Scalability Study of Particle Method with Dynamic Load Balancing

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Abstract

We introduce an efficient load-balancing algorithm for particle method (Particle Blast method and Corpuscular Particle method) in LS-DYNA®. Load-balancing is achieved by dynamically adaptively using RCB to evenly distribute workload to processors. Numerical tests demonstrated that with reformulated parallel scheme, for PBM, the speedup for an airblast problem can be 20~30 times or more when using 128~192 cores; for CPM, several times speed up can be achieved for a curtain airbag simulation.

Introduction to Particle Blast Method

Particle blast method (PBM) [1][2] is intend to model the gaseous behavior of high velocity, high temperature detonation products. PBM is developed based on corpuscular method (CPM), which has been successfully applied to airbag deployment simulation where the gas flow is slow. For blast simulation where gas flow is extremely high, the equilibrium assumption in CPM is no long valid. By reformulating the particle interaction algorithm, the PBM is capable of modelling blast loading that is typical thermally non-equilibrium system.

Since PBM was implemented in LS-DYNA in 2013, the accuracy of PBM have been demonstrated in [3][4]. Due to its simplicity and robust, this method is suitable for problems with complex geometry and boundaries. The Lagrangian nature allows non-diffusive advection. However, the performance of parallel code was not quite satisfactory. The PBM did not scale well when the total number of CPU is less than ~20. When more CPU are used, the speedup became saturated.

In this paper, we developed dynamic load-balancing algorithms for PBM. These are needed to handle millions or tens of millions of particles modeled in large distributed-memory computer systems. The basic idea is to control the domain partitioning to give each process an equal workload during the simulation run. Our method utilizes Recursive Coordinate Bisection (RCB) domain decomposition which recursively halves the model using the longest dimension of the input model. The imbalances in the execution time between parallel processes are monitored. Load-balancing is achieved by dynamically adaptively using RCB to make sure each process has equally workload.

Numerical Case 1: Air Blast Simulation

The experimental example is taken from [5] and has been studied in [2], where clamped square 3.4 mm thick AL-6XN plates are exposed to the blast loading from a spherical charge consisting of 150 g C-4. The charge was placed 150mm from the plate. The test apparatus allowed 613 mm square test plates to be fully edge-clamped using a cover plate and series of bolts. The region exposed to sand impulse was 406 mm x 406 mm. The region below the plate was hollow and shielded from the blast, enabling the target unrestricted deflection. (***Figure 1***).

