Modelling and Validation of a Guided Impact Test Rig

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1 Abstract

A simple test rig has been developed to expedite the evaluation of the knee injury This test rig has been designed to travel on the rail during impacting the cockpit. This Impact can be considered as guided and high speed impact (4m/s). The friction between the rail and the impactor contribute significant effect on the final result of the impact. The coefficient of friction acquired in quasi – static and generic value did not represent the real coefficient of friction at high speed.

A simple method of combination between experiment and simulation has been introduced to acquire the coefficient of friction between the rail and the impactor. The coefficient of friction and test rig model accuracy was validated through comparison of the acceleration and load curves. Three cases of impact have been introduced to ensure the robustness of the model and variation of the cockpit angle. The cases were basic model, additional mass of test rig by 5.6 kg and the angular impact at 60 degree.

2 Introduction

ACTS is one of the leading vehicle safety testing companies in the world. To be one of the most innovative service providers for its customers, ACTS is continuously improving its test and simulation systems.
One of the ACTS developments is a Knee Impact Test Rig. A knee impact component test is an alternate method to assess a knee injury level during a crash test. It is a simple test rig assessing the contact load between knee and cockpit and represents the impact of the crash test dummy's knee during a crash test. An impact load will be measured during the test and used as a criterion in defining the injury knee-thigh-hip complex. The results can be used as reference for the cockpit design and development.

In automotive product development there has been an ever increase in the application of Computer-Aided Engineering (CAE) techniques for simulation of a crash event, particularly due to the availability of high computing machines and parallel computing techniques. The current capability in structural crashworthiness simulation through CAE analysis is an important reason for an increase in safety standards. The two most important reasons for use of crash simulations are to know the effect of impact of the vehicle structure and to analyze the occupants' safety. These simulations offer today reasonably accurate results and save a significant amount of resources that would have been otherwise used in physical testing. Hence use of CAE techniques results in an efficient product development cycle.

The efficiency of the CAE analysis has created a demand to transform the knee impactor in to a virtual test. It will help the designer to assess performances of the cockpit from early stages. In order to meet the demand, a simulation model of a knee impactor test rig needs to be created and validated for performing virtual tests.

The test rig has been designed to move on a rail during the impact. Friction on rail is very important for obtaining the accurate impact load between impactor and cockpit. The generic coefficient of friction value always defined in a range. It requires determining the value at the specific applications and parts.

The coefficient of friction of the system depends on the interfacial conditions such as normal load, geometry, relative surface motion, sliding speed, surface roughness, type of material, system rigidity, temperature, stick slip, relative humidity, lubrication and vibration. Among these factors, sliding speed and normal load are the two major factors that play a significant role in the variation of friction and wear rate. The third law of friction, which states that friction is independent of velocity, is not generally valid. The coefficient of kinetic friction as a function of sliding velocity generally has a negative slope. Changes in the sliding velocity result in a change in the shear rate, which can influence the mechanical properties of the mating materials [3].

This paper is focusing on the development of a finite element model of a knee impactor test rig. Then the model will be validated through an impact test. Impact load and acceleration curve will be used as validation criteria. Load cell and accelerometer will be assembled in the test rig to measure the load and acceleration curve respectively. Afterwards, the curves from both - test and simulation - will be compared and analysed to conclude the accuracy of the simulation model. The simulation model was developed according to LS-Dyna explicit code.
Furthermore, a coefficient of friction acquisition method was introduced to obtain the realistic coefficient of friction within the knee impact system. A simple combination of experiment and simulation was combined for this purpose. A simulation series was conducted for correlation with the base test.

