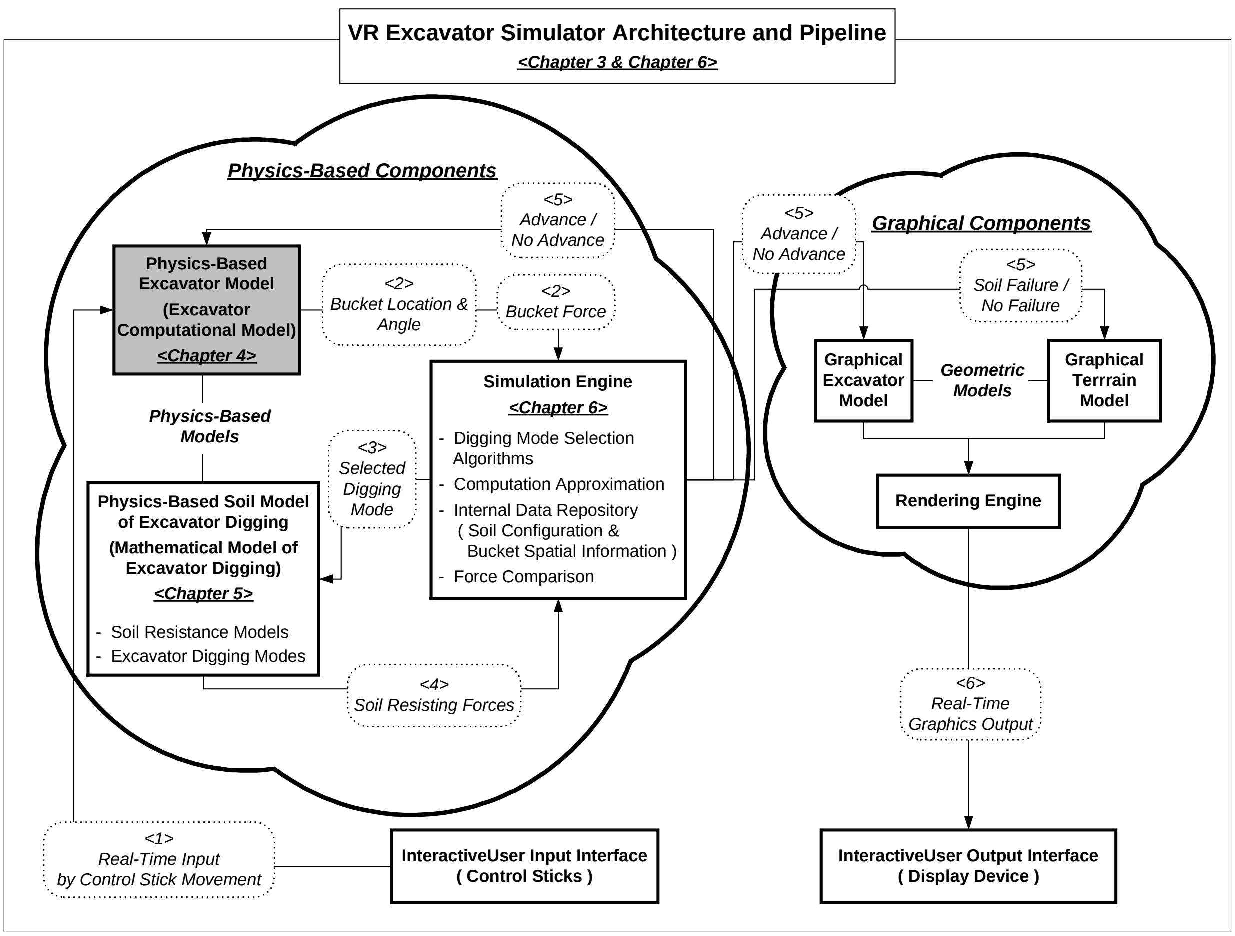

4.1 Introduction

As depicted in the VR excavator simulator architecture, the roles of the excavator computational model (or physics-based excavator model) are, firstly, the creation of spatially and temporally valid machine behavior, and, secondly, the generation of physically credible forces at a bucket. Therefore, the excavator computational model initiates the interaction with the physics-based soil model of excavator digging (or mathematical model of excavator digging) through the simulation engine. The details on the interaction between these components are described in Section 6.2.

This chapter starts with the description of some of the fundamentals of a typical hydraulic excavator system so that the essential parts and properties are identified for an abstracted representation of the machine (Section 4.2).

A typical hydraulic excavator system is modeled in two aspects: the representation of internal parts and the representation of external parts. On top of these representations, a calculation scheme for determining the locations of moving parts as well as the forces at a bucket is presented (Section 4.3). Note that in these representations, no consideration is given to the travel units of an excavator since it has no significant bearing on tool-soil interaction.

4.2 Fundamentals of Hydraulic Excavators

Hydraulic excavators are one of the construction excavating machinery mainly powered by hydraulic system. The hydraulic system of an excavator transmits hydraulic flow generated by a hydraulic pump to a working part through hydraulic oil (Brain and Harris 2002).