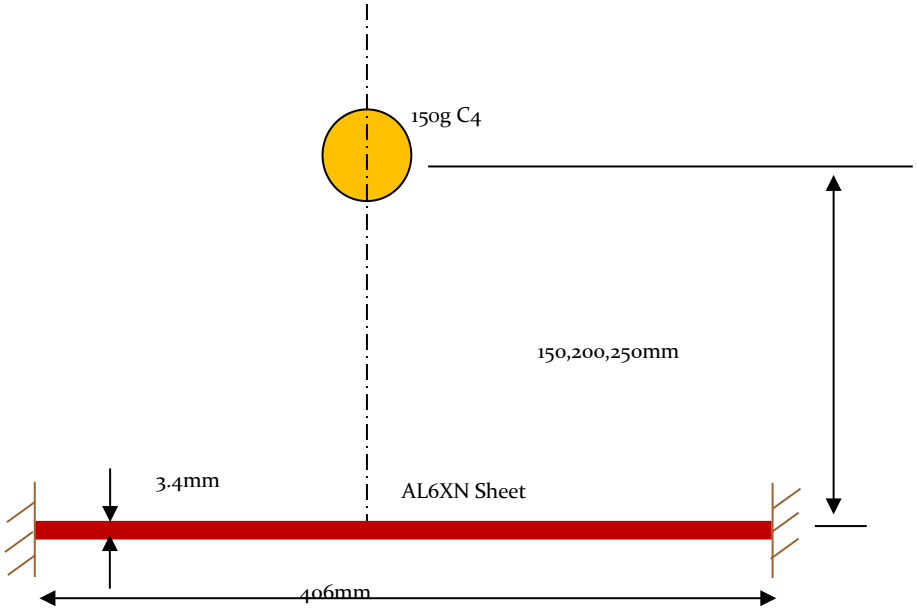

Figure 1 Sketch of the experimental set-up

The AL-6XN steel is a relatively new stainless steel with high strength, very good, and excellent corrosion resistance in chloride environments. The AL-6XN stainless steel material was modeled using a modified Johnson-Cook constitutive equation *MAT_MODIFIED_JOHNSON_COOK. The material parameters used in the simulation are adopted from [5] and listed in *Table 1*.

ρ (kg/m^3)	E(Gpa)	ν	χ	C_p (J/kgK)	α(K^{-1})	$\dot{\varepsilon}_0$(S^{-1})
8060	195	0.3	0.9	500	1.5E-5	1.E-3
A(MPa)	B(MPa)	n	C	m	Tr(K)	Tm(K)
410	1902	0.82	0.024	1.03	296	1700

Table 1 Material properties of the AL-6XN stainless steel

A cross-section of the bare charge simulation model at different time is shown in ***Figure 1***. Free boundary conditions were used such that no reflections from the boundaries are present. The number of air particles is set such that air particle mass equal to C-4 particle mass. Simulations were conducted using (N_{he}; N_{air}) = (2,000,000; 1,700,000). The comparison between numerical results with experimental results has been performed in [2] and will not be discuss here.

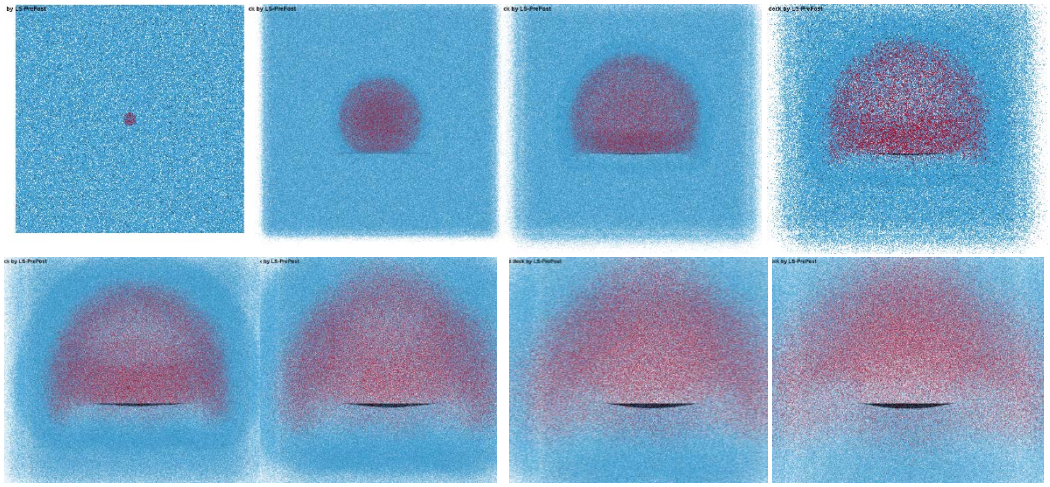

Figure 2 PBM simulation with (200000:1700000) after detonation

Table 2 list the total CPU time comparison between R122420 with current approach that with dynamic rebalancing version (RB). It can be seen that for R122420 that without rebalancing, the performance for 12 processes is already saturated: more processes just mean more simulation time, the simulation time increase from 7 hours to ~10 hours when 192 processors are used. The current approach can scale up to nearly 200 processes. Furthermore, the total CPU time is greatly reduced: with 12 processes, the CPU time is reduced from 7 hours to 1 hour 22 minute, more than 5 times speedup is obtained. The speedup increase with more processes. For the case with 192 processes, almost 30 time speedup is obtained, the total CPU time is reduced from ~10 hours to ~20 minutes.

