Modeling Dynamic Behavior of a Safety and Arming Mechanism

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Abstract*: In the development of any new high explosive ammunition, often, the most intricate and problematic component is the fuzing system. Primary purpose of the fuze is to function with the bursting charge in a munition at a specified time and place. The fuze must include a Safety and Arming Device (SAD or S&A mechanism) to ensure that the ammunition may only switch into the armed state following exposure to firing forces and after reaching a safe distance from the muzzle. S&A mechanisms are often mechanical and operate using clockwork escapement mechanisms, similar to those found in wrist watches but in a less sophisticated manner. S&A mechanism is made up of a clockwork mechanism and safety devices which prevent the clockwork from arming until predetermined environmental conditions have been met e.g. setback acceleration and spin rate above a certain threshold. Use of Finite Element Analysis approach is inevitable, since conducting live firing ammunition trials is very expensive at the beginning of design cycle. In this paper, utilizing Abaqus/Standard, the complex rigid multibody dynamics of S&A mechanism was modeled and various potential design issues in the early design & development stage were studied. In order to satisfy required "arming time" under given operating conditions, which is the main design objective of S&A mechanism; inertia and location of center of mass properties of rotor and pallet are tuned. To this end, nearly all parts within the mechanism are modeled using rigid bodies and also to obtain computationally more efficient solutions, pinion-gear pairs in gear train are modeled using flow-converter connector elements instead of using more expensive contact definition. As a result, Abaqus/Standard simulations have provided a valuable insight into operation of the fuze and address the possible weaknesses of design before manufacture and physical testing.*

Keywords*: Multi-Body Dynamics, Mechanism, Fuze, Safety and Arming Device, Clockwork, Runaway escapement, Rotor, Pallet, Pinion, Gear, Sector Gear, Connector, Flow-Converter, Spin rate, Setback acceleration, Ammunition, Artillery, Projectile, and Muzzle.*

1. Introduction

In the development of any new high explosive ammunition, often, the most intricate and problematic component is the fuzing system. Fuze is a devise designed to detonate or set forces into action to ignite or detonate the charge under specific conditions have been met. Fuses are used in ammunitions/projectiles to provide basically the functions of (1) safety, i.e., keeping the ammunition safe for storing, handling, transportation, and launching, (2) arming, i.e., sensing the environments related with operational conditions including safe separation from the muzzle and then aligning the explosive train to initiate bursting charge in the munition at a specified time and place (MIL-HDBK-757, 1994).

Fuzes can be classified with respect to different categories such as “by end item”, “by purpose”, “by tactical application”, “by location” and “by functioning action” (MIL-HDBK-757, 1994). The functioning action can also be sorted as “impact”, “time”, “proximity” and “pressure”. In our case, we deal with a mechanical time fuze which is a subclass of time fuzes. Time fuzes are used to initiate the munition at some desired time after launch. These fuzes are generally settable to a specific amount of time utilizing a clockwork device. Typically, time fuzes have set times ranges from as low as a fraction of a second to 200 seconds.

Fuzes are usually placed at the nose section of projectiles (Figure 1). A typical safety and arming (S&A) mechanism located in fuze with main components is demonstrated in Figure 1.