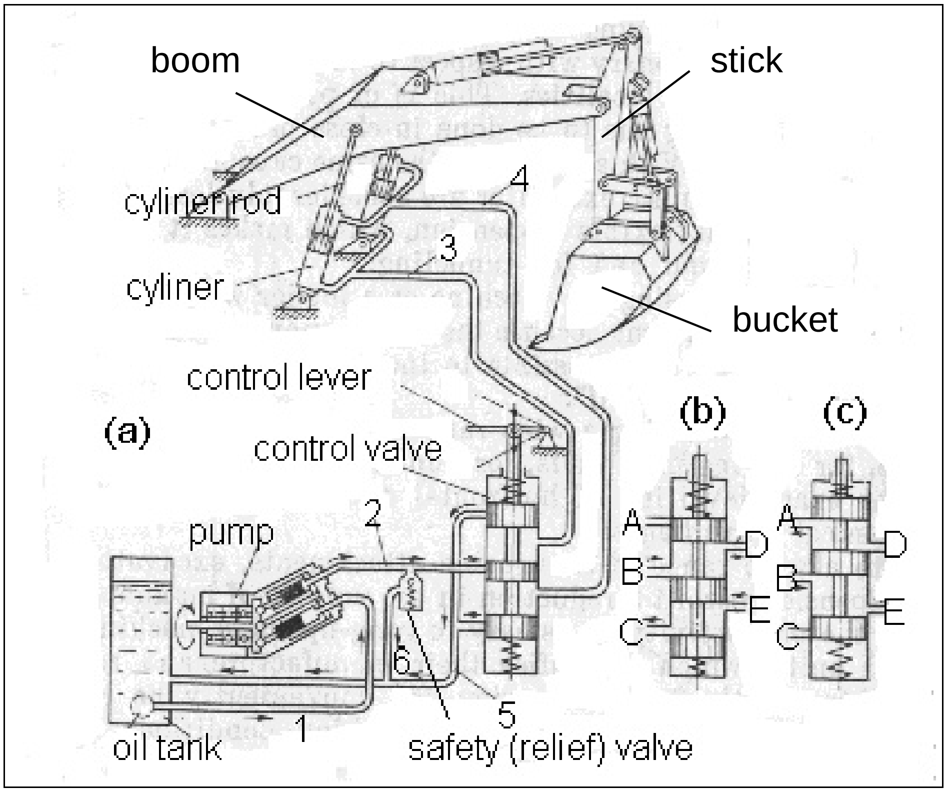

Figure 4.1 Typical Excavator System (Galperin, Dombrovsky and Mestechkin 1982)

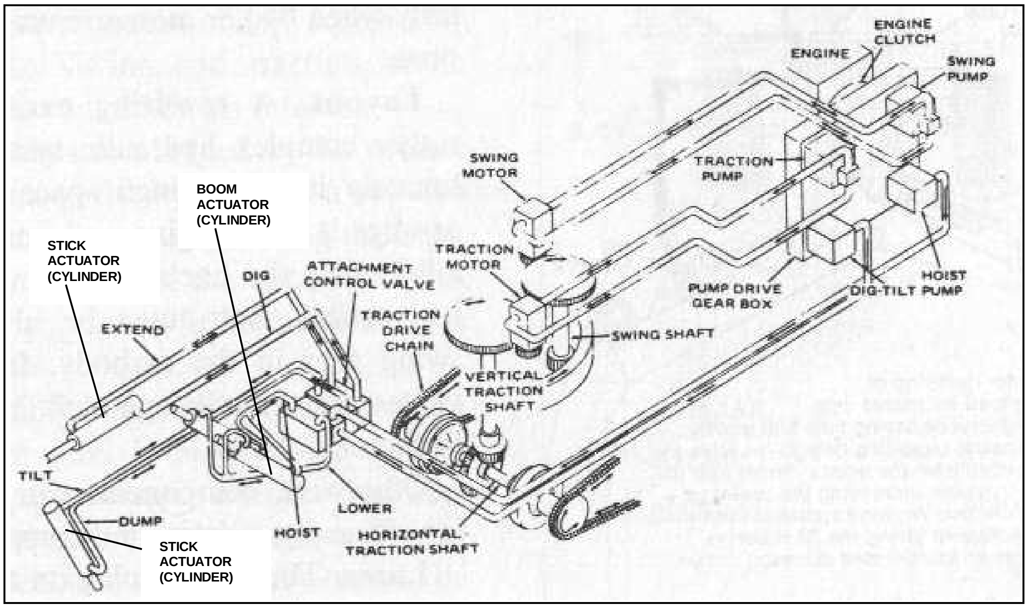

Figure 4.2 Excavator Hydraulic System (Nichols 1976)

Figure 4.1 and Figure 4.2 show some major upper-body mechanical parts and hydraulic circuits. The upper-body mainly consists of a bucket, a stick, a boom and a swing device. The hydraulic system has parts such as oil tanks, pumps, pipelines, relief (or safety) valves, directional control valves, control levers (sticks), cylinders, cylinder rods and a hydraulic swing motor (Nichols 1976; Galperin, Dombrovsky and Mestechkin 1982).

The figures also demonstrate how the system is integrated to function as a hydraulic mechanical unit. Figure 4.1 (a) shows the neutral position of the directional control valve, in which oil drawn by the pump is only flowing around the relatively short hydraulic circuit consisting of pipeline 1, pipeline 2, the safety (or relief) valve and pipeline 6. At this point, there is no movement of oil in pipeline 3, 4 and the boom hydraulic cylinders. However, when an operator pushes down the (boom control) lever down, the directional valve is shifted down and set into the position as in Figure 4.1 (b), letting ports B, C, D and E open. As a result, the oil coming from pipeline 2 flows through ports B and D. This oil flow keeps circulating through pipeline 3, pushing the piston upward in the boom cylinder to eventually make the cylinder rods move the boom upward. The oil on the other side of the cylinder gets squeezed into pipeline 4, returning to the oil tank through open ports E and C. By the same token, when the operator pull the control lever up, the boom moves downward due to the opposite oil flow as shown in Figure 4.1 (c). The functionality of the safety valve not mentioned above is that when the pressure in the pipeline is excessive, the safety valve gets open to maintain the normal pressure, resulting in the short oil circuit formed by pipeline 1, 2 and 6 (Galperin, Dombrovsky and Mestechkin 1982).

