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Design and analysis of a tall building with an active mass damper

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ABSTRACT: The authors have developed a Tuned Mass Damper (TMD) with the aim of improving the habitability of buildings during frequent medium winds and to reduce the vibrations caused by strong winds and earthquakes. The system was installed in the Chiba Port Tower in 1986 and Fukuoka Tower in 1989. From dynamic response analysis using measured data of earthquake and wind actions on those towers, the response control effects of the TMD have been confirmed. On the basis of this TMD for tower structures, an Active Mass Damper (AMD) is being developed and installed in a tall building now under construction. This report describes the design criteria, design specifications, and mechanisms of this AMD. In addition, dynamic analysis of the building fitted with the AMD is carried out and the response control effects of the AMD are examined from the energy point of view.

STRUCTURAL OUTLINE OF THE BUILDING

The building in which the device to be installed is the head office of a company. Located in Tokyo, Japan, its construction was commenced in August 1990 and completion is scheduled for August 1993. It is a high rise building 130 m high, 21 stories above, 5 under the ground, and a total floor area of 63,000 m^2. This building is a steel structure with a T-shaped outline in one elevation (x-direction) and a simple tower shape with an aspect ratio of five (130m tall / 26m wide) in the other (Y-direction). At the ground, it is 56 m long in the X-direction, increasing with 20 m cantilever extending from the 8th floor to a maximum of 96 m. This building adopts a mega-frame structure consisting of 9m deep truss girders and 4m deep built-up columns. This frame supports the 20 m cantilevered portions while also reducing the deflections of the building caused by strong winds and earthquakes. However, to further reduce vibrations, it is not sufficient to simply increase the rigidity of the forms; rather it is necessary to improve the damping. For this reason, the AMD will be installed on the roof floor to reduce vibrations caused by strong winds and earthquakes and thus improve habitability.

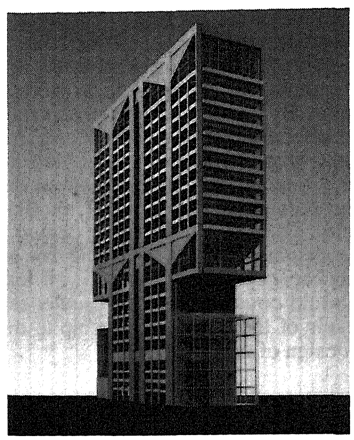

Fig. 1. Full view of building.

Table 1. Weights and periods.

Weight of structure		39,800tons
1st-mode effective mass	X-direction	30,400tons
	Y-direction	30,000tons
Natural period	X-direction	2.96sec
	Y-direction	2.97sec

DESIGN CRITERIA

The design of the building takes no account of the stress reduction achieved by the AMD, but is designed to withstand a failure of the building caused by strong winds and earthquakes under the condition of the fixed AMD. The design criteria for the AMD are described below.

1. To reduce deformation of the building during strong winds and earthquakes,and improve habitability, the AMD will be installed on the roof.

2. The mass damper will operate continuously, in a condition of frequent moderate winds and weak earthquakes to rare strong winds and severe earthquakes.

3. The natural period of the mass damper will match with the natural period of the building, as it will act as a TMD. The mass damper will normally operate on active control. When the external force exceeds the control

range of the AMD, the device will act as a TMD.

4. The optimum regulator theory is adopted as the active control method. Gains I and II, described below, are varied to suit the magnitude of the external forces. That is, with frequent moderate winds and weak earthquakes, control will be by I only. During rare strong winds and moderate earthquakes the control will be switched between I and II continuously.

Gain I: Minimizes vibration of the building.
Gain II: Maintains the stroke ,the controlling force and the control speed (amount of oil flow) of the actuator within the limit of its capacity.

5. During a service interruption, the mass damper will operate as a TMD. This assumes, however, that the control system continues to receive power from the emergency power supply incorporated in the device (capacity: about 20 minutes) or the building's emergency generator, allowing the damping factor of the TMD to be changed to suit the magnitude of the external forces.

These control concepts (variable gain control) are explained using a comparison of the response of the non-controlled buildings , with optimum TMD, and with optimum AMD (Fig. 2). In these figures, the X-axis is the input acceleration of earthquakes and the Y-axis is respective displacements of the mass damper and the floor response acceleration of the building.