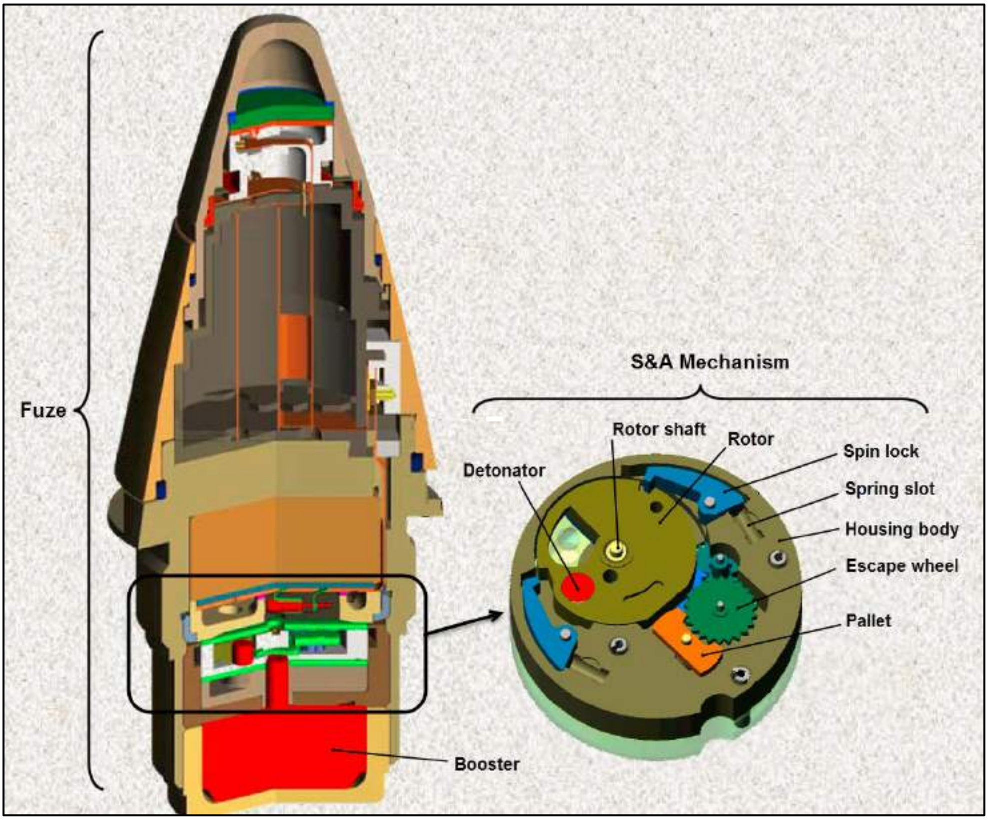

Figure 1. Typical safety and arming mechanism in fuze (Will, 2007).

In designing a fuze S&A mechanism, it is very important to use the environmental forces that are most predictable and consistent. It is good practice and usually mandatory to use at least two separate and independent environmental forces. In our case, these forces result from the launching and ballistic environments: (a) inertial setback acceleration force especially when the projectile travels through the barrel due to expansion of burning gases and (b) centrifugal force (rotational velocity) due to spinning of the projectile around its longitudinal axis. Spinning of the projectile around its longitudinal axis is realized by manufacturing helical grooves inside of the barrel. This spinning serves to gyroscopically stabilize the projectile by improving its aerodynamic stability and accuracy.

Arming process consists mainly of the actions involved in aligning the explosive train elements or in removing the barriers along the train. The time (arming) for this process to take place is controlled so that the fuze cannot fuze until it has travelled a safe distance from the launching site. For design purpose, it is often more realistic to express the arming action in terms of elapsed time from launch (MIL-HDBK-757(AR), 1994).

Hence to measure the elapsed time, S&A mechanisms are often mechanical and operate using clockwork escapement mechanisms, similar to those found in wrist watches but in a less sophisticated manner. The clockwork mechanism is being frequently used in the production of S&A devices for all modern types of fuses for artillery projectiles because of its precision, physical stability and above all its reliability (Krstic, 2005).

A typical S&A mechanism is illustrated in Figure 1 and Figure 2 basically consists of (1) a rotor with a sector gear, (2) a gear train which transmits the rotor torque, (3) escapement mechanism (escape wheel and pallet), (4) preloaded setback pin, (5) preloaded spin locks, and (6) a detonator carried by rotor.

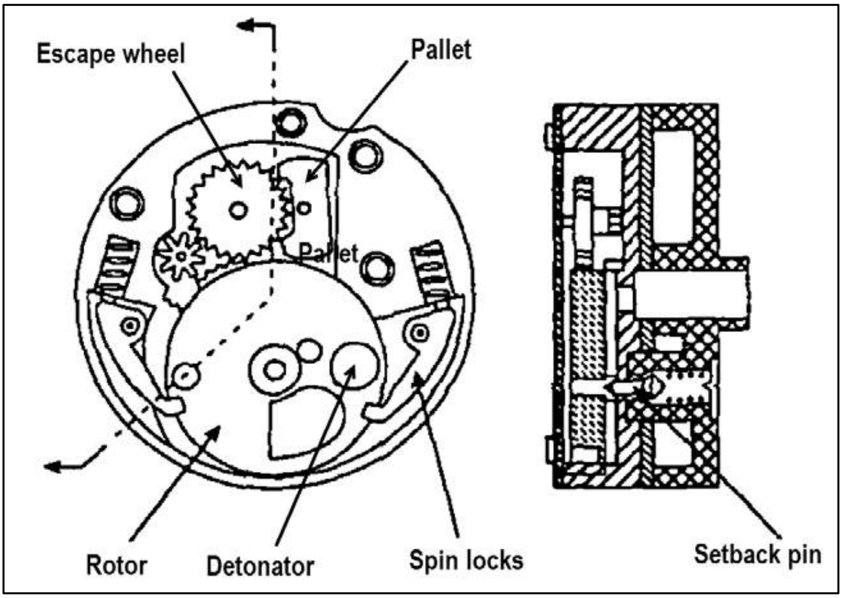

Figure 2. Typical Setback Pin and Spin Locks shown in S&A Mechanism (MIL-HDBK-757(AR), 1994).

