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“Impact Dynamics of Rotating Plates: Evaluating Material and Speed Effects for Aircraft Blade Design”

Researcher:

Mohammad Alobaid
Construction Training Institute, PAAET, Kuwait

ABSTRACT:

This study investigates the dynamic response of a rotating circular plate impacted by a rigid sphere, with potential applications in understanding bird strikes on aircraft axial compressor blades. Using LS-DYNA for simulation, the relationships between plate internal energy, sphere kinetic energy, and plate tip displacement are examined under varying rotational speeds and materials. The objective is to evaluate the effectiveness of different materials and rotational speeds in enhancing the impact resistance and stability of the plate, providing insights into the optimal design of aircraft blades. Through comparative analysis, this research aims to identify the key factors that influence energy absorption and deformation behavior in rotating plates, thereby contributing to improved safety and performance in aerospace engineering.

KEYWORDS: Impact dynamics, Rotating plates, LS-DYNA simulation, Aerospace materials.

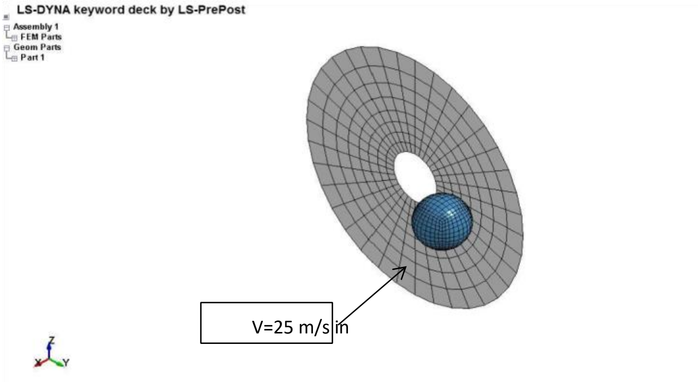
Introduction:

In a study by He et al.[1], three constitutive models, Johnson-Cook (JC), Modified Johnson-Cook (MJC), and Arrhenius-type, were investigated for their ability to predict high-temperature flow stress in 20CrMo alloy steel. The MJC and Arrhenius models were found to be more accurate than the JC model, particularly at lower strain rates, due to their incorporation of the interaction between strain rate and temperature. This suggests that models that account for this coupling effect are preferable for improved flow stress prediction in 20CrMo steel at high temperatures. Venkatesan et al.[2] investigated the impact response of a semi-infinite aluminum target struck by a projectile at normal and oblique angles. Their focus was on energy absorption and damage mechanisms. They found that oblique impacts increased the area of plastic deformation and influenced the projectile's trajectory compared to normal impacts. This highlights the importance of considering impact angle when designing structures for ballistic protection. Backman and Goldsmith[3] addressed the mechanics of projectile penetration into targets in a comprehensive study. Their work in the International Journal of Engineering Science explored various factors influencing penetration depth, including projectile and target material properties, impact velocity, and projectile geometry. This in-depth analysis provides a foundational understanding of projectile penetration mechanics, valuable for further research in terminal ballistics. Balaji et al.[4] investigated the ballistic resistance of friction stir welded (FSW) AA5083 aluminum alloy targets under single and multiple projectile impacts . They employed finite element analysis (FEA) and experimental tests to compare projectile penetration and target deformation. The study revealed a correlation between the number of impacts and the increase in kinetic energy absorbed and residual target velocity. This finding highlights the importance of considering multiple projectile strikes when designing armor using FSW AA5083. Wang et al.[5] used finite element modeling to simulate cutting forces experienced by 7075-T6 aluminum alloy during conventional and high-speed machining . The Johnson-Cook material model was implemented to predict cutting forces in different directions. Their results suggest that the model's accuracy depends on machining speed. Different parameter sets within the model were required for accurate prediction at conventional and high-speed conditions. This highlights the need for considering machining speed when selecting material constants for finite element models in machining simulations. Xiao et al.[6] investigated the influence of the Lode angle on predicting ballistic resistance in Weldox 700 E steel plates struck by blunt projectiles. Their experiment employed blunt projectiles and finite element models to analyze fracture behavior. They found that while both Lode-dependent and independent fracture criteria predicted similar ballistic limits, the material's true ductile behavior differed depending on the dominant stress state. This suggests that incorporating the Lode angle might be necessary for a more accurate understanding of material behavior under ballistic impact. In a foundational work for high-strain rate material modeling, Johnson[7] presented a constitutive model for metals undergoing large strains, high strain rates, and high temperatures. This model is well-suited for computational applications due to its use of readily available variables. Material constants were obtained through various tests, including torsion and Hopkinson bar techniques. The model's accuracy was validated by comparing simulations with cylinder impact test data. Wiehahn et al.[8] investigated the deformation and tearing of thin plates subjected to high strain rates using finite element analysis . Their focus was on incorporating temperature-dependent material properties, a previously neglected factor. The study suggests that these properties significantly influence failure mechanisms. Localized shear banding, not previously considered, is identified as a key factor in tearing through the plate thickness. This highlights the importance of temperature-dependent material properties for accurate prediction of high-strain rate deformation and failure in thin plates. Garcia et al.[9] investigated the effect of incorporating polycaprolactone nanofibers into glass fiber reinforced polymer composites. The study examined how these nanofibers influence the material's response to vibrations and impacts. Findings showed that while the nanofibers didn't significantly alter the natural frequencies, they did increase the material's damping capacity. Additionally, simulations showed improved damage resistance under impact compared to unmodified composites. This suggests polycaprolactone nanofibers could be beneficial for controlling vibrations and enhancing impact resistance in composite structures. In a pivotal work for material modeling, Johnson[10] introduced a constitutive model for metals undergoing extreme conditions: large strains, high strain rates, and high temperatures . The model's focus on readily available variables makes it computationally efficient. Material constants were determined through various tests, including torsion and Hopkinson bar techniques. The model's effectiveness was validated by comparing simulations with experimental cylinder impact data.