3 LS –Dyna friction formulation

LS Dyna friction model is based on the Coulomb friction model that includes static and dynamic friction conditions. It introduces an exponential interpolation function for smooth transition between static and dynamic friction. Eq. 8 describes the base formula for the Coulomb friction model.

$$F_f = \mu F_N \tag{1}$$

Where F_f is friction force, μ is the total coefficient of friction and F_N is the normal force. Then the total coefficient of friction formulation expanded to a static and a dynamic coefficient of friction. The exponential formulation for the transition from static and dynamic are given in the following formulation.

$$\mu = \mu_d + (\mu_s - \mu_d)e^{-c|v|} \tag{2}$$

$$v = \frac{\Delta e}{\Delta t} \tag{3}$$

Where μ_d is dynamic friction and μ_s is static friction. C is decay constant that provides transition between dynamic and static friction. V is the relative velocity between slave node and master segment. Δe is the incremental movement of the slave node and Δt is the time step size.
This friction formulation is integrated inside the contact algorithm in LS-Dyna.

In case of knee impactor test rig modelling, the friction formulation in LS-Dyna is sufficient with an assumption of dry friction contact and transition between static and dynamic is modelled by a decay coefficient. In addition the variation of friction force as a function of velocity is modelled through exponential formulation in Eq. 2.

4 Methodology

The outline of the development for the knee impactor test rig finite element model has been visualized through a flow chart, in *Fig. 1* below. The detail of the step will be discussed in the next sections.

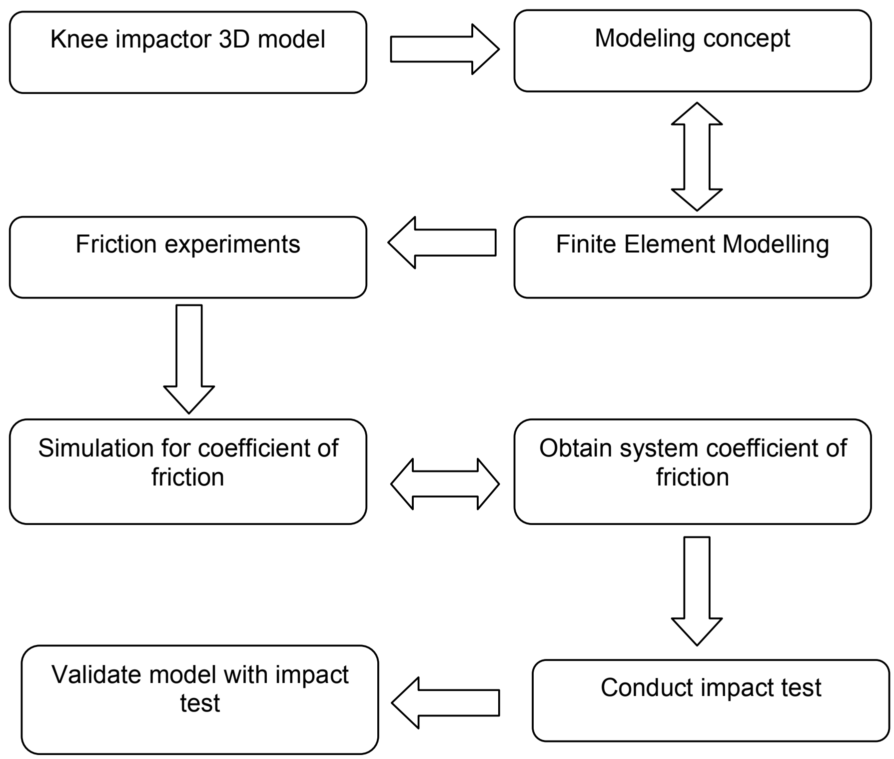

Fig. 1: Test rig modelling and validation overview

The process began with the available 3D model for the test rig. Then, the model has been transformed to the universal format Initial Graphic Exchange Specification (IGES) for the meshing processing. A modelling concept was defined before creating the finite-element model. This is a reversible process. During finite-element modelling, the concept can be reviewed for easier modelling without sacrificing the accuracies.
The next step is the acquisition of coefficients of friction within the system. The process started with the friction experiment using quasi static and dynamic methods. After that, a simulation series was run to correlate the friction behaviour between slider and rail. The coefficient of friction used during the simulation has been recorded and varied in correlating the friction.
The final step is validating the knee impactor model. An impact test was conducted to validate the model. The same test set-up was duplicated in the simulation. The acceleration curve and impact load curve were compared as validation criteria.