As far as the excavator control is concerned, the machine has different combinations in terms of moving the parts in an excavator upper-body. Typical hydraulic control units are shown in Figure 4.3. For experienced operators, it is common practice to operate some of the upper-body parts together to maximize digging productivity. To the extreme degree, it is possible to drive all of parts simultaneously by moving two control sticks in a diagonal direction.

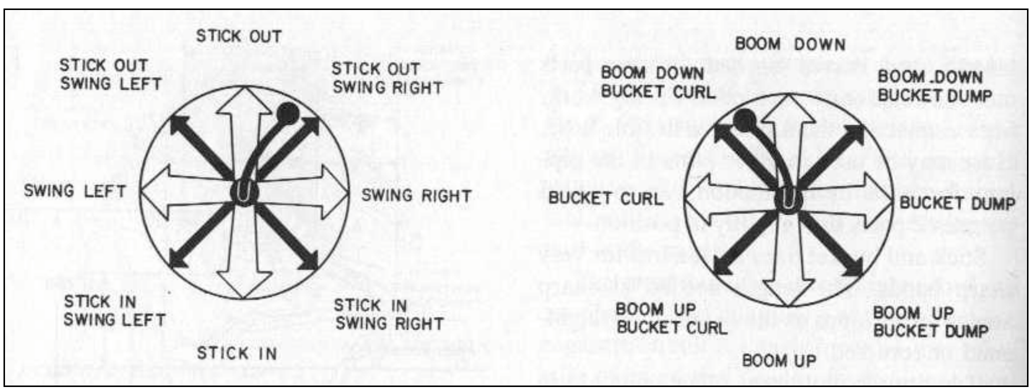

Figure 4.3 Excavator Control Units - Control Levers (Nichols 1976)

4.3 Hydraulic Excavator Representations

4.3.1 Internal Representation (Hydraulic System & Control Units)

The internal representation is mainly composed of a hydraulic system and control units as shown in Figure 4.4. They are responsible for generating and regulating movements of an excavator's structural parts. Some of the important properties for hydraulic circuits include cylinder cross-sectional areas (capacities), maximum piston travel lengths, a hydraulic flow rate (volume/time) and a hydraulic pressure. The control units have properties such as control lever positions and combination of levers.

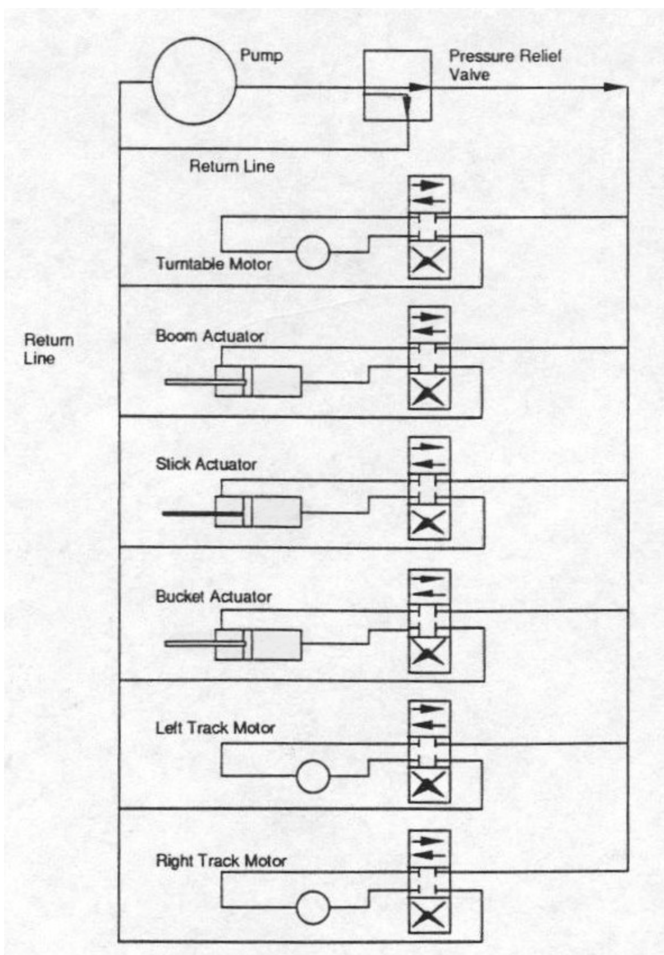

Figure 4.4 Excavator Internal Representation (Wakefield and O'Brien 1994)

4.3.2 External Representation (Excavator Structure)

The external representation is related to some structural parts that are tightly linked to the internal hydraulic system. In other words, their motional behaviors are only the end-effects of the internal parts' hydraulic displacements. The external representation should contain properties such as relative locations of members, member dimensions (length and width), rod extension or retraction and member weights. The representation is described in Figure 4.5.