A typical, gear train which consists many pinion-gear pairs explicitly shown in Figure 3 transmits torque from rotor to escape wheel by decreasing the torque and increasing the rotational speed

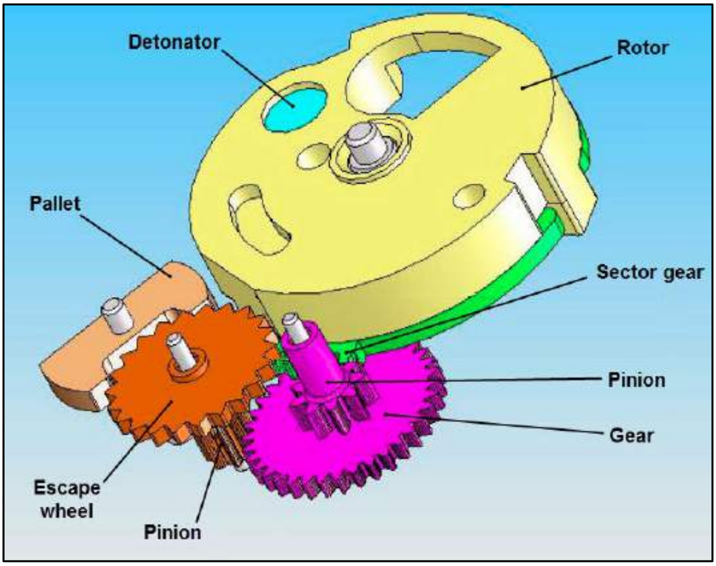

Figure 3. Gear Train and Runaway Escapement of a typical S&A mechanism (Krstic, 2005).

There are three general types of escapements namely, (1) the untuned two-center type, (2) the tuned two-center type and, (3) the tuned three-center type. In our case, type-(1) escapement is utilized which is also known as with different names: (a) runaway escapement, (b) verge escapement, or (c) inertial governor (Mundy, 1991). Runaway escapement can be considered as the heart of S&A mechanism and it consists of mainly two components which are a pallet and an escape wheel (Figure 4). Pallet is simply an oscillating inertial mass whose duty is to make interference with the rotation of escape wheel at high frequency. If the torque applied to the escape wheel is increased, the pallet will oscillate more rapidly and the escape wheel will rotate more rapidly, since the pallet is not a true simple harmonic oscillator which is found in mechanical watches. Runaway escapement behaves like a mechanical damper to control the rotational motion of the rotor.

In application, there are two types of pallets which are shown in Figure 4, (a) flat sided pallet, and (b) pin pallet. In this study, we deal with pin pallet (Figure 4 (b)), although the typical S&A mechanism includes flat-sided pallet as given in Figure 1, Figure 2 and Figure 3.

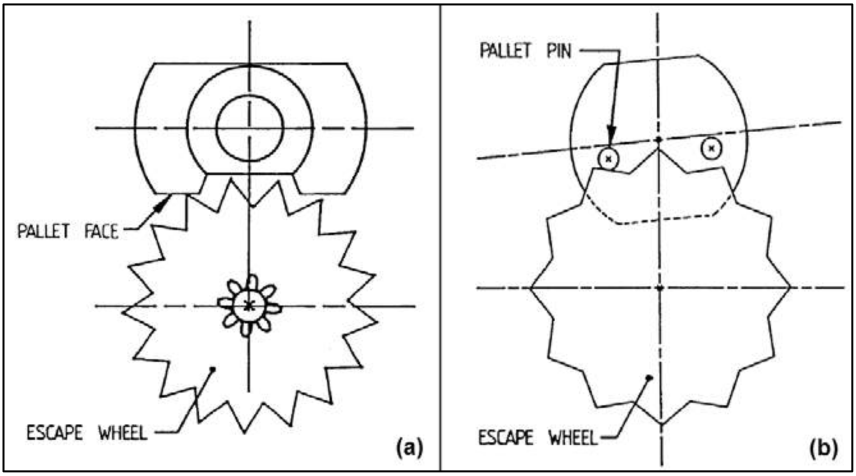

Figure 4. Runaway Escapements: (a) Pallet with Flat Pallet Faces, (b) Pallet with Pin Pallets (Mundy, 1991).