4.1 Coefficient of friction measurement

An alternate and simple method is required to obtain a coefficient of friction at high speed between slider and rail. The method must also be realizable in the ACTS laboratory. Furthermore, this coefficient of friction needs to be obtained as a total system not only at component level, because surface finish and assembly tolerance of the test rig also contribute to the different friction values compared to generic value from data sheet and the quasi-static test.

A method combining testing and simulation has been introduced in order to obtain a coefficient of friction value between slider and rail. This method will use the acceleration curve measured by the accelerometer assembled in the knee impactor head.

As described in Fig 2, the knee impactor moves freely without external energy at the second phase. The deceleration of the knee impactor is only based on the friction between slider and rail. At this phase, the coefficient of friction of the railing system can be obtained.

The process of obtaining a coefficient of friction starts with running the test at high speed, and change the configurations such as impact angle and speed. The acceleration curve was extracted from the accelerometer inside the knee impactor head. However, the acceleration curve cannot be used for the comparison between simulation and test. In this case, integration has been applied to the acceleration curve so that a velocity curve can be obtained. The useful value from this velocity curve is the curve slope at the second phase.
After that, the slope of the velocity curve was used as the base curve for the simulation phase. In this phase, the coefficients of friction value parameters in the contact algorithm were optimized. After that, the slope of the velocity curves from the simulation were compared to the slope of the velocity curve from the test.

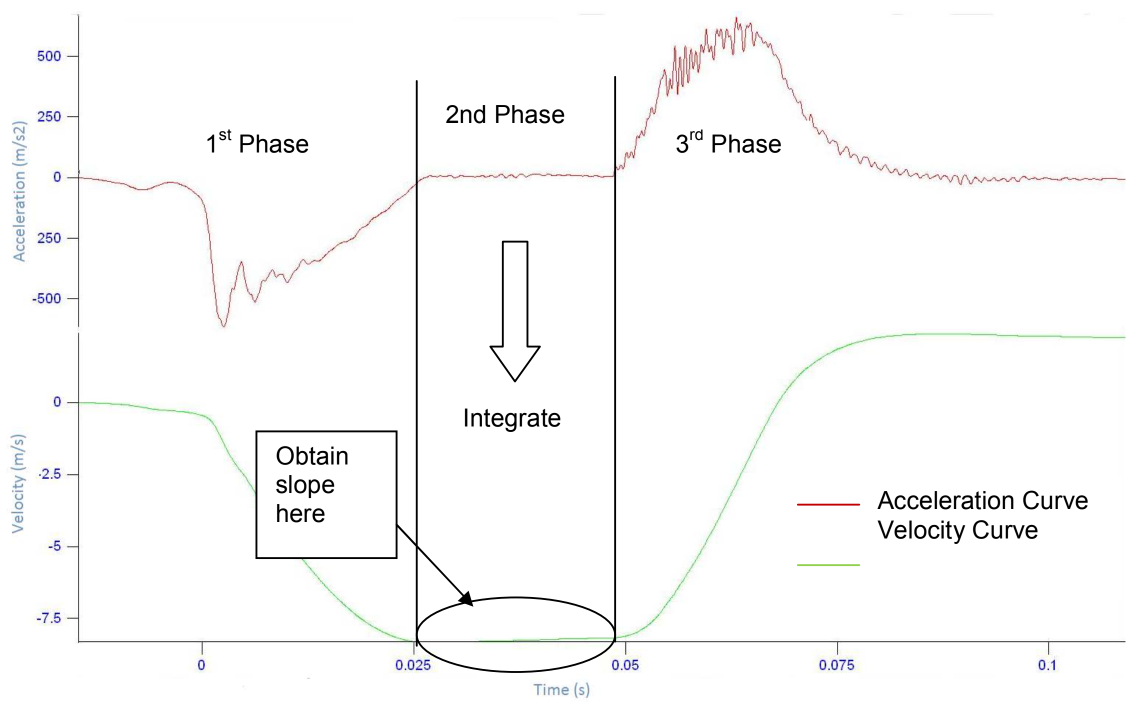

Fig. 2: The process of obtaining the velocity slope

Figure 3 illustrates the process of the velocity slope calculation. The velocity curve was extracted from the acceleration curve by differentiating the curve. The obtained slope at the second phase started with the release point between velocity generators until before impact occurred.