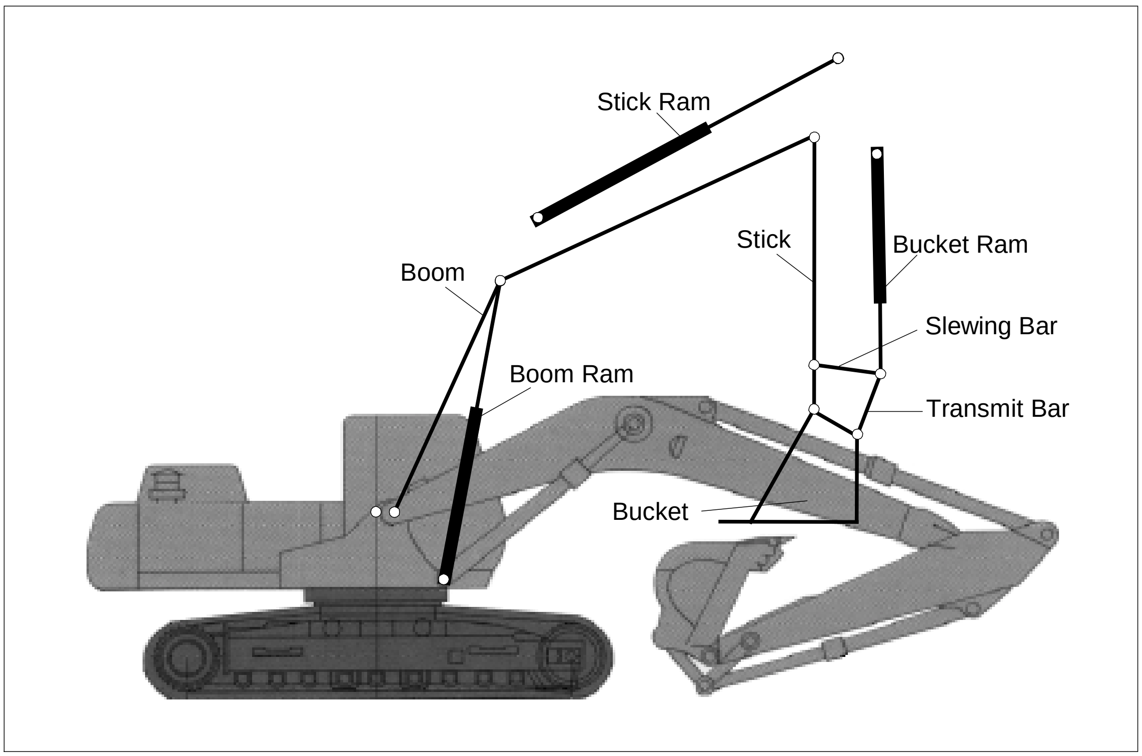

Figure 4.5 Excavator External Representation

4.3.3 Calculation Scheme for Bucket Spatial Information and Bucket Forces

Essential properties identified in the internal and external representations are used to calculate valid physical responses of a machine, eventually responses of a bucket in the form of motion and force. The motion calculation starts by computing piston displacements by considering a hydraulic flow rate and ram cross-sectional areas along with a time segment of operation, which is formulated as follows.

$$\text{Piston Displacement} = (\text{flow rate} / \text{ram cross-sectional area}) \times \text{segmental time duration} \tag{4-1}$$

Once this calculation is done for rams (cylinders) corresponding to the operation, spatial information of the members can be calculated by a series of geometrical analyses.

Bucket force calculation begins by multiplying a hydraulic pressure with a cylinder cross-sectional area to produce a ram (cylinder) force for each ram. Each ram force is statically combined together to determine the end-effect forces at a bucket (bucket forces).

Figure 4.6 shows the breakdown of forces involved in determining a boom ram induced bucket force (B_{r_bmr}). The boom ram induced bucket force (B_{r_bmr}) is determined by considering a moment equilibrium against a boom rotation point (P_{bm_r}) as follows.