In this study, a circular deformable plate rotating about its x-axis and impacted by a sphere was modeled using LS-PrePost. Using LS-DYNA, the relationships between the plate's internal energy, the sphere's kinetic energy, and the plate's tip displacement were investigated with respect to varying plate rotational speeds and materials. Additionally, the effectiveness of finer and coarser meshes was analyzed.

Problem Description

In Figure 1, a circular deformable plate is rotating with an angular velocity of 5000 rpm about its central x-axis and is struck by a rigid spherical projectile with a velocity of 25 m/s near its periphery, normal to the plate. The rigid sphere impacts the circular plate at a distance of 50 mm from the plate center along the y-axis. The circular plate has dimensions of $R_{out} = 100$ mm, $R_{in} = 20$ mm, and a thickness of 2 mm. The rigid sphere has a radius of 20 mm. The plate is made of an aluminum alloy with a density of 2700 kg/m³, a Young's modulus of 70 GPa, a Poisson's ratio of 0.3, a yield stress of 267 MPa, and a tangent modulus of 320 MPa. The sphere is made of an alloy with a density of 7800 kg/m³, a Young's modulus of 200 GPa, and a Poisson's ratio of 0.3. The simulation should be run explicitly with a termination time of 10 ms.



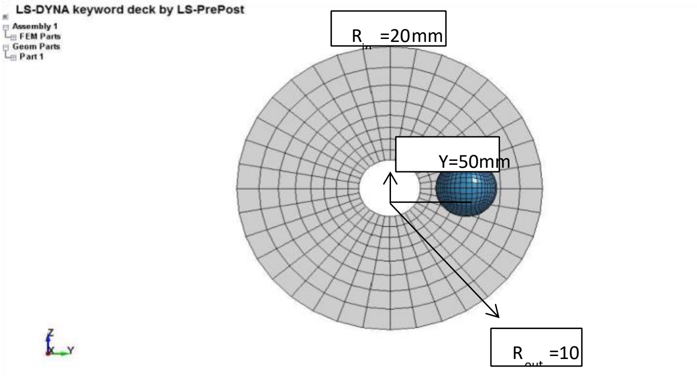


Figure 1.: Impact model
Analysis Procedure

1. Run the following cases to check the convergence.

Case Number	Mesh (plate) Density / Density in	Mesh (sphere) Density	Plate Element Type
1	26 / 26	5	2 (NIP=5)
2	36 / 36	10	2 (NIP=5)
3	44 / 44	14	2 (NIP=5)

a) Compare the plate internal energy as a function of time for all cases.
b) Compare the sphere kinetic energy as a function of time for all cases.

2. Choose Case (2) and run the model with different plate angular velocities = 4000 rpm, 5000 rpm, and 6000 rpm, and compare:

a) Plate internal energy as a function of time.
b) Spherical kinetic energy as a function of time.
c) The displacement at the plate tip in the x-direction.

3. Try using nickel instead of aluminum alloy. How does that affect the results? (Choose case 2 with angular velocity = 5000 rpm).