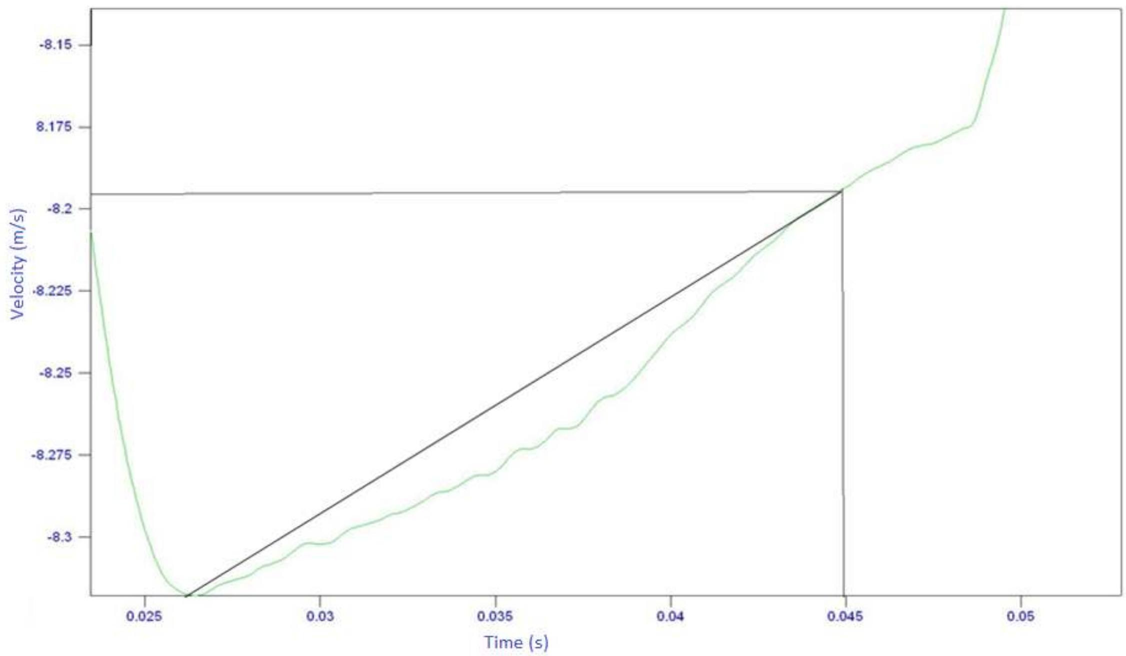

Fig. 3: Velocity curve at phase 2 from test

The slope from the velocity curve has been zoomed up to provide a clear view on the velocity curve slope. It is shown in figure 3.

5 Results and discussions

A series of tests has been conducted to be correlate simulation. The velocity slope has been calculated from the acceleration curve from the test (see table 1).

Test No	Impact Angle (°)	Impact Speed (m/s)	Velocity Slope (E -03)
1	0	4.68	3.85
2	0	7.06	4.02
3	60	4.75	4.25
4	60	4.73	4.28
5	60	4.74	4.02

Table 1: Velocity slope for different case

The tests were conducted at two different angles - zero degree and sixty degree. The target impact speed varies from 4.68 meter per second to 7.06 meter per second.
The simulations were conducted by varying the static and dynamic coefficient of friction in the slider and the rail interface. The results of the simulations run with different coefficient of friction were presented in table 2.

Static	Dynamic	Slope (E-03)
0.32	0.26	7.16
0.30	0.21	5.76
0.20	0.16	4.28
0.19	0.15	3.31

Table 2: Coefficient of friction obtained from simulation.

The coefficient of friction with the value of 0.20 and 0.16 for dynamic and static respectively produces the closest velocity slope value between test and simulation. It will be used during the model validation phase.