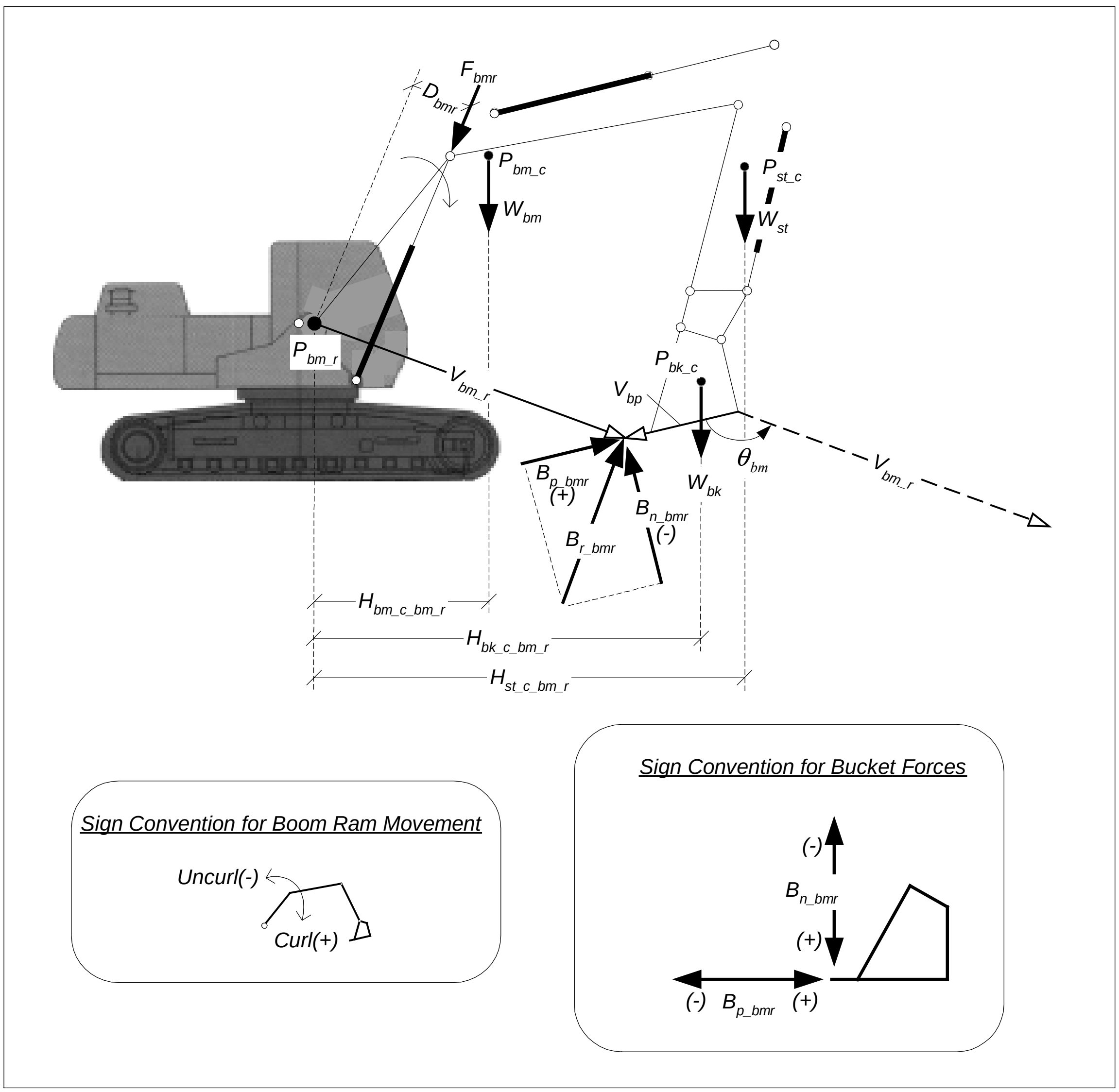

Figure 4.6 Boom Ram Induced Bucket Force Calculation

$$(\pm F_{bmr}) \cdot D_{bmr} + (\pm W_{bm}) \cdot H_{bm\_c\_bm\_r} + (\pm W_{st}) \cdot H_{st\_c\_bm\_r} + (\pm W_{bk}) \cdot H_{bk\_c\_bm\_r} = (\pm B_{r\_bmr}) \cdot |V_{bm\_r}|$$

$$\pm B_{r\_bmr} = \frac{(\pm F_{bmr}) \cdot D_{bmr} + (\pm W_{bm}) \cdot H_{bm\_c\_bm\_r} + (\pm W_{st}) \cdot H_{st\_c\_bm\_r} + (\pm W_{bk}) \cdot H_{bk\_c\_bm\_r}}{|V_{bm\_r}|} \quad (4\text{-}2)$$

Where,

- P_{bm_r}: boom rotation point
- P_{bm_c}: boom centroid
- P_{st_c}: stick centroid
- P_{bk_c}: bucket centroid

- F_{bmr}: boom ram force (+: when F_{bmr} generates a curling moment; -: otherwise)
- W_{bm}: boom weight (+: when W_{bm} generates a curling moment; -: otherwise)
- W_{st}: stick weight (+: when W_{st} generates a curling moment; -: otherwise)
- W_{bk}: bucket weight including soil weight (+: when W_{bk} generates a curling moment; -: otherwise)

- V_{bm_r}: vector from P_{bm_r} to the tip of bucket tooth
- V_{bp}: vector from bucket corner to the tip of bucket tooth

- D_{bmr}: distance of F_{bmr} to P_{bm_r}
- $H_{bm\_c\_bm\_r}$: horizontal distance between P_{bm_c} and P_{bm_r}
- $H_{bk\_c\_bm\_r}$: horizontal distance between P_{bk_c} and P_{bm_r}
- $H_{st\_c\_bm\_r}$: horizontal distance between P_{st_c} and P_{bm_r}

- θ_{bm}: angle measured from V_{bp} to V_{bm_r} in an uncurling direction

- B_{r_bmr}: boom ram induced bucket force (acting on the tip of bucket tooth, normal to V_{bm_r})
- B_{p_bmr}: component of boom ram induced bucket force parallel to bucket bottom plate

- B_{n_bmr}: component of boom ram induced bucket force normal to bucket bottom plate

Once the boom ram induced bucket force (B_{r_bmr}) is determined, it is decomposed into two force components. B_{p_bmr} is a force component acting parallel to the bucket bottom plate and B_{n_bmr} is a force component acting normal to the bucket bottom plate.

$$^{\pm}B_{p\_bmr} = (^{\pm}B_{r\_bmr}) \cdot \sin\theta_{bm} \tag{4-3}$$

$$^{\pm}B_{n\_bmr} = (^{\pm}B_{r\_bmr}) \cdot \cos\theta_{bm} \tag{4-4}$$

Note that only the positive values of B_{p_bmr} and B_{n_bmr} represent forces that can be used to break soil media. As in figure 4.6, for example, the positive B_{p_bmr} can be utilized to push the bucket tip into the soil. However, the negative B_{n_bmr} can not be applied to break soil (no excavator operator applies this negative force to excavate soil).

Figure 4.7 shows all the force components and dimensions associated with a stick ram induced bucket force (B_{r_str}). Taking a moment against a stick rotation point (P_{st_r}), the stick ram induced bucket force (B_{r_str}) is expressed in the following.