When input motions are small, the response control effects are the same as with optimum AMD. As the input increases, the optimum AMD displacement exceeds the limit of its capacity. By switching the gain, although the response control effects are somewhat reduced, the mass damper will be within its operating range. As the input level becomes yet larger, the displacement of the optimum TMD, whose damping factor is 0.07, exceeds the limit of its capacity. Then ,by increasing the damping factor to h=0.40,the displacement of the TMD can be within the limit of its capacity. The design policy is that the mass damper should continue operating under the condition of any levels of the external forces up to the level defined in the design of the building.

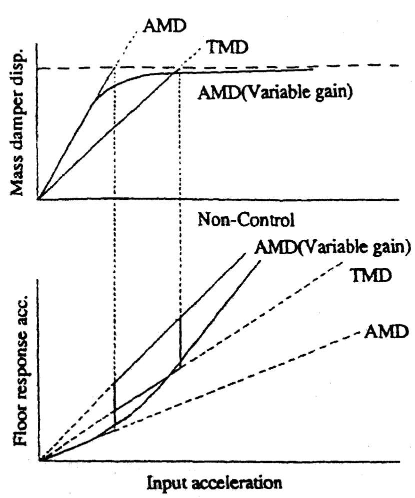

Fig. 2. Concept of variable gain control

MECHANISM OF THE AMD

The mechanism of the AMD is shown in Fig. 3.

The mass is 200 tons, which is about 0.7% of the 1st-mode effective mass of the building. Storage tanks (20 tons x 6 units) account for 60% of this mass.

The support mechanism consists of 6 multi-stage laminated rubber bearings with a natural period equal to the natural period of the building, about 3 seconds, so as to enable support without friction. These multi-stage laminated rubber bearings consist of multi-layer rubber bearings that are used in the base isolation, stacked in 9 stages. They allow an elastic deformation of about +/- 1m. The bearings are constructed from alternating rubber sheets and steel plates in a sandwich design, allowing large deformation with low rigidity in the horizontal direction while giving high rigidity in the vertical direction.

The controlling force is supplied by a hydraulic actuator supplied from a hydraulic pump and an accumulator tank. The high-pressure fluid is nonflammable liquid glycol, thus avoiding any problems with the storage of flammable materials in quantity on the floor. It is also highly stable.

The sensors used to measure building vibrations are installed on the 1st, 8th, and 15th floors, and the floor with mass damper. Fig. 4 shows the location of AMD and measuring devices and Table 2 gives the constants of the AMD.

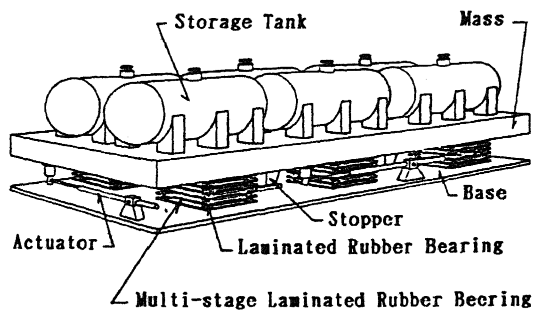

Fig. 3. Mechanism of AMD.

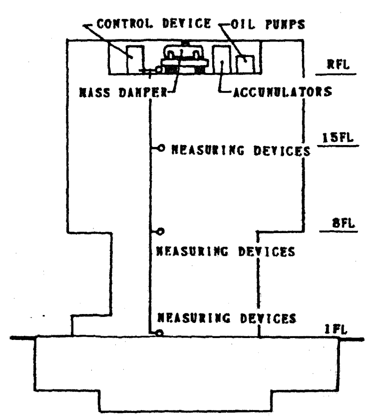

Fig. 4. Location of AMD and measuring.

