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Free Aerial Fall Capsule for Microgravity Experiment of a 20 Sec Class

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Abstract

Conceptual design of a new convenient free fall capsule was developed for conducting animal experiment. In order to provide microgravity environment for at least 20 sec, technical feasibility of an atmospheric balloon borne system was examined. An experiment capsule is hung up by a balloon up to 3,000 m height. Free fall down to 1,000 m creates 20 sec microgravity environment inside the capsule. The terminal velocity of 196m/s, reaching after the fall, should be safely decelerated by deploying a parachute or any other appropriate way. The landing velocity is managed to be suppressed to around 1m/s. In order to cancel fluid dynamical drag during the free fall, use of a thruster system is one of the candidates. Our design goal is to develop the capsule that could be repetitively operated at affordable expenses. Safe recovery of the system after free fall might be the key for such concept. We hope our system would cradle many seeds of application by providing convenient access to microgravity.

Nomenclature:

m : mass of the dropping capsule (kg)
X : position of the dropping capsule (downward positive)(m)
X_I : position of the inner capsule (downward positive)(m)
δX: tolerance of X-direction between a inside surface of the dropping capsule and a outside surface of the inner capsule, and is equal to X-X_I (m)
X_a : minimum tolerance of δX (m)
X_b : maximum tolerance of δX (m)
t : time (s)
ρ: density of air (kg/m^3)
g : gravity constant (9.8m/s^2)
T_a: thrust force of augmentation thruster (N)
C_d: drag coefficient of the dropping capsule (-)
S_c: sectional area of the dropping capsule (m^2)
S_p : area of parachute (m^2)
C_p: drag coefficient of parachute (-)
T_r : thrust of retro motor (N)
F_s: force acted by side wind to the side of dropping capsule (N)
C_s: drag coefficient of the side of dropping capsule (-)
S_w : area of the side of dropping capsule (m^2)
V_w: velocity of side wind (m/s)
suffix 0: initial condition

1. Experiment Specific Requirements

(1) Observation of live mice and acquisition of their vital signals can be made through a period of microgravity. Capability for experiment shall be similar to that of JAMIC[(1)]. Transition from 1 G to microgravity at the start of free fall shall be stepwise, and physical environment in the experimental section shall be silent and noiseless as possible. It has to be operated likely in one's field and at affordable expenses less than another real way.
(2) Science merit of extending period of microgravity from 10 sec (once available at JAMIC) to 20 sec is enormous in the field of biomedical study.
The advantage of 20sec microgravity over 10sec one(once available at JAMIC) is that it affords detailed analyses on brain dysfunction such as panic-like disorder and amnesia (obtained at 10sec exposure).
Moreover, the recovery processes from such brain dysfunction could be observed during the following 10 sec microgravity.
(3) Physical size of experimental section for mice shall be larger than 0.3m for its width, depth and height.
(4) Environmental condition for keeping live animal shall be at normal environment for those species. Temperature, atmospheric pressure and other factors shall be controllable.

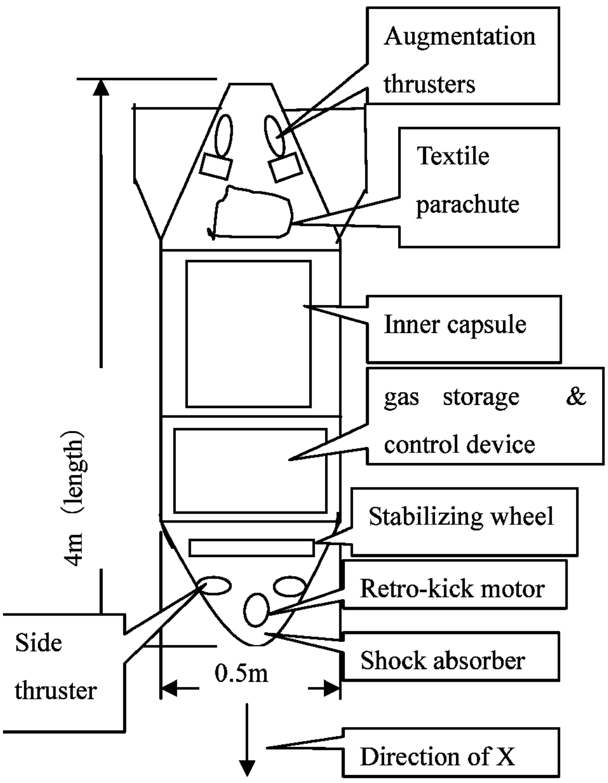
2. Design Criteria

(1) Select the shape to reduce air drag during its free fall.
(2) Consider thruster system to compensate air drag during free fall, and conduct trade off between