Immediately after firing, projectile starts moving through the barrel, the inertial and centrifugal forces overtake resistances of springs, and finally release i.e., unlock the rotor from its safety position. Rotor generates a torque since its center of gravity has some inherent eccentricity with its own axis of rotation (pivot point) which is shown in Figure 5. Torque generated is delivered to gear train through the sector gear attached to the rotor (Figure 3). At the same time, the runaway escapement mechanism regulates the rotor spin motion i.e., so that detonator cap placed on the rotor is aligned with the rest of the explosive train -ready for busting the charge- at the end of arming time period.

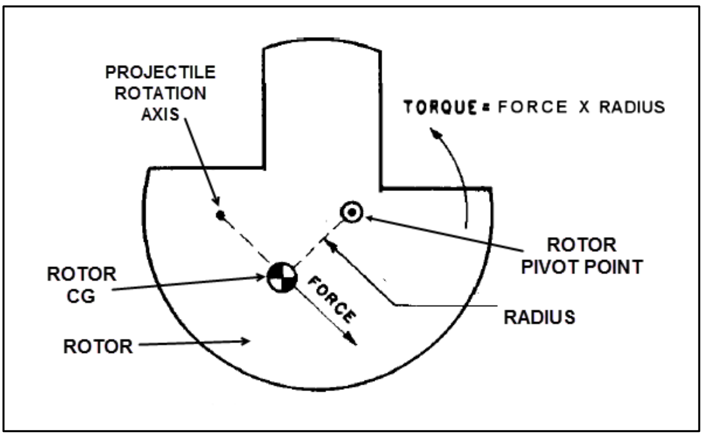

Figure 5. Torque generated by rotor due to centrifugal force (AMCP 706-210, 1969).

Since, conducting live firing ammunition trials is very expensive at the beginning of design cycle. Then use of Finite Element Analysis approach is inevitable at this point. In this paper, utilizing Abaqus/Standard, the complex rigid multibody dynamics of S&A mechanism was modeled and various potential design issues in the early design & development stage were studied. In order to satisfy required “arming time” under given operating conditions, which is the main design objective of S&A mechanism; inertia and location of center of mass properties of rotor and pallet are tuned successfully.

2. Finite Element Model

Since S&A device is under development, our company does not allow us to share details of the model of the S&A mechanism, therefore in this paper; we give a very simplified version of the S&A mechanism.

In this study, Finite Element (FE) model is established using Abaqus/CAE version 2016. All parts in the FE model are modeled as a rigid body. A few parts in the FE model are meshed to be able to define contact assignments, since Abaqus/Standard does only allow defining contact between two bodies provided that one of them is deformable. Contrary to this, Abaqus/Explicit allows to define contact between two rigid bodies.

Firstly, for each rigid body, a reference point is created to assign its point mass/inertia properties. Secondly, a display body constraint is assigned for each body for visualization purpose during simulation. Thirdly, if a rigid body needs additional nodes to attach connector elements – in addition to its reference node – then, a rigid body constraint (tie/pin nodes) is assigned to itself.

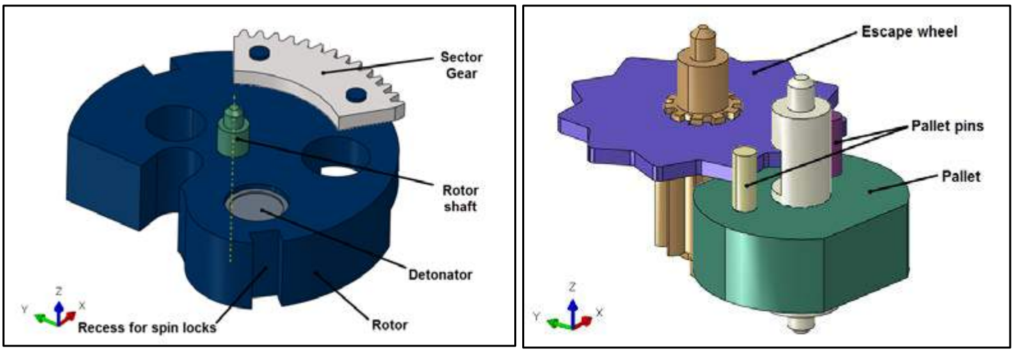

Figure 6. Initial rotor and runaway escapement model of S&A Mechanism.

Initial design of rotor and runaway escapement parts modeled as rigidly is partially shown in Figure 6. Materials assigned to these parts can be stainless steel, aluminum or brass alloy.

In order to obtain computationally more efficient solutions, pinion-gear pairs in gear train are modeled using flow-converter connector elements instead of using more expensive contact definition (Figure 7).