#of CPUs	Total CPU time(s)		
	SVN 122420	RB	Speedup
12	25190(7h0m)	4916(1h22m)	5.12
24	24681(6h51m)	3188(53m)	7.77
48	26540(7h22m)	2168(36m)	12.24
96	30719(8h32m)	1482(25m)	20.73
192	35627(9h54m)	1217(20m)	29.27

Table 2 Total CPU time

#of CPUs	Particle to Particle Contact time(s)		
	SVN 122420	RB	Speedup
12	15506	2596	5.97
24	15809	1411.2	11.20
48	17183	739.7	23.23
96	19912	394.9	50.42
192	22468	239.1	93.97

Table 3 Particle-Particle Contact time

#of CPUs	Particle to Structure C time(s)		
	SVN 122420	RB	Speedup
12	4982.6	1714.1	2.91
24	4742.3	1350.7	3.51
48	5118.1	1127.5	4.54
96	6585.0	849.2	7.75
192	8863.7	731.9	12.11

Table 4 Particle-Structure Contact time

Table 3 and Table 4 list the CPU time for particle-particle contact and particle-structure contact. Particle-particle contact clearly achieve much better scalability. With 192 processors, nearly 2 order of speedup is obtained for particle-particle contact compared to R122420. The CPU time spent on particle-particle contact is reduced from more than 6 hours (22468s) to less than 4 minutes (239.1s). The speedup for particle-structure contact time is not as good as particle-particle contact, due to the fact that particle and structure are decomposed separately, but still get ~12 time for 192 processors.

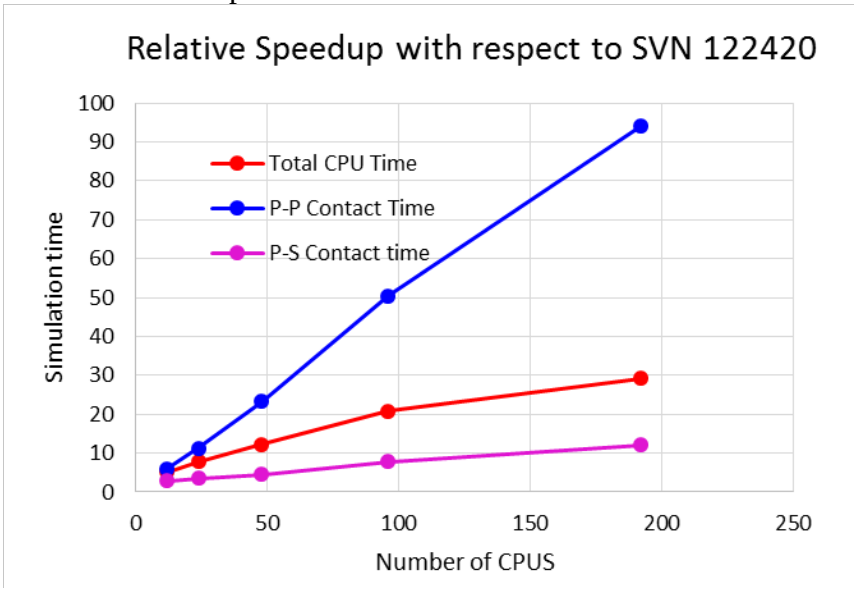

Figure 3 Relative Speedup with respect to SVN 122420

The relative speedup curve for total CPU time, particle-particle contact, and particle-structure contact is shown in ***Figure 3***.