The values obtained through experiment and simulation combination method represent the total system of the knee impactor test rig. However, it is different from the value obtained through quasi-static method and from the data sheet from the manufacturer. This shows that the coefficient of friction must be obtained at the operational condition in real systems. The data sheet value is only a reference because there are various factors contributing to the coefficient of friction value for any system.

Sliding speed is one of major factors that define the different coefficients of friction for the same system. In case of the data sheet, the value of a coefficient of friction is always given in range and independent of the velocity - this is not realistic. The friction force is a function of the velocity. For most materials, friction decreases when the velocity increases. The dependence of friction on velocity may be explained in the following way. When velocity increases, momentum transfer in the normal direction increases, producing an upward force on the upper surface. This results in an increase separation between two surfaces, which will decrease the real area of contact.

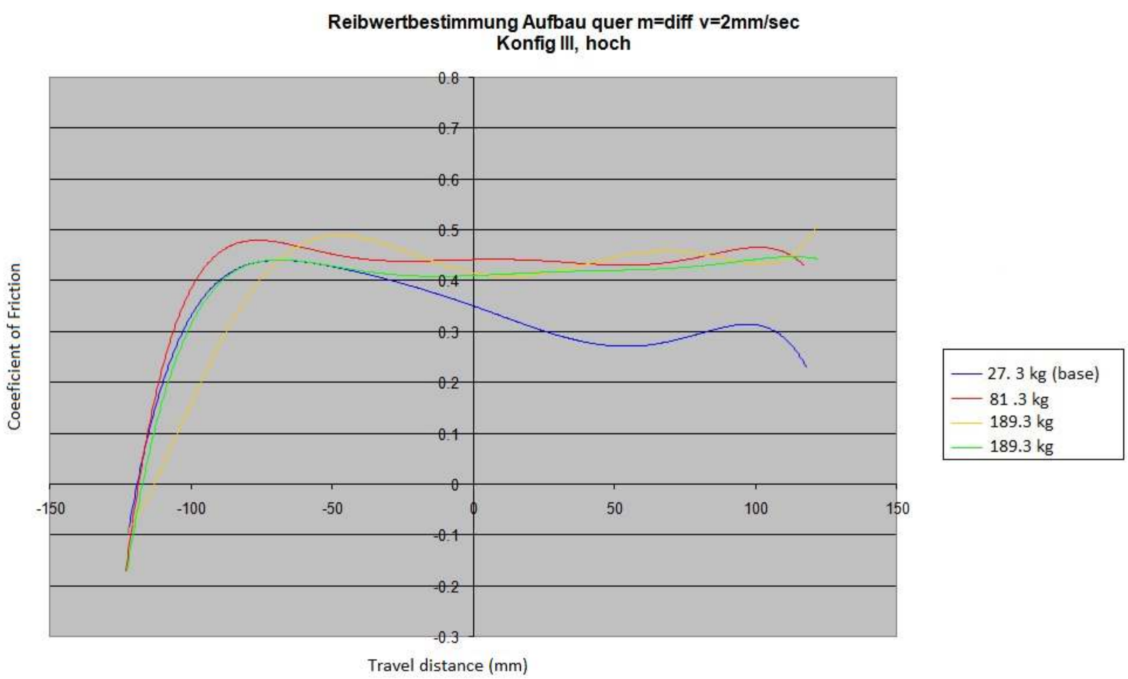

Fig. 4: Coefficient of friction from quasi-static test

This also explains the high value of the coefficient of friction obtained from the quasi-static test. On the other hand, it can be observed that the value of the base (without adding the additional mass) is decreasing with an increasing stroke. This is occurred because at the beginning, the impactor needs to overcome the resistance resulting from an imperfect assembly and matching between slider and the rail while it moves further. This factor is reducing because of the above reason (upward force on the upper surface). While for the additional weight cases, the coefficient of friction does not decrease because the quasi static sliding speed does not produce enough upward force to overcome an imperfection of the assembly.