Table 2. Constants of the AMD

Mass		200 tons
Maxium amplitude		+/-1.0 m
Natural period		3.0 sec
Support mechanism		Multi-stage laminated rubber bearing
Actuator components	Max. output	30tonf in all directions
	Hydraulic pump	30 kW×4 units
	Auxiliary pump	11 kW×1 units
	Accumulator	2,000 liters
Damping factor of support mechanism		2 %
Max. damping factor of TMD		40 %

4. EVALUATION BASED ON ENERGY

As an evaluation of its vibration control effects, a method based on energy is proposed here. The equation of motion for a building with an AMD can be expressed as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\}-[M]\{1\}\ddot{z} \tag{1}$$

where,

- $[M]$: Mass matrix
- $[C]$: Damping matrix
- $[K]$: Stiffness matrix
- $\{F\}$: Controlling force of actuator
- $\{x\}$: Displacement vector
- $\{\dot{x}\}$: Velocity vector
- $\{\ddot{x}\}$: Acceleration vector
- $\ddot{z}$: External force due to earthquake
- $\{1\}$: Unit vector
- N : Total number of building stories

By multiplying both sides of equation (1) by $\{\dot{x}\}^T dt$ and integrating, the equation becomes,

$$\int\{\dot{x}\}^T[M]\{\ddot{x}\}dt+\int\{\dot{x}\}^T[C]\{\dot{x}\}dt+\int\{\dot{x}\}^T[K]\{x\}dt$$
$$=\int\{\dot{x}\}^T\{F\}dt-\int\{\dot{x}\}^T[M]\{1\}\ddot{z}dt \tag{2}$$

In addition, equation (2) can be expressed by separating it into the mass damper system and the structure system as follows:

$$1/2m_d(\dot{x}_d+\dot{x}_N)^2+1/2\{\dot{x}_s\}^T[M_s]\{\dot{x}_s\}+\int c_d\dot{x}_d^2dt$$
$$+\int\{\dot{x}_s\}^T[C_s]\{\dot{x}_s\}dt+1/2k_dx_d^2+1/2\{x_s\}^T[K_s]\{x_s\}$$
$$=\int\dot{x}_dFdt-\int m_d(\dot{x}_d+\dot{x}_N)\ddot{z}dt-\int\{\dot{x}_s\}^T[M_s]\{1\}\ddot{z}dt \tag{3}$$

In equation (3), subscripts s represents the structure system and d indicates the mass damper system. $x_d, \dot{x}_d, \ddot{x}_d$ are displacement, velocity, and acceleration of the mass damper relative to the top floor of the structure.

In addition, by replacing them with the following:

- EK_d : Kinematic energy of mass damper
- EK_s : Kinematic energy of structure
- ED_d : Energy absorbed by damping of mass damper
- ED_s : Energy absorbed by damping of structure
- ES_d : Strain energy of mass damper
- ES_s : Strain energy of structure
- EA : Work of actuator
- I_d : Seismic input energy into mass damper
- I_s : Seismic input energy into structure

the equation becomes an energy balance as shown below.

$$EK_d+EK_s+ES_d+ES_s+ED_d+ED_s=EA+I_d+I_s \tag{4}$$

The right-hand side of the equation represents the sum of seismic input energy into the building-mass damper system and that of the actuator and the left-hand side is the sum of the energies expended by the building and mass damper.

Also, for a TMD, the controlling force of the actuator becomes zero, and equation (4) can be written with EA eliminated.

In the case of a non-damped building, equation (4) can be re-written without the term for the mass damper:

$$EK_s+ES_s+ED_s=I_s \tag{5}$$

By comparing the kinematic energy and the strain energy of the building ($EK_s + ES_s$) as shown in equations (4) and (5) in the three cases, the response values instead of displacement and acceleration etc., can be examined. By comparing the energies absorbed by the structure and the mass damper, the vibration controlling effects can be examined. Also, from the work done by actuator, the Gains efficiency can be checked.

EXAMINATION OF RESPONSE CONTROL EFFECTS USING DYNAMIC RESPONSE ANALYSIS

The building is modeled as a 19-mass full matrix model with regard to the X-direction of the building.

As shown in Fig. 5, a 20-mass building model is used for the analysis with one mass representing the mass damper on the top floor. Five control models are studied for this analysis model.

Model N-1, a non-controlled building
Model T-1, a building with an optimum TMD(h=0.07)
Model A-1, a building with a Gain I AMD
Model A-2, a building with a Gain II AMD
Model T-2, a building with a TMD(h=0.40)

The time history of a record of earthquake EL CENTRO,CALIFORNIA MAY 5, 1940, NS is used as the input data adjusted to each maximum acceleration level shown below.