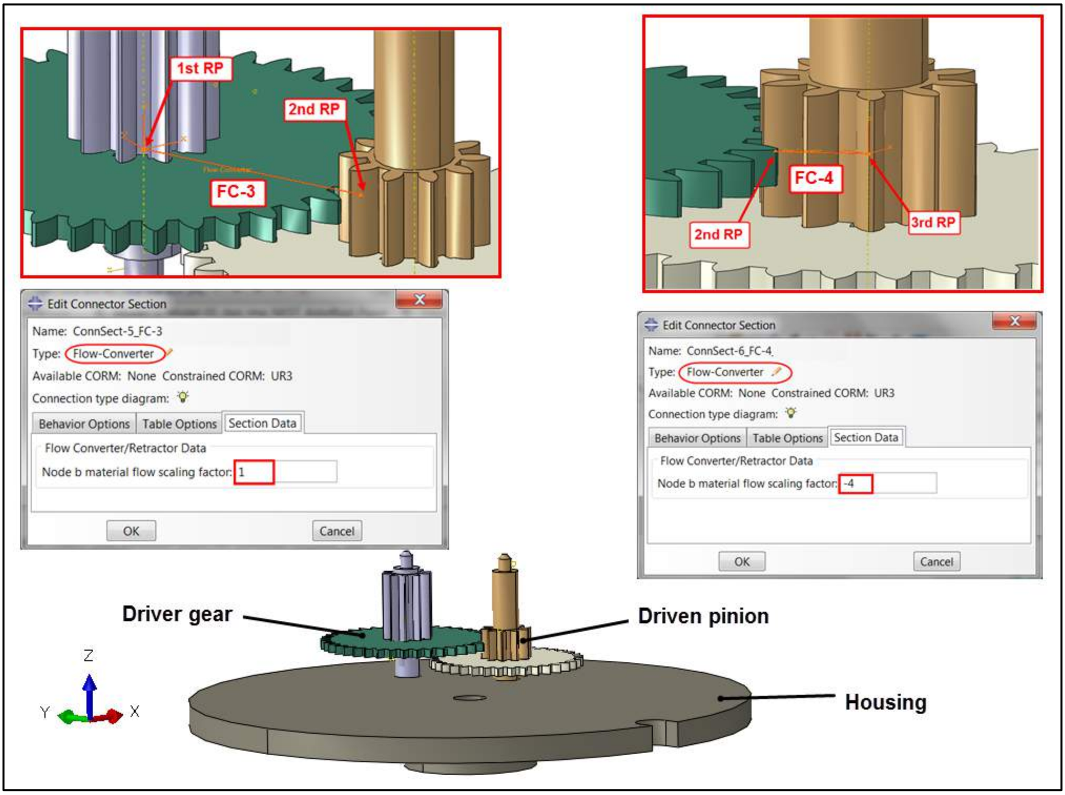

Figure 7. Modeling gear contact using connector elements

As shown in Figure 7 the pinion and gear are each modeled with a hinge and a flow-converter sharing a node (1st RP and 3rd RP). The second node of flow-converter FC-3 and FC-4 is common (2nd RP). This node (2nd RP) is defined as tie node in the definition of rigid body constraint of housing part so its motion is exactly the same with the motion of housing. The gear ratio of 4.0 is maintained by defining the scaling factor β (with proper sign) in flow-converters FC-3 and FC-4; for this case, the scaling factors are 1.0 and –4.0, respectively (Figure 7).

In FE model, contact definitions are kept at minimum in order to run Abaqus/Standard simulations faster. Also utilizing analytical rigid bodies in contact simulations is computationally cheaper, thus additional “dummy” analytic rigid bodies and “dummy” deformable bodies are created and attached to original rigid bodies using “tie” or “kinematic coupling” type constraints as shown in Figure 7. In addition to this, all contact definitions made in FE model is frictionless. Approach used in one of the most critical contact definition is demonstrated in Figure 7.