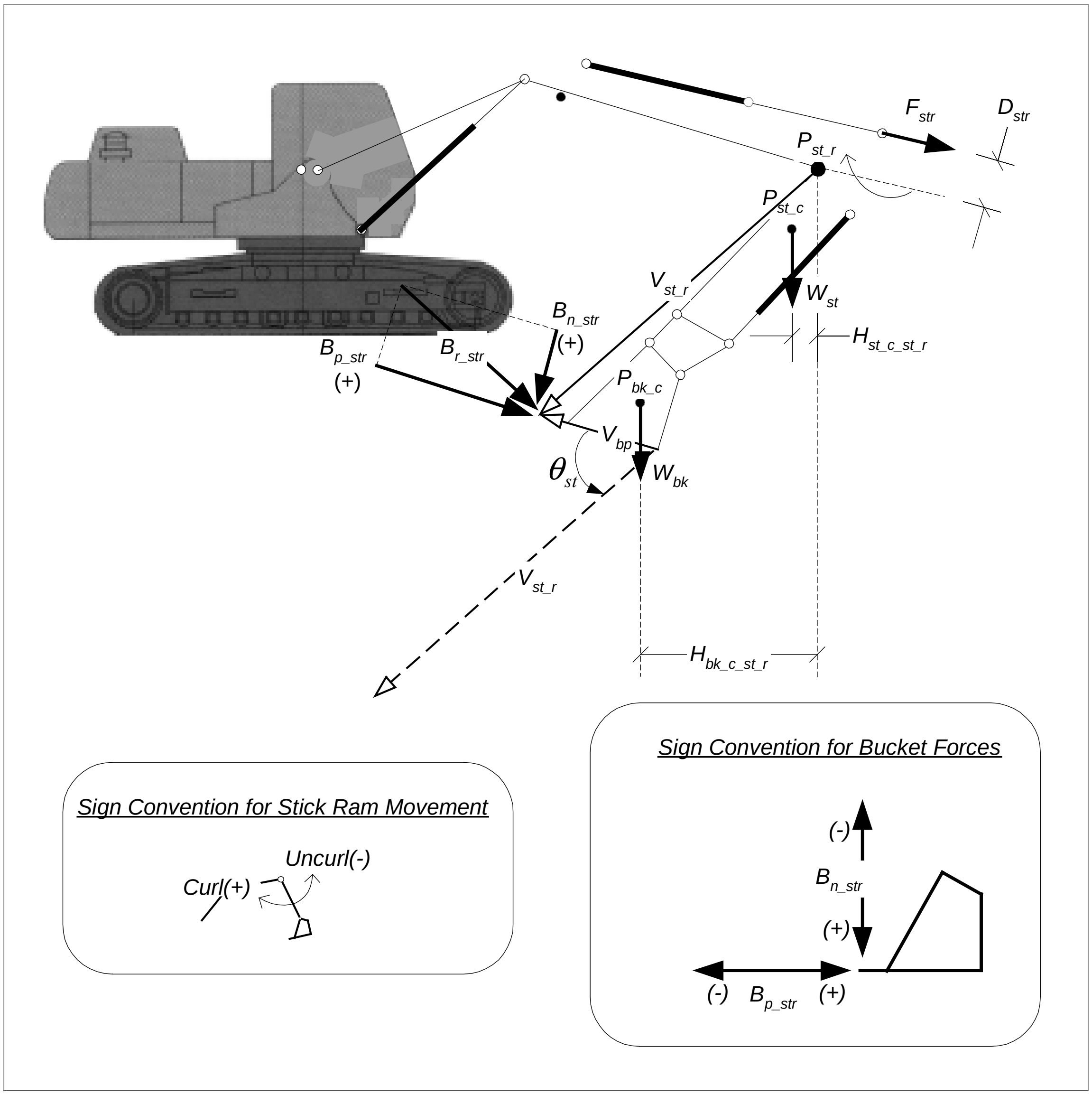

Figure 4.7 Stick Ram Induced Bucket Force Calculation

$$^{\pm}B_{r\_str} = \frac{(^{\pm}F_{str}) \cdot D_{str} + (^{\pm}W_{st}) \cdot H_{st\_c\_st\_r} + (^{\pm}W_{bk}) \cdot H_{bk\_c\_st\_r}}{\left|V_{st\_r}\right|} \tag{4-5}$$

$$^{\pm}B_{p\_str} = (^{\pm}B_{r\_str}) \cdot \sin\theta_{st} \tag{4-6}$$

$$^{\pm}B_{n\_str} = (^{\pm}B_{r\_str}) \cdot \cos\theta_{st} \tag{4-7}$$

Where,

- P_{st_r}: stick rotation point
- P_{st_c}: stick centroid
- P_{bk_c}: bucket centroid

- F_{str}: stick ram force (+: when F_{str} generates a curling moment; -: otherwise)
- W_{st}: stick weight (+: when W_{st} generates a curling moment; -: otherwise)
- W_{bk}: bucket weight including soil weight (+: when W_{bk} generates a curling moment; -: otherwise)

- V_{st_r}: vector from P_{st_r} to the tip of bucket tooth
- V_{bp}: vector from bucket corner to the tip of bucket tooth
- D_{str}: distance of F_{str} to P_{st_r}
- $H_{bk\_c\_st\_r}$: horizontal distance between P_{bk_c} and P_{st_r}
- $H_{st\_c\_st\_r}$: horizontal distance between P_{st_c} and P_{st_r}

- θ_{st}: angle measured from V_{bp} to V_{st_r} in an uncurling direction

- B_{r_str}: stick ram induced bucket force (acting on the tip of bucket tooth, normal to V_{st_r})
- B_{p_str}: component of stick ram induced bucket force parallel to bucket bottom plate
- B_{n_str}: component of stick ram induced bucket force normal to bucket bottom plate

Figure 4.8 displays the forces and the dimensions associated with a bucket ram induced bucket force (B_{r_bkr}). Since a bucket ram force (F_{bkr}) is not applied directly to the bucket, the determination of B_{r_bkr} requires two moment equilibriums, firstly, against a slewing bar rotation point (P_{sb_r}) and, secondly, against a bucket rotation point (P_{bk_r}).