To verify the response control effects of Gain I,a dynamic analysis with a maximum input acceleration of 15 m/s^2 was performed and Fig. 6 shows a comparison

of the results for models A-1and N-1.

To verify the response control effects of Gain II,a dynamic analysis with a maximum input acceleration of 200 cm/s^2 was performed and Fig. 7 shows a comparison of the results for models A-1 and N-1.

For the maximum seismic motion in building design, a dynamic analysis of the TMD with h=0.40 was performed under the condition that the maximum input acceleration is 500 cm/s^2 and the results are shown in Fig. 8.

Also, Figs. 9-13 show the time history of dissipated energy and the input energy for the each model. Table 3 gives the maximum response displacement and acceleration. Table 4 shows the ratio of each energy to input energy of the non-controlled building.

From these analyses, the following results were obtained.

- The AMD with Gain I reduces not only the 1st vibration mode, but also the 2nd vibration mode of the building and is able to reduce the maximum displacement at the top to 1/3 that of the non-controlled building, and to 1/2 that of the building with a TMD (Fig. 6 and Table 3).
- In the case of Gain II, with an input seismic motion of maximum acceleration 200 cm/s^2, the stroke of the AMD is 99 cm and its control force is 24.3tonf. Those maximum values are within allowable range respectively. The maximum displacement of the top floor of building is reduced to about 80% that of the non-controlled building (Fig. 7 and Table 3).
- In the case of TMD with a damping factor of h=0.40, with an input seismic motion of maximum acceleration 500 cm/s^2, the relative displacement is 96.5cm. This maximum value is within the allowable range. The maximum displacement of the top floor is reduced to about 90% that of a non-controlled building (Fig. 8 and Table 3).
- The ratio of the seismic input energy into the controlled building to that into the non-controlled building is found to be reduced as control becomes stronger, i.e. 0.9 in the case of a building with a TMD damper, 0.9 in the case of a building with an AMD damper with Gain II, and 0.6 with Gain I, where all values are compared with a non-controlled building.
- An evaluation of response control effects using the kinematic energy and strain energy of the building yields values nearer to r.m.s. values than to the maximum values of absolute acceleration and relative displacement of the top floor of the building.
- The sum of the damping energies of the building and the mass damper is about equal to the seismic input energy and the greater the damping energy of the mass damper, the bigger the response control effects.
- The work done by the actuator in a building with an AMD damper is an index that shows the intensity of the gain and for gains where the response control effects are large, the work done by the actuator accumulates as the vibration of the building increases and when the vibration of the building comes to an end, the accumulated value falls, it draws closer to zero.(see Fig.11) Where the gain is weaker, it shows a negative value as it acts as a braking force, becoming absorbing energy by damping that acts the same as ED_d on the right-hand side of the equation (4), and accumulating the energy.(see Fig.12)

Table 3. Maximum and r.m.s. response values

Max. acc. of input			15cm/s^2			200cm/s^2		500cm/s^2	
Analysis model			N-1	T-1	A-1	N-1	A-2	N-1	T-2
Roof floor	Relative displacment (cm)	Max.	2.8	2.0	1.0	37.7	27.0	94.5	83.3
		r.m.s	1.2	0.7	0.2	15.5	9.3	38.7	30.8
	Absolute acceleration (cm/s^2)	Max.	27.1	26.8	15.1	361.6	345.5	904.1	874.9
		r.m.s	6.5	4.8	2.2	86.1	64.1	215.4	185.0
Mass damper	Relative displacment (cm)	Max.	—	10.4	27.8	—	99.0	—	96.5
		r.m.s	—	3.8	6.3	—	36.4	—	38.3
	Controlling force (t)	Max.	—	—	30.9	—	24.3	—	—
		r.m.s	—	—	6.1	—	7.7	—	—
Equivalent vel. V_E(cm/s)1)			5.0	4.8	3.7	66.4	61.8	166.6	161.4

1) The total energy input is expressed by equivalent velocity $V_E=\sqrt{2I/M}$. Where I:the total energy input($I=I_s+I_d$), M:mass of structure