cold gas thruster system and/or hybrid rocket propellant thruster.
(3) Consider side thruster system to compensate air drag upon side winds during free fall.
(4) Increase vane stability for weathercock.
(5) Equip a device to decrease disturbance caused by sideway wind. Stabilize free fall angle close to vertical direction by wheel and side thrusters.
(6) Optimize soft landing system with parachutes and/or retro-kick motor.
(7) Minimize risk of crash at landing with shock absorbing device.
(8) Assess environmental factors at mice experiment section, such as sound, atmospheric pressure, temperature and others.
(9) Employ the double capsule system for higher microgravity experiments.
(10) Trade design of the drop capsule to meet the experiment requirements.

3. Summary of Design

The total mass of the dropping capsule is estimated about 150kg including mission payload and the inner capsule (in which experimental facilities are boarded) sized about 0.3m in diameter and 0.5m of height.



4. Motion of the Dropping Capsule during Free Fall

Forces acting on the dropping capsule are originated in gravity, air drag, viscosity, buoyancy and thrust of augmentation thrusters.

Viscosity is expressed as $6\pi\eta r dX/dt$.

Here π, η, r and dX/dt are circular constant, viscosity, typical radius and velocity, respectively.

In this case, the maximum resistance force of aerial viscosity at the maximum velocity of 196m/s of the capsule is 0.0665N.

This force is quite smaller than gravitational force applied on the dropping capsule, mg (≒1500N), and it can be neglected from the motion equation.

Buoyancy is expressed as $\rho g V$.

Here V is a volume of the capsule.

In this case, it is calculated that a buoyancy of the capsule is 0.00588N. This force is very smaller than the gravitational force.

Therefore, external forces dominating during aerial fall are gravity, air drag and thrust of augmentation thrusters.

Them motion equation of the capsule can be expressed as:

$$md^2X/dt^2=mg-C_d\rho S_c(dX/dt)^2/2+T_a \quad \text{---(1)}$$

Equation (1) can be solved by mathematical integration between t_n and t_{n+1} as:

$$Y(n+1)=(E(n+1)-1)/(E(n+1)+1) \quad \text{---(2)}$$

Here,

$$Y(n)\equiv dX(n)/dt_n$$

$$E(n+1)\equiv(1+\kappa(n)Y(n))/(1-\kappa(n)Y(n)) * \exp(2g\kappa(n)\mu(n)^2(t_{n+1}-t_n))$$

$$\kappa(n)\equiv\lambda(n)/\mu(n)$$

$$\lambda(n)\equiv\sqrt{(1/2)C_d\rho(n)S_c/(mg)}$$

$$\mu(n)\equiv\sqrt{1+T_a(n)/(mg)}$$

Suffix (n) means quantity at t_n and suffix (n+1) means quantity at t_{n+1}, respectively.

t_n means time of n in second.

Equation (2) gives velocity of the dropping capsule with thrust of the augmentation thrusters at time t_{n+1}, which can be calculated by step-by-step arithmetical operations starting from each initial values at t_0 .

Attitude X(n+1) of the dropping capsule at a time t_{n+1} is expressed as:

$$X(n+1)=X(n)+(t_{n+1}-t_n)(Y(n+1)+Y(n))/2 \quad \text{---(3)}$$

An altitude of the inner capsule at a time t_{n+1} is expressed as like as free fall in vacuum as :

$$X_I(n+1)=(1/2)g t_{n+1}^2 \quad \text{---(4)}$$

The inner capsule shall not contact with anywhere inside the dropping capsule to realize a good microgravity condition.

Namely, tolerance of δX has to be $X_b \geqq \delta X \geqq X_a$.

This condition of $X_b \geqq \delta X \geqq X_a$ can be kept by operating augmentation thrusters timely.