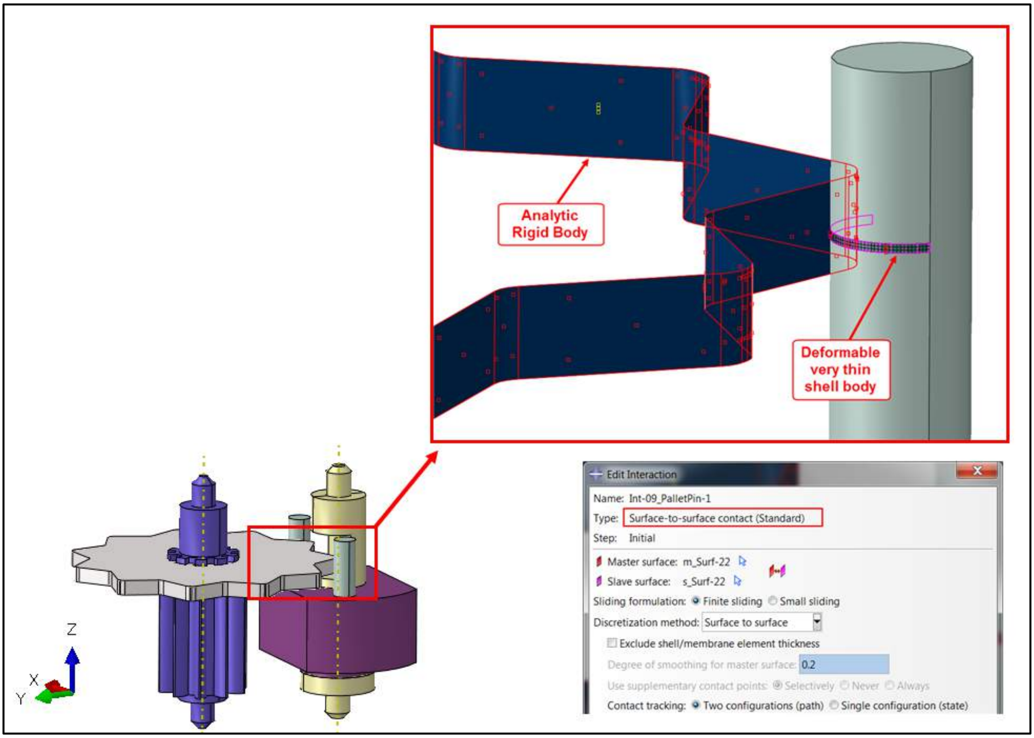

Figure 8. Modeling contact between two rigid bodies in Abaqus/Standard.

Centrifugal force and setback acceleration loadings are applied to the FE model using the boundary conditions (Figure 9). For this purpose, cylindrical connector element is used to impose absolute axial acceleration and angular velocity (spin rate) to the housing of S&A mechanism. Setback acceleration and spin rate amplitude curves applied to housing is given in Figure 10.