In order to ensure the robustness of the validation three types of impact were introduced. The case is a basic model, additional mass and 60 degree impact. All of the types run at different speeds between 4 m/s and 6 m/s. The summary of the test is shown in table 3.

Test No	Additional Weight (kg)	Impact Angle (°)	Impact Speed (m/s)
1	NO	0	4.68
2	5.6	0	4.28
3	NO	60	4.73

Table 3: Summary of the validation test

The deceleration curves and the load curves were compared to assess the validation of the model.

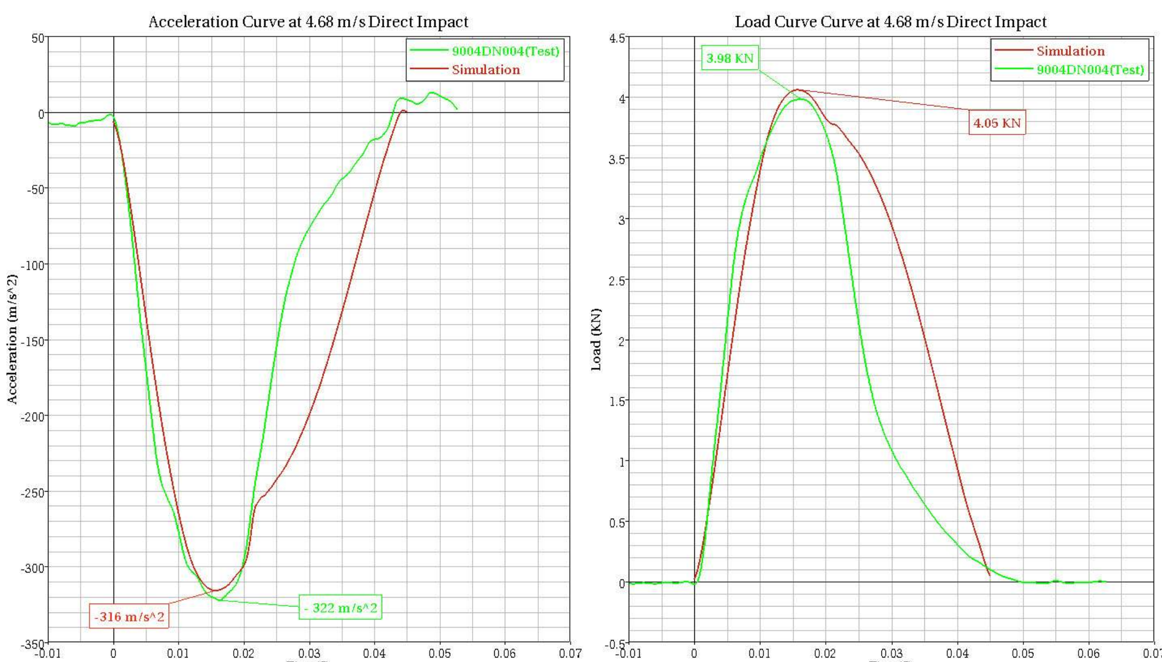

Fig.5: Acceleration and load curves comparison for basic model

A comparison of acceleration and load curves between test and simulation for basic model is presented in figure 5. In the acceleration curve, we can see that the loading is similar between test and simulation. The acceleration peak is at 322 m/s^2 in the test and the acceleration peaks in the simulation at 316 m/s^2. The difference between the peaks for this case is only 1.94 percent. On the other hand, the loading curve for the load cell is also similar between the simulation and the test. The peak for the test is 3.98 KN, and the peak for the simulation is 4.05 KN. This results in 1.97 percent difference. Impact duration for the test is about 43 milliseconds and for the simulation 44 milliseconds. It can be concluded that for this case, the simulation model was correlated with the test rig.