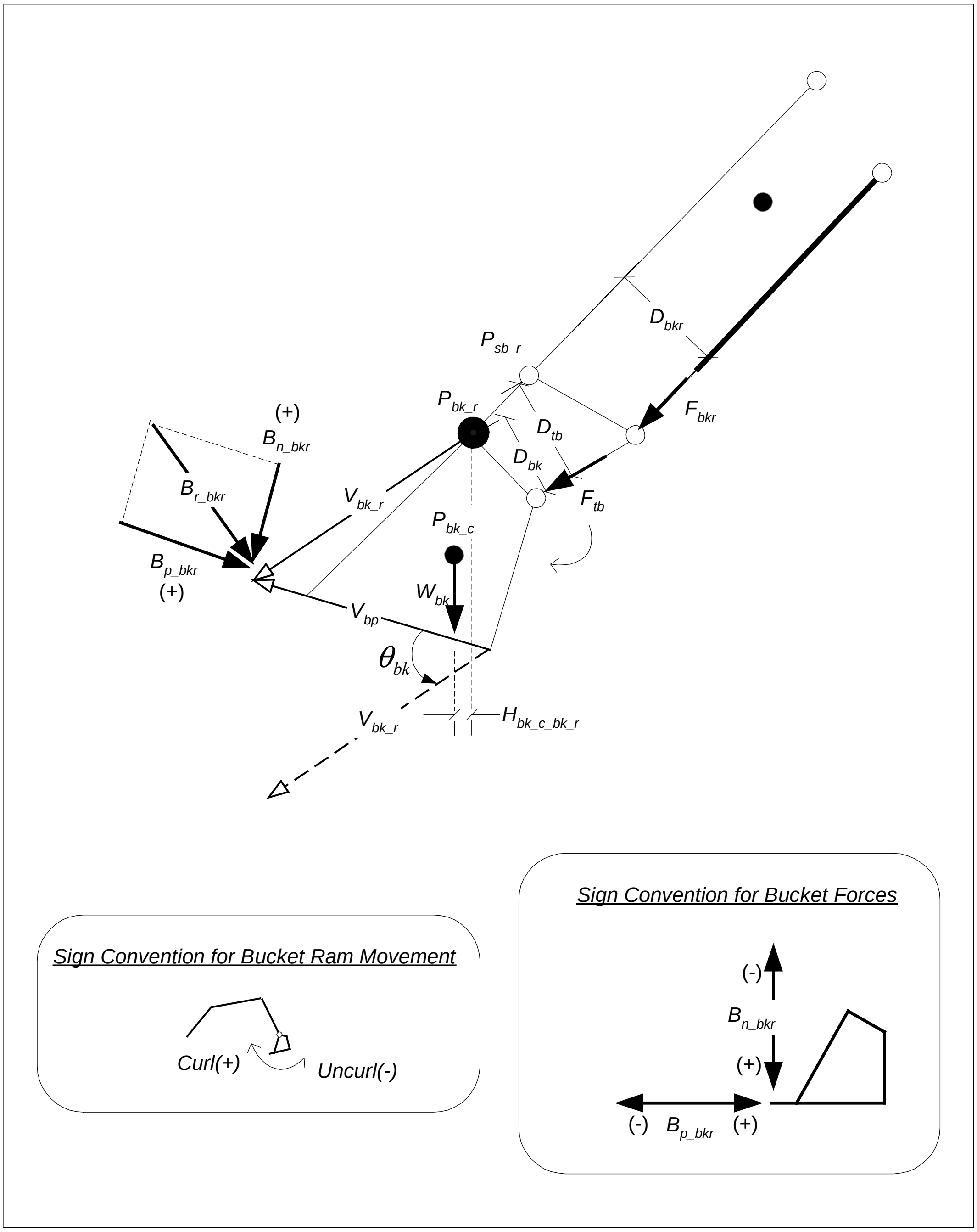

Figure 4.8 Bucket Ram Induced Bucket Force Calculation

$$^{\pm}F_{tb} = \frac{D_{bkr} \cdot (^{\pm}F_{bkr})}{D_{tb}} \tag{4-8}$$

$$^{\pm}B_{r\_bkr} = \frac{(^{\pm}F_{tb}) \cdot D_{bk} + (^{\pm}W_{bk}) \cdot H_{bk\_c\_bk\_r}}{\left|V_{bk\_r}\right|} \tag{4-9}$$

$$^{\pm}B_{p\_bkr} = (^{\pm}B_{r\_bkr}) \cdot \sin\theta_{bk} \tag{4-10}$$

$$^{\pm}B_{n\_bkr} = (^{\pm}B_{r\_bkr}) \cdot \cos\theta_{bk} \tag{4-11}$$

Where,

- P_{sb_r}: slewing bar rotation point
- P_{bk_r}: bucket rotation point
- P_{bk_c}: bucket centroid

- F_{bkr}: bucket ram force (+: when F_{bkr} generates a curling moment; -: otherwise)
- F_{tb}: bucket ram force transmitted through transmit bar (+: when F_{tb} generates a curling moment; -: otherwise)
- W_{bk}: bucket weight including soil weight (+: when W_{bk} generates a curling moment; -: otherwise)

- V_{bk_r}: vector from P_{bk_r} to the tip of bucket tooth
- V_{bp}: vector from bucket corner to the tip of bucket tooth

- D_{bkr}: distance of F_{bkr} to P_{sb_r}
- D_{tb}: distance of F_{tb} to P_{sb_r}
- D_{bk}: distance of F_{tb} to P_{bk_r}
- $H_{bk\_c\_bk\_r}$: horizontal distance between P_{bk_c} and P_{bk_r}

- θ_{bk}: angle measured from V_{bp} to V_{bk_r} in an uncurling direction

- B_{r_bkr}: bucket ram induced bucket force (acting on the tip of bucket tooth, normal to V_{bk_r})
- B_{p_bkr}: component of bucket ram induced bucket force parallel to bucket bottom plate
- B_{n_bkr}: component of bucket ram induced bucket force normal to bucket bottom plate

When some or all of a bucket ram , a stick ram, and a boom ram are applied simultaneously as shown in Figure 4.9, the components of a total bucket force can be determined by combining (4-3), (4-6) or (4-10) for a total bucket force parallel to the bucket bottom plate ($\boldsymbol{B_p}$), and (4-4), (4-7) or (4-11) for a total bucket force normal to the bucket bottom plate ($\boldsymbol{B_n}$).