Numerical Case 2: Cylinder Test on C-4

The cylinder test [6] is often used to characterize the material EOS of high explosive. It consists of a pipe made of OHFC copper that is filled with the high explosive to be characterized. The explosive is initiated at one end, whereupon a detonation wave travels along the pipe. The pipe wall motion is monitored and its radial velocity at various locations along the pipe axis can be used to determine the properties of the high explosive. ***Figure 4*** shows a model simulation where a copper pipe with an inner radius of 12.715mm, a wall thickness 2.593mm and a length of 300mm was filled with 5,000,000 C4 HE particles

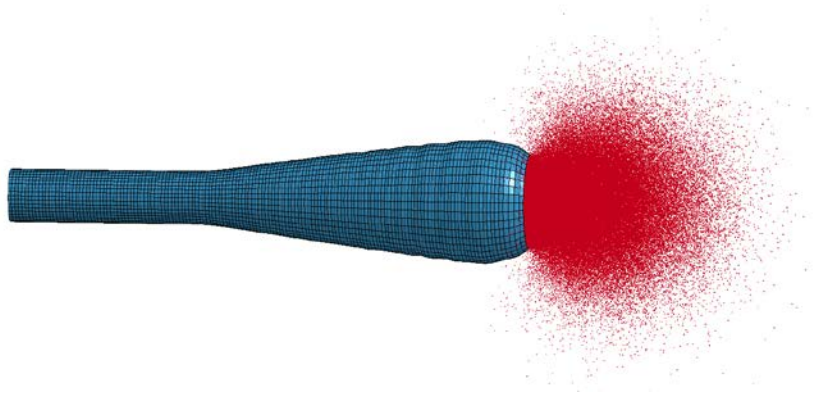

Figure 4 Simulation of a cylinder test

Table 5 list the total CPU time comparison between R122420 with rebalancing version (RB). It can be seen that for R122420 that without rebalancing, when the number of processors increased from 32 to 128, the total CPU time is almost remain unchanged. The current approach can get nearly perfect linear scale up even update up to 128 processes. When 128 processes are used, ~ 22 time speedup is obtained. Table 3 and Table 4 list the CPU time for particle-particle contact and particle-structure contact. Again, the most of the time reduction come from particle-particle contact, as shown in Table 6 and Table 7. **Figure 5** shows the relative speedup curve for total CPU time, particle-particle contact, and particle-structure contact.

#of CPUs	Total CPU time(s)		
	SVN 122420	RB	Speedup
32	10098	1665	6.06
64	10058	862	11.67
128	9690	427	22.7

Table 5 Total CPU time

#of CPUs	Particle to Particle Contact time(s)		
	SVN 122420	Dev	Speedup
32	8189	1204	6.80
64	8380	533.5	15.7
128	8067	225	35.9

Table 6 Particle-Particle Contact time

#of CPUs	Particle to Structure Coupling time(s)		
	SVN 122420	Dev	Speedup
32	1380	242.8	5.68
64	1197	164.7	7.3
128	1212	85.2	14.2