Results

The figures 2 and 3 illustrate the plate's internal energy and kinetic energy as a function of time for three different mesh cases. In Figure 2, the internal energy of the plate shows a rapid increase initially, followed by a more gradual rise and stabilization. Case 3 exhibits the highest internal energy, indicating that a finer mesh may capture more detailed deformation energy. In Figure 3, the kinetic energy of the sphere decreases sharply initially due to impact, then rebounds and stabilizes. Case 3 demonstrates the highest kinetic energy. These results suggest that a finer mesh can more accurately simulate the energy dynamics during impact, leading to more reliable results in simulations.

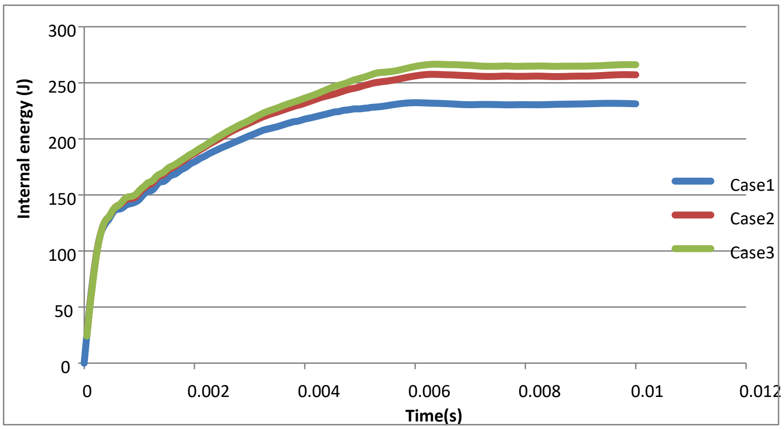


Figure 2.: Internal energy of the plate as a function of time for all different mesh cases.

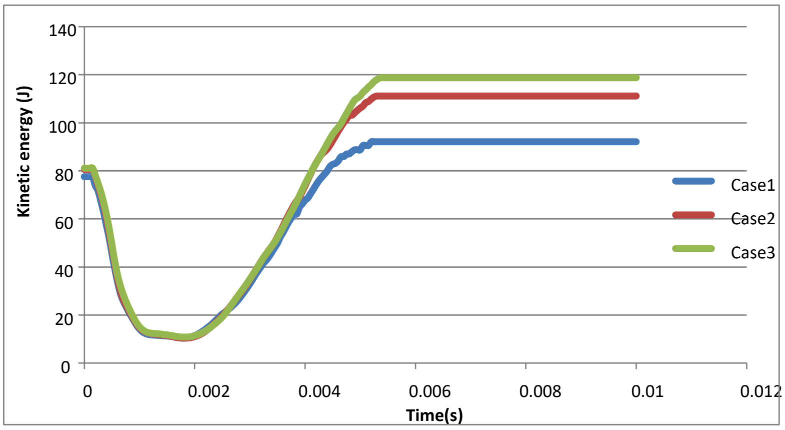


Figure 3.: Kinetic energy of the sphere as a function of time for all different mesh cases.

The figures 2 and 2 illustrate the plate's internal energy and the sphere's kinetic energy as a function of time for Case 2 at different plate angular velocities. In Figure 2, it is evident that the internal energy of the plate increases more rapidly and reaches a higher maximum value as the plate's angular velocity increases. This indicates that higher rotational speeds result in greater energy absorption by the plate. Figure 5 shows the kinetic energy of the sphere, where higher angular velocities lead to a more significant reduction in kinetic energy, reflecting more efficient energy transfer to the plate. These observations suggest that increasing the rotational speed of the plate enhances its ability to absorb and dissipate impact energy.

2)

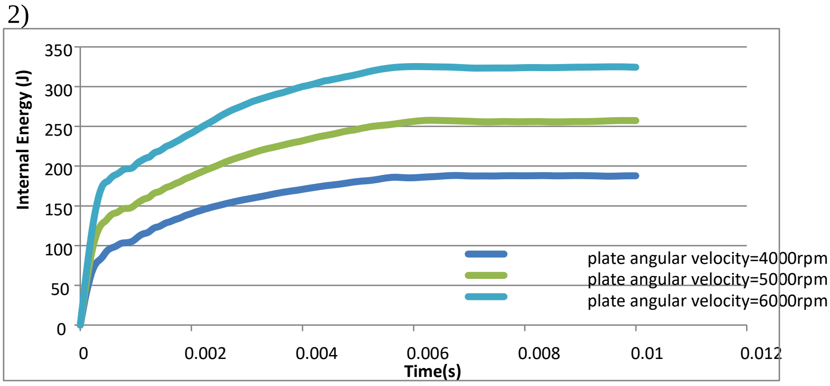


Figure 4.: Internal energy of the plate as a function of time for different angular velocities