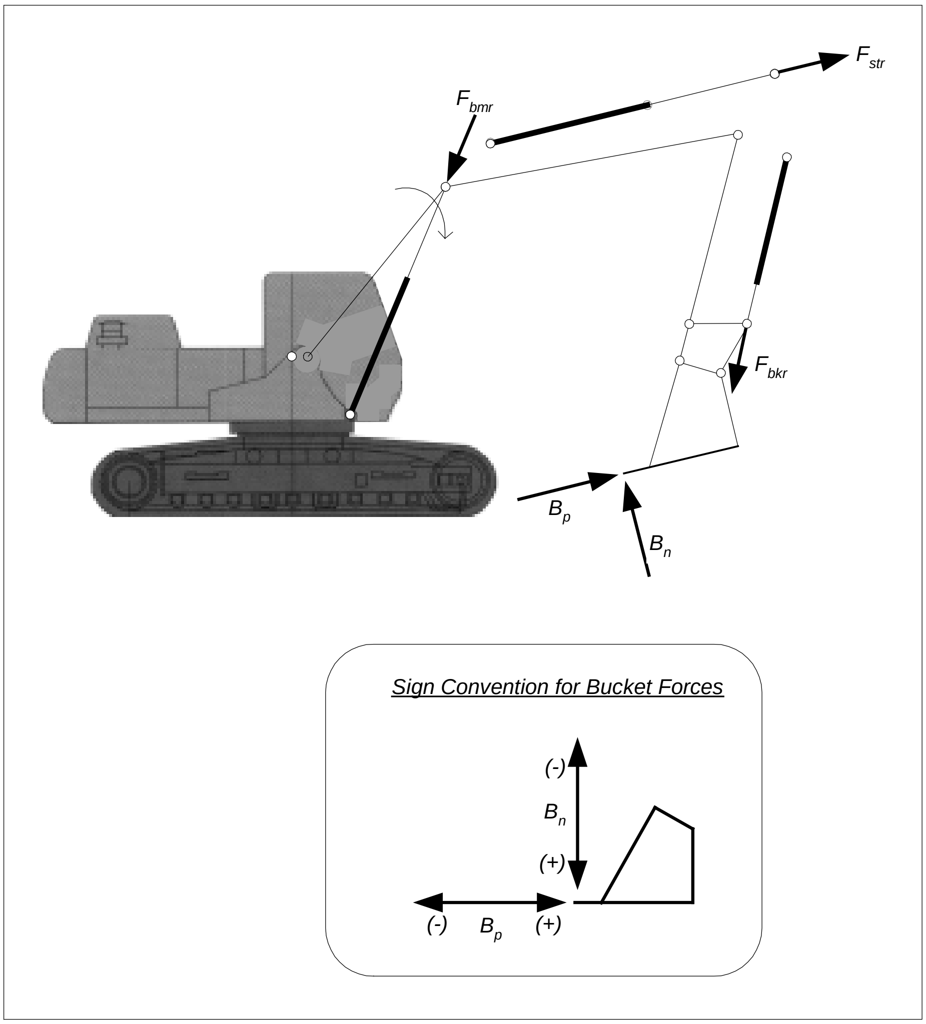

Figure 4.9 Parallel and Normal Components of a Total Bucket Force

$$^{\pm}B_p = (^{\pm}B_{p\_bmr}) + (^{\pm}B_{p\_str}) + (^{\pm}B_{p\_bkr}) \tag{4-12}$$

$$^{\pm}B_n = (^{\pm}B_{n\_bmr}) + (^{\pm}B_{n\_str}) + (^{\pm}B_{n\_bkr}) \tag{4-13}$$

Where,

- F_{bmr}: boom ram force
- F_{str}: stick ram force
- F_{bkr}: bucket ram force

- B_p: component of total bucket force parallel to bucket bottom plate
- B_n: component of total bucket force normal to bucket bottom plate
- B_{p_bmr}: component of boom ram induced bucket force parallel to bucket bottom plate
- B_{n_bmr}: component of boom ram induced bucket force normal to bucket bottom plate
- B_{p_str}: component of stick ram induced bucket force parallel to bucket bottom plate
- B_{n_str}: component of stick ram induced bucket force normal to bucket bottom plate
- B_{p_bkr}: component of bucket ram induced bucket force parallel to bucket bottom plate
- B_{n_bkr}: component of bucket ram induced bucket force normal to bucket bottom plate

The signs of forces $\boldsymbol{B_p}$ and $\boldsymbol{B_n}$ determines whether they can be used for excavating soil or not. Negative forces represent a situation where an excavator is not engaged in any digging actions. Only when a force component (either $\boldsymbol{B_p}$ or $\boldsymbol{B_n}$) is positive, it is compared with a corresponding resistance force to check the excavatability of an excavator against soil.

Note that when the bucket goes through soil media, its dynamic effect due to velocity and acceleration is considered to be negligible. Therefore, the dynamic force is not included in the force determination procedure.

4.4 Conclusion

The excavator computational model (or physics-based excavator model) represents essential internal and external parts of a typical (hydraulic) excavator to generate physically meaningful machine responses. Specifically, it calculates the locations of excavator moving parts (a boom, a stick and a bucket) and the forces at a bucket using the calculation scheme presented in this chapter. The calculation result from the excavator computational model is used by the simulation engine to ensure the interaction between the excavator bucket and the soil.