For an example, result of simulation is shown in **Table 1**, under condition of that the dropping capsule assuming C_d=0.2 based on JAMIC data(1) and the inner capsule which starts to fall from altitude of 3000m at t_0 to altitude of 1000m at t_{20} with acting augmentation thrusters timely in order to meet tolerance of 0.2m$\geqq \delta X \geqq$-0.1m.

Table 1a An available solution of T_a

t_n(s)	T_a(N)	Altitude of X(m)	Altitude of X_1(m)	Tolerance δX(m)
0	0	3000	3000	0
2	0	2980.419	2980.4	-0.0191
4	20	2921.594	2921.6	0.006
6	40	2823.549	2823.6	0.0514
8	100	2686.361	2686.4	0.0388
10	180	2509.987	2510	0.0129
12	240	2294.299	2294.4	0.1013
14	320	2039.457	2039.6	0.1425
16	460	1745.498	1745.6	0.1022
18	620	1412.342	1412.4	0.0580
20	800	1039.95	1040	0.0498

Table 1b A combination of augmentation thrusters

tn (s)	Ta (N)	20N	40N	80N	100 N	300 N	300 N
0	0						
2	0						
4	20	ON					
6	40		ON				
8	100				ON		
10	180			ON	ON		
12	240		ON	ON	ON		
14	320	ON				ON	
16	460	ON	ON		ON	ON	
18	620	ON				ON	ON
20	800	ON		ON	ON	ON	ON

For example, augmentation thrusters of each one 20N, 40N, 80N, 100N and two 300N (5 kinds and 6 thrusters) are configured and control them by valve operation of open/close at the defined time sequence.

Integration of equation (3) between t_0 and t_{20} leads also to that a total impulse of T_a is 5200(N-s).

5. Motion of the Dropping Capsule during Deceleration after Deployment of Parachute

Air drag term of parachute is added to equation (1) and setting T_a=0.

Namely,

$$md\text{^}2X/dt\text{^}2=mg-C_d\rho S_c(dX/dt)\text{^}2/2 -C_p\rho S_p(dX/dt)\text{^}2/2 \text{ ---(5)}$$

Equation (5) can be solved mathematically similar to equation (1), with a minor difference below.

$$\lambda\equiv\sqrt{((1/2)C_d\rho S_c/(mg)+(1/2)C_p\rho S_p/(mg))}$$

Velocity of the dropping capsule reaches about 196m/s at the end of free aerial fall down to altitude of 1000m, and then the parachute starts to deploy in a short time.

Simulation with C_p=1.0 and S_p=20m^2 (diameter is 5m), starting slow down velocity of the dropping capsule at t_{20} of altitude of 1000m shows terminal velocity of 1/ κ=11.3m/s at t_{27} of altitude of 524m.

The time course of this deceleration is shown in **Table 2.**

Table 2 Decent process with parachute

t_n (s)	Area of parachute (m^2)	Velocity of capsule (m/s)	Altitude (m)
20	0	196	1000
21	0.1964	180	812
22	0.7854	124	660
23	7.069	32.3	582
24	19.64	13.4	559
25	19.64	11.7	547
26	19.64	11.4	535
27	19.64	11.3	524

6. Motion of the Dropping Capsule during Deceleration with Parachute Expansion and Retro Motor Firing

A term T_r of retro motor comes into the motion equation.

It has to be evaluated time and amount of thrust of retro motor required to decelerate velocity down to 1.0m/s for safety landing.

Namely,

$$md^2X/dt^2=mg-C_d\rho S_c(dX/dt)^2/2 \\ -C_p\rho S_p(dX/dt)^2/2-T_r \quad ---(6)$$

Equation (6) can be solved numerically.

It was solved by Runge-Kutta method with a time step of 0.2second and velocities of the capsule respect to each retro motor of 1600N, 1700N, --- and 2000N.

Cases of 1600N and 2000N show in **Table 3**.

Table 3a Retro-motor of 1600N

t_n (s)	T_r (N)	Velocity of capsule (m/s)	Descent altitude(m)
27	1600	11.3	0
28	1600	4.64	-6.84
29	1600	2.68	-10.4
30	1600	1.46	-12.4
31	1600	0.499	-13.4

Table 3b Retro-motor of 2000N

t_n (s)	T_r (N)	Velocity of capsule (m/s)	Descent altitude(m)
27	2000	11.3	0
27.4	2000	5.88	-3.28
27.8	2000	3.51	-5.13
28.2	2000	1.76	-6.18
28.6	2000	0.248	-6.58

Table 3a shows that time of 4 seconds with firing retro motor of 1600N and total impulse of 6400N-s is required till reducing velocity to less than 1.0m/s, and firing shall be made from altitude of about 13m.