Table 7 Particle-Structure Contact time

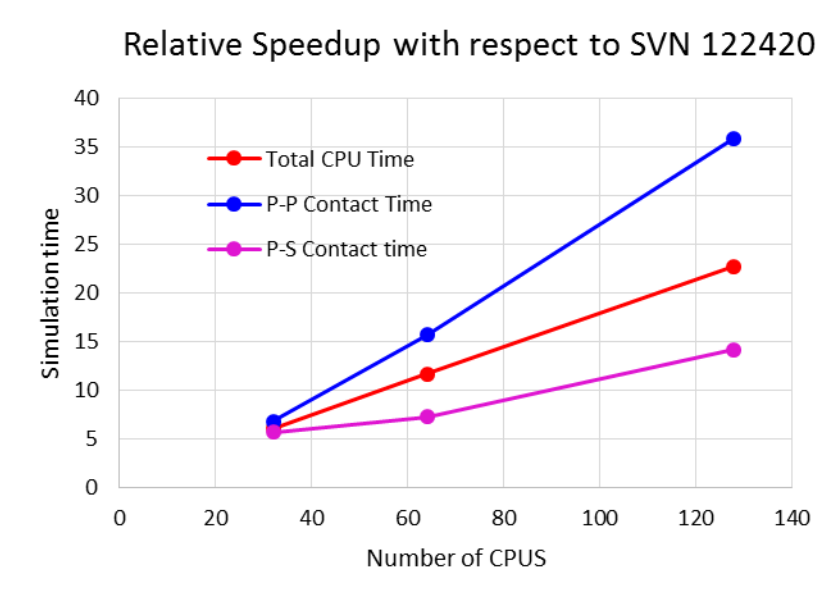

Figure 5 Relative Speedup with respect to SVN 122420

Numerical Case 3: Ground Blast with Cylindrical Shaped Charge

The experimental example is taken from [7], where blast trials with the explosives placed in a steel pot were performed. The experimental set up is shown in Figure 10, where a ground blast rig with the sides 3 × 2 m and total height 2.7 m includes a hanging test module. The test module consists of a square target plate of steel quality Weldox 700E with dimension 600 × 600 × 8 mm, held in place at the corners with a plate holder. The inner diagonal length of the plate holder is 627 mm. The total weight of the test module is 2120kg. The explosive type was plastic explosive m/46, consisting of 86% PETN and 14% fuel oil, with a density 1500kg/m^3. The charge shape was cylindrical with diameter to thickness ratio of 3 and total weight 0.75kg. More detailed experimental setup can be found at [7].