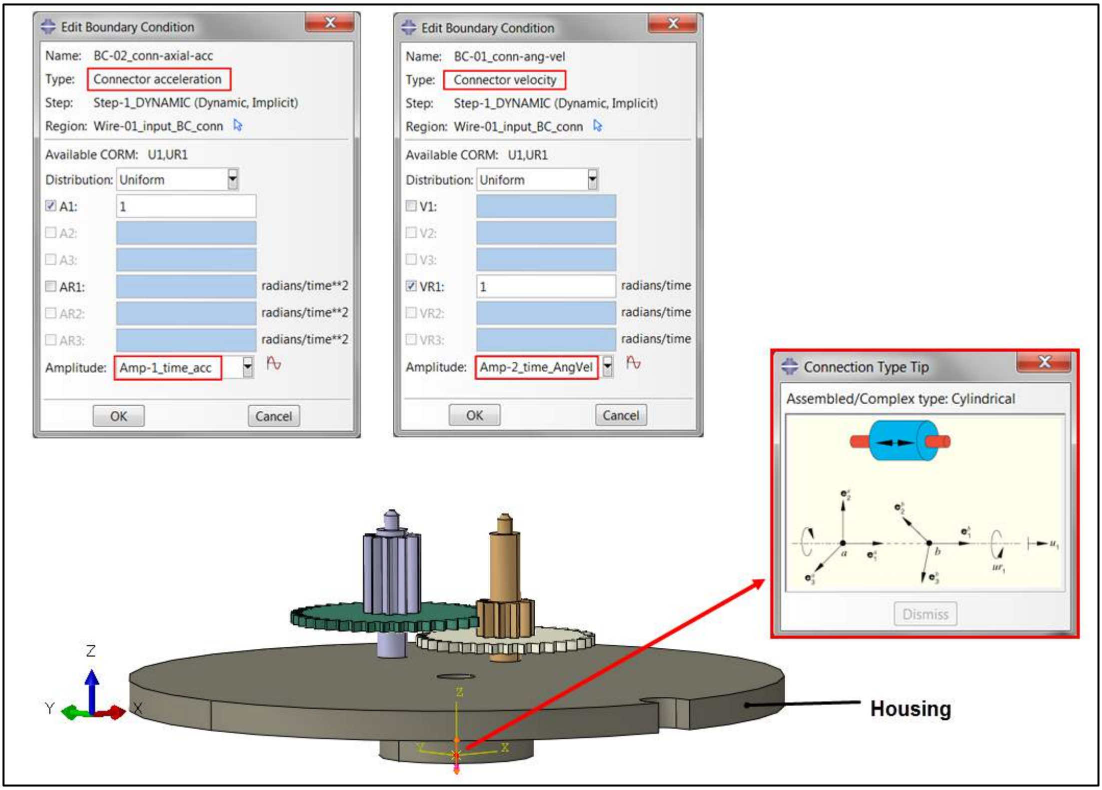

Figure 9. Application of loading to S&A mechanism using boundary conditions

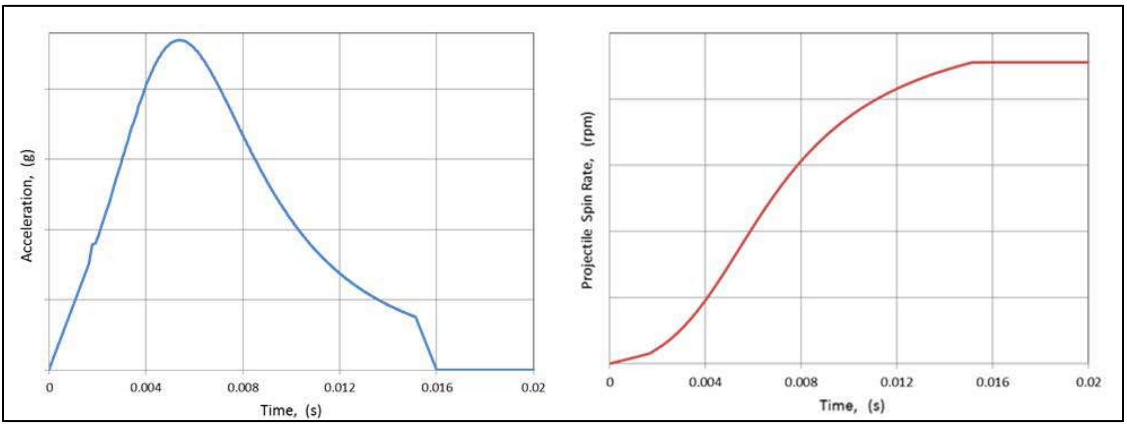

Figure 10. Setback acceleration and spin rate loading amplitude curves.

3. Results

Analysis result of initial FE model shows that S&A mechanism has a serious locking problem at the beginning of rotor motion as shown in Figure 11. After a small amount of rotation of the rotor, it can be seen from Figure 11 that the mechanism is locked because of various reasons. Assuming that applied loading to the mechanism remains the same, locking problem can be solved by various iterative design changes.

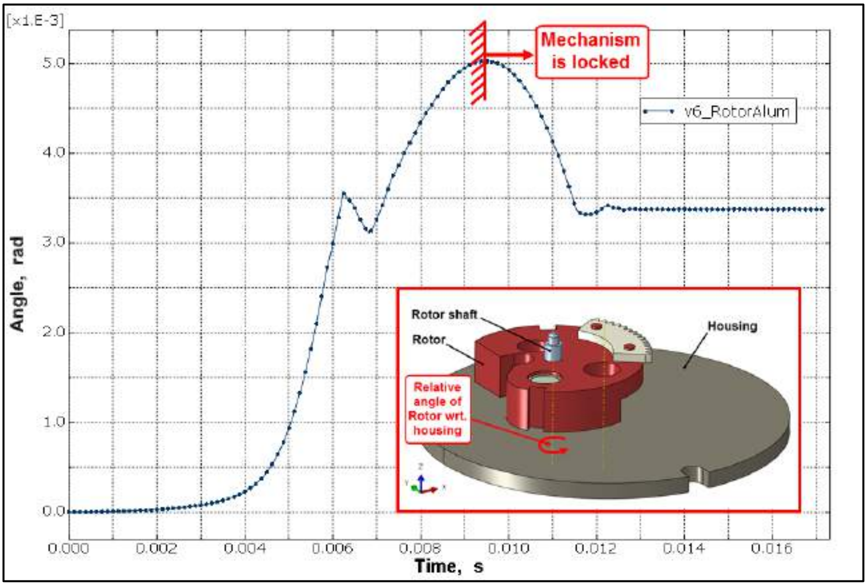

Figure 11. Relative angle for aluminum rotor (initial FE model).