Table.3b shows that a time of 1.6 seconds with firing retro motor of 2000N and total impulse of 3200N-s is required to reduce velocity to 1.0m/s and it takes a descent altitude of about 7m.

7. On Effect of Side Wind

Japanese government of meteorology informs velocity and direction of wind on many places in Japan at every hour and every day on each altitude of 0m, 1000m, 2000m, 3000m and so on till 10km in its web page.

Since their information says that wind blows random direction with varying velocities, we suppose that maximum velocity to do free aerial fall is 10m/s.

Because direction of random wind can not be predicted, many side thrusters directed to four cardinal points are to be provided on sides of the capsule.

A wind velocity of 10m/s induces horizontal air drag force on the capsule during aerial drop and the capsule may move to some horizontal direction.

This movement shall be minimized to keep good microgravity condition.

This air drag can be expressed as :

$$F_s = C_s\rho S_c V_w^2/2 \quad ---(7)$$

Postulating C_s=1.0, S_c=2m^2 and V_w=10m/s, it is calculated F_s =100N. Then a total impulse during 20 seconds of side thrusters is estimated to be 2000N-s.

This requirement of total impulse can be reduced to 1000N-s by taking mean velocity 5m/s of wind.

8. Thruster System

Above considerations leads that total impulse required for three kinds of thruster can be summarized as :

(1) 5200N-s of augmentation thrusters
(2) 1000N-s of side thrusters for side wind.
(3) 3200N-s of retro motor of T_r=2000N

Total amount of impulse required to this system is 9400N-s.

Including 10% margin, total impulse required is about 11000N-s.

First of all, thruster systems of cold gas propellant was considered for those all.

Design parameters are

(1) Thruster chamber pressure = 2MPa
(2) *Isp* = 50s
(3) Blow down from 15MPa at t_0 to 2MPa at t_{20}
(4) open/close valve operation similar to JAMIC case[(1)].

Design of a thruster source gas container to meet above parameters is;

(1) required volume ≒ 0.19m^3 at 15MPa dry air
(2) size of container ≒ φ0.4m*1.5m(length)
(3) estimated mass of gas container made of stainless steel ≒ 140kg

Mass of this container is enormous and less feasible to configure the thruster system with this stainless steel container, because of its dominating about 93% mass of the dropping capsule.

A feasible concept might be;

(1) augmentation thrusters and side thrusters system with cold gas propellant for total impulse of 6200N-s. Mass of this system may be 95kg.
(2) retro motor system is made of an ordinary rocket motor such as gas jet system of one or two kind of propellant, hybrid rocket such as CAMUI[(2)] , solid propellant rocket or new rocket such as steam rocket[(3)] with total impulse about 4000N-s. Its mass of this system may be 5kg.

9. Conclusion

(1) Free aerial fall capsule for microgravity experiment of 20 seconds class is basically feasible.

(2) Inner capsule can float without contact at anywhere inside of the dropping capsule positioned by acting augmentation thrusters and side thrusters timely to compensate air drag during the free aerial fall.

(3) Thruster systems consisting solely of cold gas propellant is less technically feasible, because of its exceeding mass of source gas container.

(4) In order to develop feasible system, we have to study what combination of rocket motors is good for the thruster system in our case.

(5) A concept of augmentation thrusters system and side thrusters system with cold gas propellant, and retro motor system with an ordinary rocket motor such as gas jet of one or two kinds of propellant, hybrid rocket such as CAMUI[2], solid propellant or new rocket such as steam rocket[3] might be good for our application.

(6) Also, we have to study on other items, such as stabilizing wheel, parachute, vane, shock absorber, valve operation control algorithm and so on.

(7) In particular, since the velocity and direction of random side wind could not be well predicted, to develop an effective closed loop feedback system is vitally important, which can well detected and control the horizontal shift of the outer capsule to avoid the outer capsule hit the inner capsule during the fall.

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