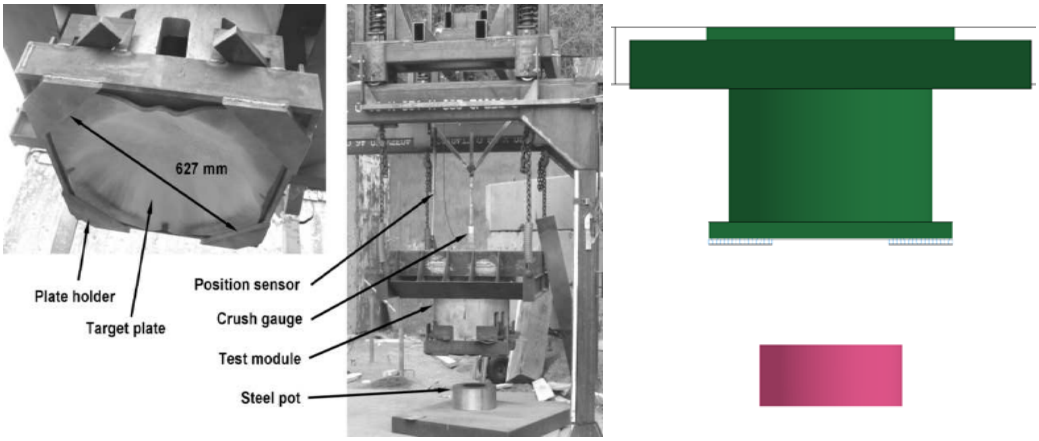

Figure 6 Experimental setup for the ground blast

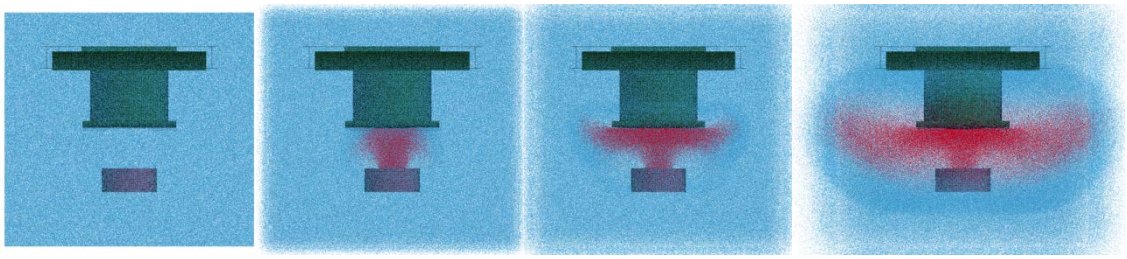

Figure 7 *PBM simulation with (200000:1300000) after detonation*

Simulations were conducted using (N_{he}; N_{air}) = (2,000,000; 1,300,000). A cross-section of the bare charge simulation model at different time is shown in *Figure 7*. Table 2 list the total CPU time, particle-particle contact time, and particle-structure contact time comparison between R122420 with rebalancing version (RB). Again R122420 is saturated for 12 processors, the total CPU time increase steadily up to ~16 hours for 96 processors, and then sharply to more than 21 hours for 192 processors. The current approach can scale even up to nearly 200 processes. When 192 processes are used, more than 31 time speedup is obtained, the total CPU time is reduced from ~21 hours to ~40 minutes. The speedup for particle-particle contact is even enormous and reach to ~95 for 192 processors. For particle-structure contact, a relative good speedup is also obtained, with 192 processors, ~27 speedup is obtained. The relative speedup for total CPU time, particle-particle contact, and particle-structure contact is shown in ***Figure 8***.

#of CPUs	Total CPU time(s)		
	SVN 122420	Dev	Speedup
12	52549(14h36m)	8431 (2h20m)	6.2
24	51193(14h13m)	5517(1h32m)	9.28
48	56933 (15h48m)	3596 (1h)	15.8
96	57281(15h54m)	2825 (47m)	20.3
192	75810(21h03m)	2414(40m)	31.4

Table 8 Total CPU time

#of CPUs	Particle to Particle Contact time(s)		
	SVN 122420	Dev	Speedup
12	29425	4173.4	7.1
24	29087	2453.3	11.86
48	34156	1321.5	25.8
96	34171	808.7	42.3
192	44812	473.8	94.6

Table 9 Particle-Particle Contact time

#of CPUs	Particle to Structure Coupling time(s)		
	SVN 122420	Dev	Speedup
12	11898	1351.5	8.80
24	12180	1077.6	11.30
48	13132	877.72	14.96
96	14531	803.19	18.09
192	21695	795.3	27.28

Table 10 Particle-Structure Contact time

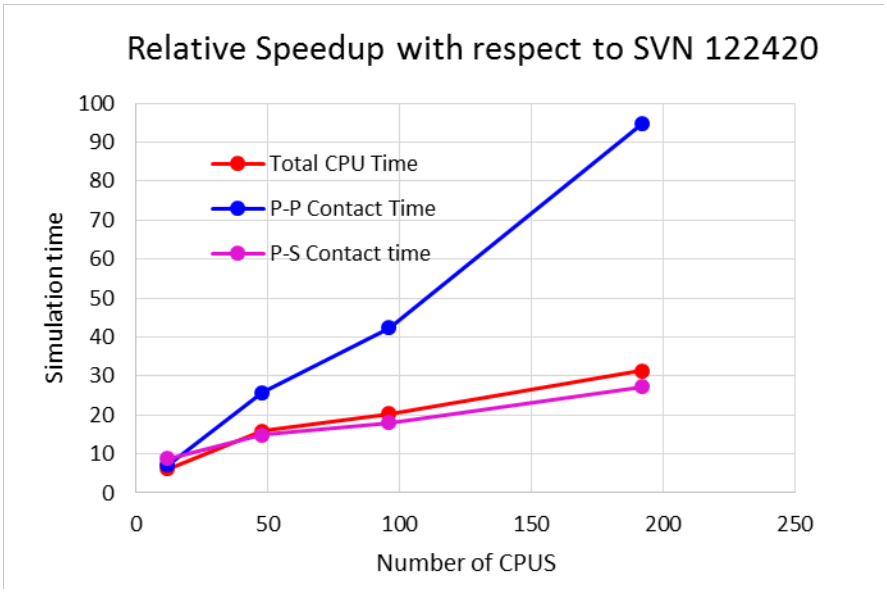

Figure 8 Relative Speedup with respect to SVN 122420

Summary

We introduce dynamic load balancing approach for particle blast method (PBM). By applying a Recursive Coordinate Bisection (RCB) domain decomposition scheme, a minimization of communication expense and evenly distributed workload can be achieved. Several numerical test demonstrate the efficiency of the approach.

References

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