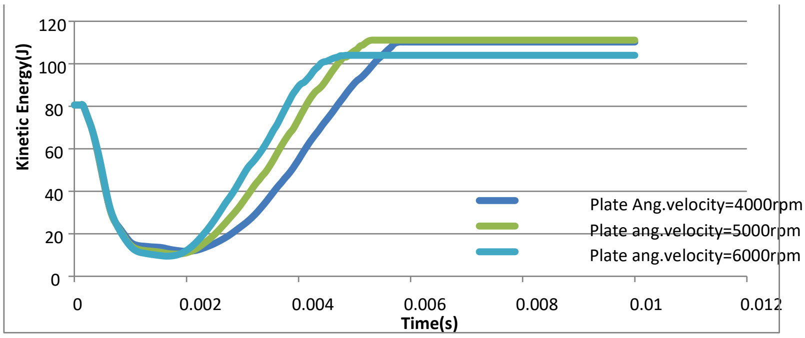


Figure 5.: Kinetic energy of the plate as a function of time for different angular velocities

Figure 6 shows the displacement in the x-direction of Case 2 as a function of time for different plate angular velocities, with a diagram illustrating the node used to measure this displacement at the plate's tip. Higher angular velocities, such as 6000 rpm, lead to faster stabilization and less fluctuation in the displacement over time compared to lower angular velocities like 4000 rpm. This suggests that higher rotational speeds enhance the plate's ability to return to equilibrium more quickly after impact, thus potentially reducing the overall deformation and improving structural resilience during dynamic loading events.

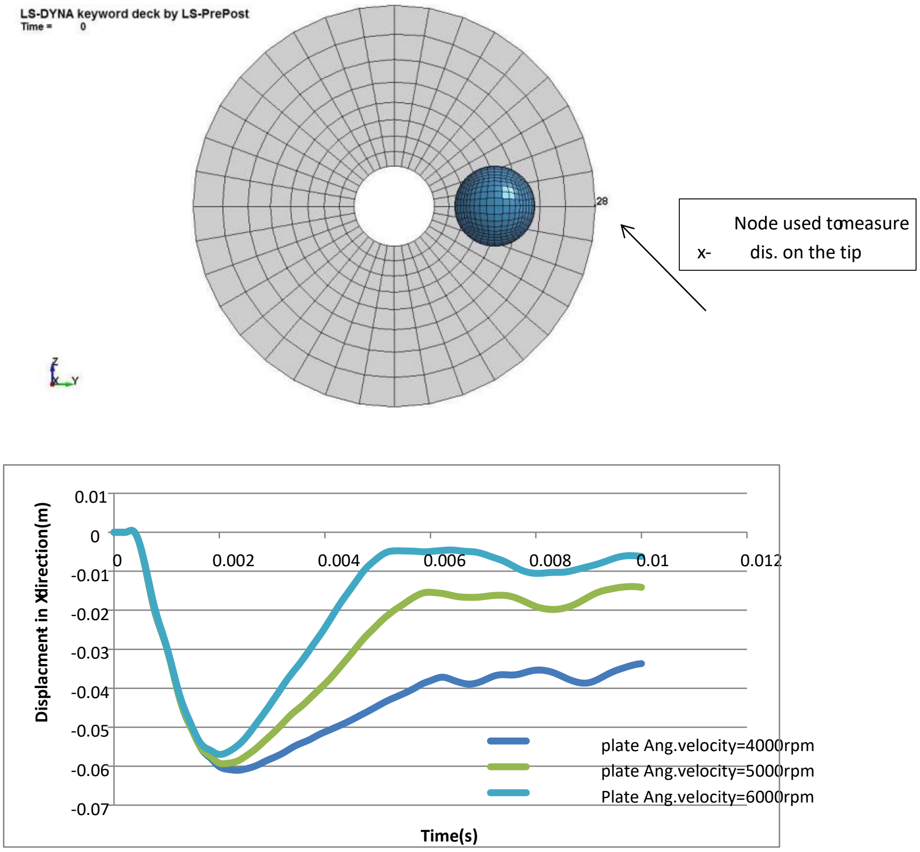


Figure 6.: The displacement in x direction of case(2) as a function of time for different plate angular velocities

Figures 7 and 8 compare the internal energy of the plate and the kinetic energy of the sphere, respectively, for Case 2 using two different plate materials: nickel and aluminum alloy. In Figure 6, the internal energy of the nickel plate is significantly higher than that of the aluminum alloy plate, indicating that nickel absorbs more energy during impact. This higher energy absorption is reflected in Figure 7, where the kinetic energy of the sphere decreases more rapidly and to a lower value with the nickel plate. These results suggest that nickel, due to its higher density and mechanical properties, is more effective in dissipating impact energy, leading to reduced kinetic energy retention in the sphere. This makes nickel a potentially better material for applications requiring high energy absorption and impact resistance.