Table 4. The ratio of each energy to nput energy of non-controlled building

Analysis model		N-1	T-1	T-2	A-1	A-2
Structure	Kinematic energy(EK_s/I)	0.56	0.45	0.45	0.16	0.43
	Strain energy (ES_s/I)	0.53	0.26	0.41	0.06	0.27
	Damping energy (ED_s/I)	0.75	0.43	0.56	0.13	0.43
	Input energy (I_s/I)	1.0	0.91	0.94	0.58	0.86
Mass damper	Kinematic energy(EK_d/I)	—	0.10	0.01	1.14	0.06
	Strain energy (ES_d/I)	—	0.10	0.01	0.69	0.05
	Damping energy (ED_d/I)	—	0.46	0.25	0.42	0.07
	Work of actuator (EA/I)	—	—	—	1.10	-0.35
	Input energy (I_d/I)	—	0.01	0.003	0.06	0.01
Total input energy (($EA+I_d+I_s$)/I)		1.0	0.90	0.94	1.42	0.72

I:Input energy of non-controlled building(I_s)

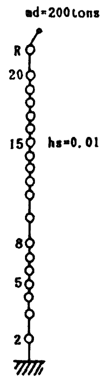

Fig. 5. Analysis module

CONCLUDING REMARKS

A mass damper that operates continuously over the range from frequent to strong winds, and from weak to severe earthquakes has been developed.

Under the condition of frequent moderate winds and weak earthquakes the AMD minimizes vibration of the building.

Under the condition of rare strong winds and moderate earthquakes, the stroke and the control force of the AMD are within the limit of the actuator capacity respectively.

Under the condition of severe earthquakes the mass damper acts as a TMD.

It has been shown that the response control effect of each system, i.e. non-controlled building, the TMD, the AMD, can be evaluated more clearly by using the evaluation method with the energy than by using the acceleration or displacement.

The kinematic energy and strain energy of the building can be used to evaluate the reduction of acceleration and relative displacement of the building.

The damping energy can also be used to evaluate the response control effects.

The work done by the actuator is useful as a measure of the AMD Gain.

We hope to develop a mass damper suitable for installation in a building by continuing our examination on the basis of this work.

ACKNOWLEDGEMENTS

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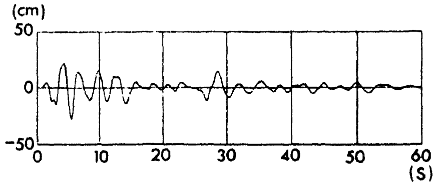
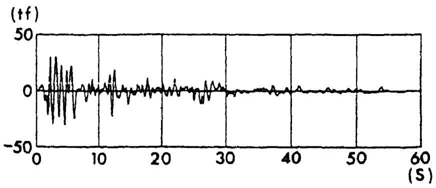
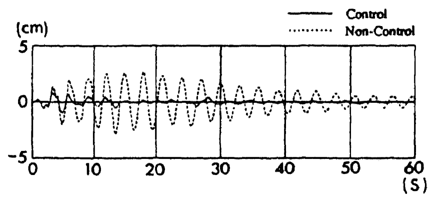