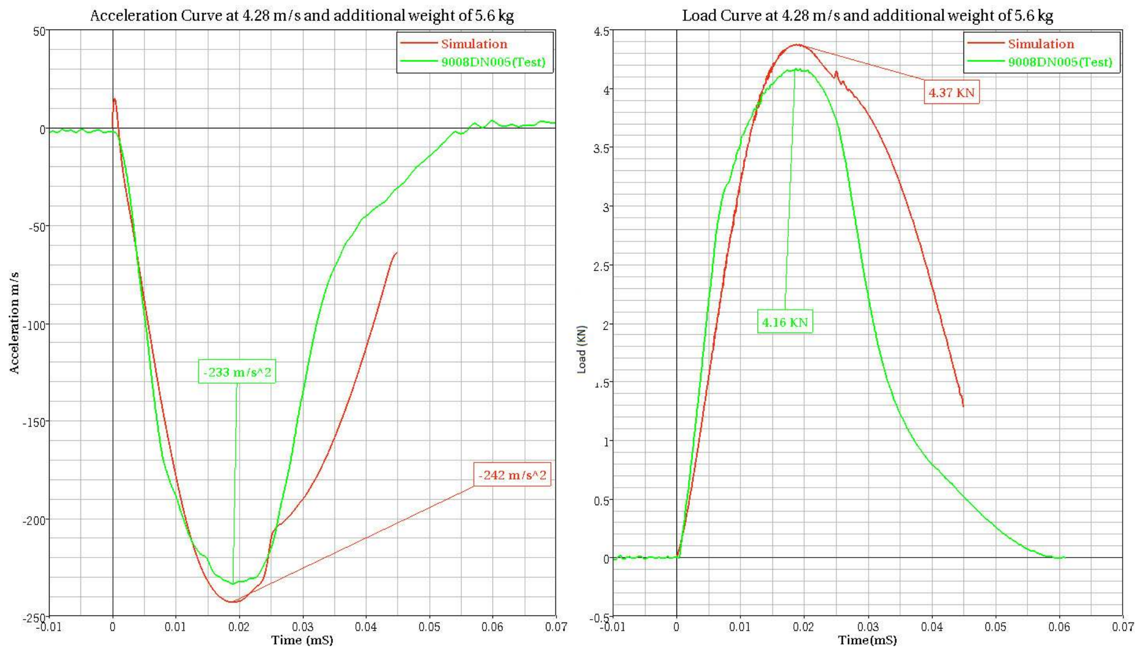

Fig. 6: Acceleration and load curves comparison with additional 5.6 kg mass

In the second configuration, 5.6 kg mass was added. The position and geometry of the mass has been discussed in the previous chapter. Figure 6 presented the comparison of the acceleration and load curves between test and simulation. The loading shape for both, acceleration and load curves, were similar between test and simulation. The acceleration peak for test is 233 m/s^2 and for the simulation is 242 m/s^2. The difference between the peaks is about 4.3 percent. On the other hand, the load curve peak for the test is 4.16 KN and for the simulation is 4.37 KN. This results in about 4.34 percent difference. In this case, impact duration was longer than base configuration. It was about 59 milliseconds.