In order to remove locking problem and to satisfy arming time requirement – which is around from 120 ms to 200 ms – following design changes can be recommended:

- Geometry and/or material of the rotor, thus changing CG of the rotor results in a change in the torque generated by rotor
- Geometry and/or material of the runaway escapement (especially the pallet body)
- Stiffness of preloaded springs

After the application of many design changes/iterations to the FE model of S&A mechanism, it can be seen in Figure 12 and Figure 13 that successful solutions are obtained.

Although geometry details of S&A mechanism is not given here, solutions – satisfying desired arming time – for aluminum rotor material and brass rotor material are given in Figure 12 and Figure 13 respectively.

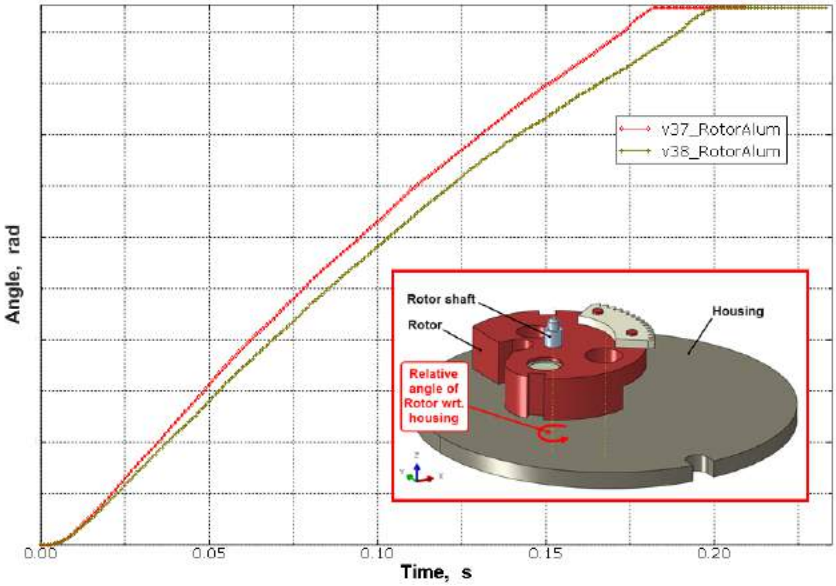

Figure 12. Relative angle for aluminum rotor (improved FE models).

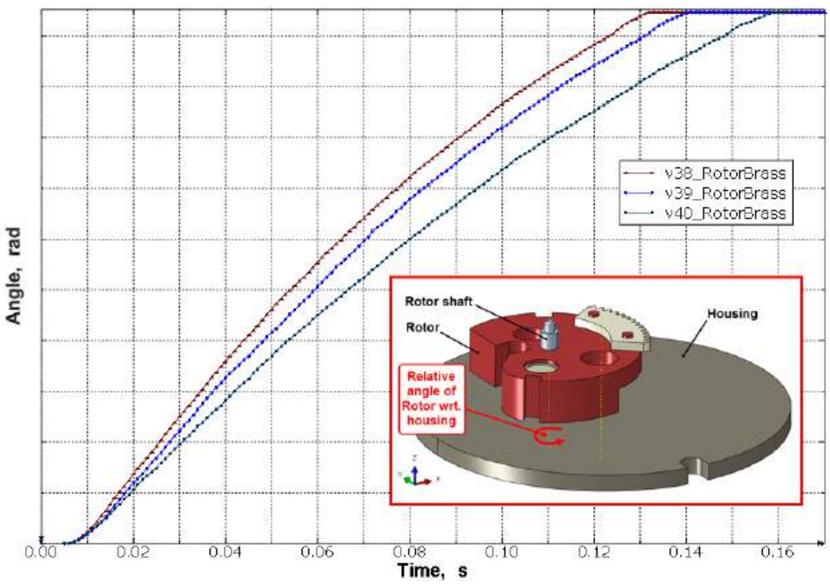

Figure 13. Relative angle for brass rotor (improved FE models).

4. Discussions

Utilizing Abaqus/Standard, the complex rigid multibody dynamics of S&A mechanism was modeled and various potential design issues in the early design & development stage were studied.

In order to get desired arming time (from 120 ms to 200 ms), many design iterations have been done using rigid multi-body FE model and results obtained gives useful hints to mechanical design.

As a near future study, verification and tuning FE model results with the simplest benchtop tests will be carried out on a step by step basis. This also can help tune friction value between bodies. As a far future study, verification and tuning FE model with firing tests will be carried out with telemetry data.

Additionally, some critical parts in the model can be converted from rigid bodies to deformable elastic bodies in order to investigate any possible failures due to extreme loading environment.

As a result, Abaqus/Standard simulations have provided a valuable insight into the operation of the fuze and identified the possible weaknesses of the mechanical design before manufacturing and physical testing.

5. References

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