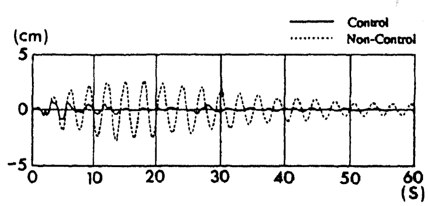
(a) Relative displacement of the AMD



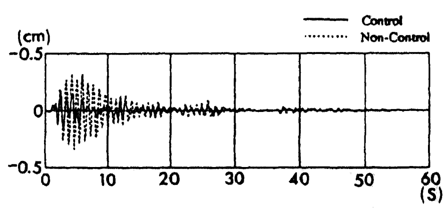
(b) Controlling force of actuator



(c) Relative displacement of roof floor

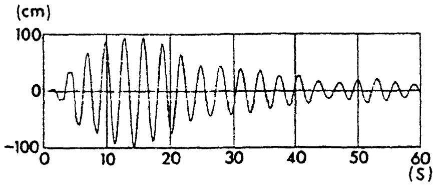


(d) 1st-mode displacement of roof floor

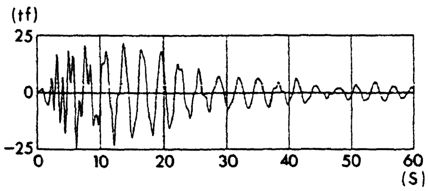


(e) 2nd-mode displacement of roof floor

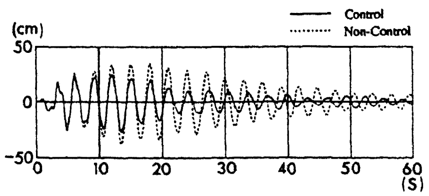
Fig. 6. Comparison between responses for non-control and AMD (EL CENTRO NS 15 cm/s^2).



(a) Relative displacement of the AMD

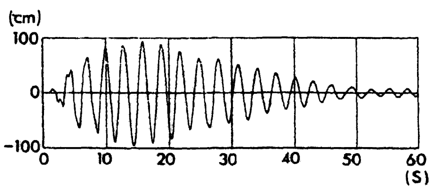


(b) Controlling force of actuator

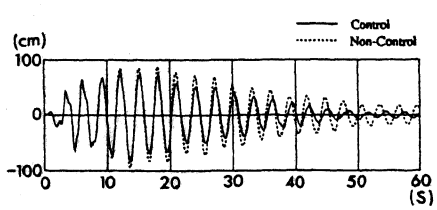


(c) Relative displacement of roof floor

Fig. 7. Comparison between response values at Gain II (EL CENTRO NS 200 cm/s^2).



(a) Relative displacement of the TMD



(b) Relative displacement of roof floor

Fig. 8. Response to design maximum seismic motion (EL CENTRO NS 500 cm/s^2).

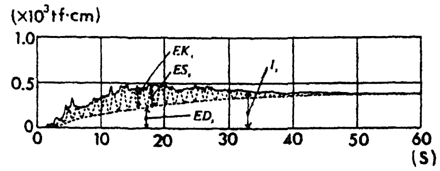


Fig. 9. Various energies of non-controlled building (N-1) (EL CENTRO NS 15 cm/s^2).

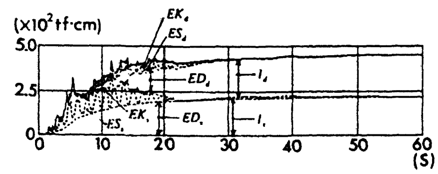
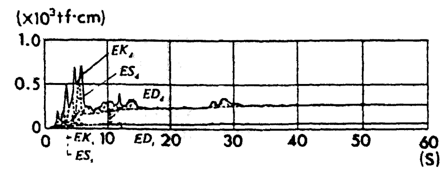
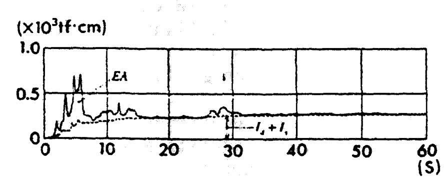


Fig. 10. Various energies of building with TMD (T-1) (EL CENTRO NS 15 cm/s^2).



(a) Dissipated energy



(b) Input energy

Fig. 11. Various energies of building with AMD (A-1) (EL CENTRO NS 15 cm/s^2).

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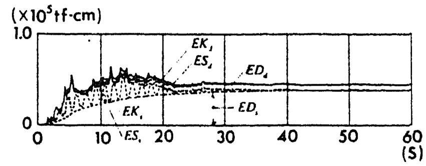
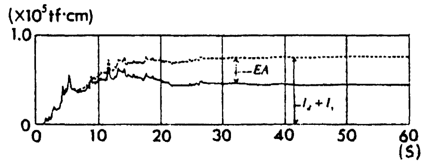


(a) Dissipated energy



(b) Input energy

Fig. 12. Various energies of building with AMD (A-2) (EL CENTRO NS 200 cm/s^2).

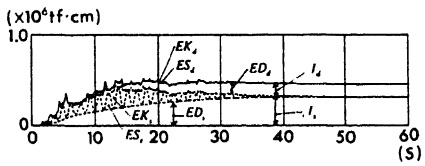


Fig. 13 Various energies of building with TMD (T-2) (EL CENTRO NS 500 cm/s^2).