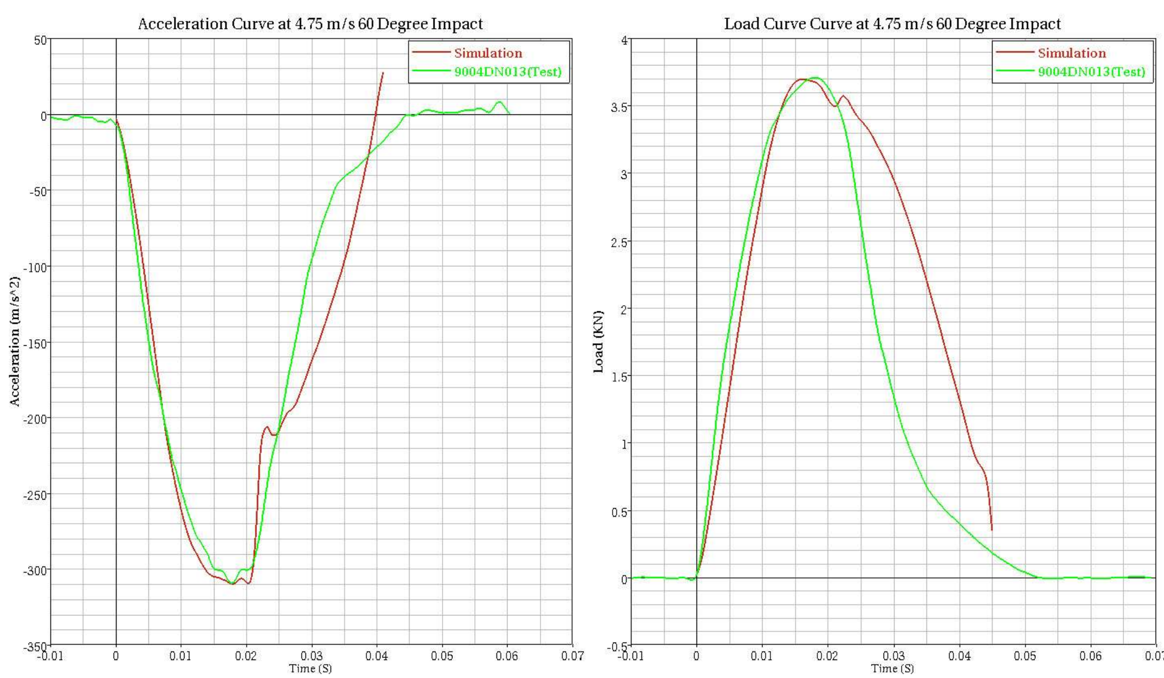

Fig. 7: Acceleration and load curves comparison for 60 degree impact

To study further on the robustness of the model, the third configuration was introduced. In this configuration impact, the angle was rotated to 60 degrees. This is according to the mean value from the cockpit angle. The loading curve for both, acceleration and load curves, are similar between simulation and test. The acceleration and load curves' comparison was presented in figure 7. The peak for both acceleration curves from simulation and testing is about 315 m/s^2. Both impact load peak from simulation and testing - are about 3.9 KN. The impact duration for testing is about 49 milliseconds and impact duration for the simulation is about 45 milliseconds. However, this is acceptable because the duration for the unloading curve is not representated as a real behaviour due to its behaviour from the material model.

The simulation model can be considered representative for the tests rig's behaviour since the correlation result was good. The loading curve between simulation and test for all cases are considerably matching as shown in previous figure. The peak values are matching between test and simulation for all cases with a maximum of 5 percent difference. Impact duration is the same for simulation and test for all cases during the loading phase. However, there is small difference in the unloading phases but the curves can be ignored due to the nature of the material model.

6 Conclusion

The knee impactor test rig was moving on the rail during the cockpit impact. It can be considered as a guided impact case. In this case, the friction on the rail will influence the final impact result either in terms of acceleration or load. LS-Dyna was used as the solver for the simulation. Friction formulation is integrated in the contact definition. In the case of dry friction, this model is adequate to be used. The validation between simulation model and the test based on this formulation was good and satisfactory.

The values obtained through experiment and simulation combination method represent the total system of the knee impactor test rig. However, it is different from the value obtained through quasi-static method and from the data sheet from the manufacturer. This shows that the coefficient of friction must be obtained at the operational condition in real systems. The data sheet value is only a reference because there are various factors contributing to the coefficient of friction value for any system

The validation was conducted by comparing the loading curve which defines the position of peak load time and the peak load. This can be explained because femur load injury level is defined by the peak load and the peak load time. The unloading curve of the material model does not contribute to the injury assessment of the femur load injury. Thus, no effort on matching it was invested.

The validation in the time domain was done with three different impact types. The first case was the basic model, and the second case was with additional mass of 5.6 kg. The third case was an impact with the angle of 60 degrees. All different types were introduced to ensure the robustness of the simulation model. In addition, the operation test configurations also vary in different vehicles and types. This is due to the different design of cockpit and the dummies used.
The simulation model developed in this study matches the test rig performance. The analysis shows, that the model correlated well with the actual test. The difference between the simulation modelling and real test are within 5 percent in terms of the acceleration curve and impact load.

7 Literature

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