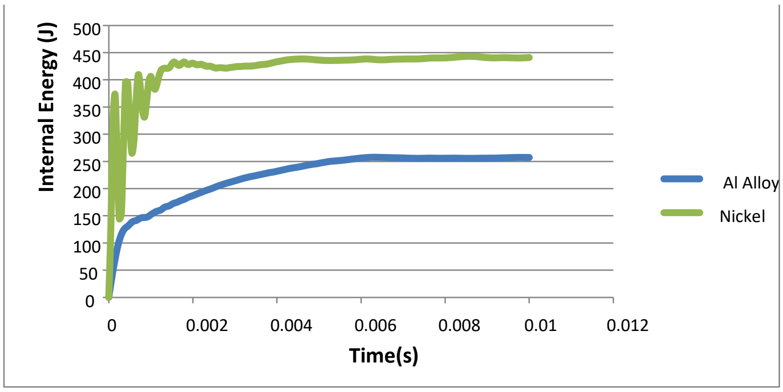


Figure 7.: Internal energy of the plate of case2 as a function of time for 2 different plate materials, Nickel and Al alloy.

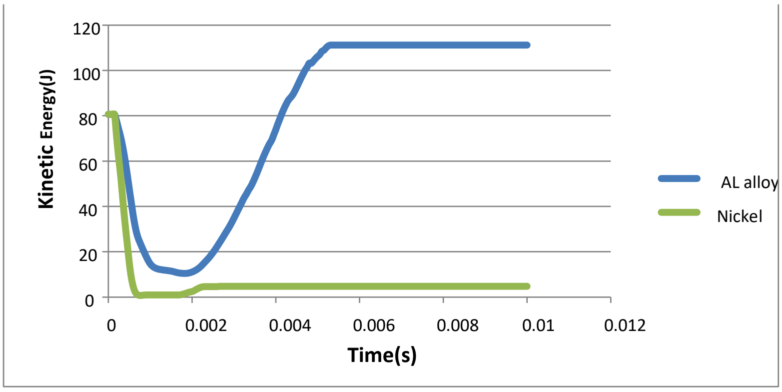


Figure 8.: Kinetic energy of the plate of case2 as a function of time for 2 different plate materials, Nickel and Al alloy.

The Figure 9 shows the displacement in the x-direction for Case 2 with two different plate materials: aluminum alloy and nickel. The aluminum alloy plate experiences greater overall deformation compared to the nickel plate. Additionally, the nickel plate returns to its original position much quicker than the aluminum alloy. This indicates that nickel, with its higher stiffness and density, reacts more dynamically and recovers faster from the impact, while the aluminum alloy, being less stiff, deforms more and takes longer to stabilize.

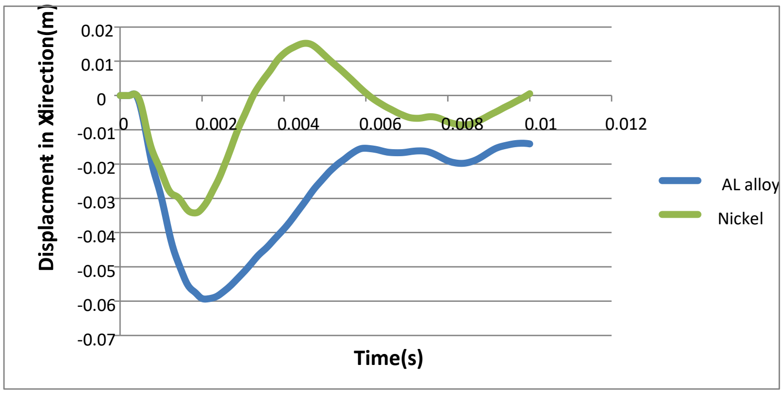


Figure 9.: The displacement in x direction of case(2) as a function of time for different plate materials AL alloy and nickel.

Conclusion

One obvious application of this study is in understanding bird strikes on aircraft axial compressor blades. The study demonstrates the impact of rotational speed and material selection on the circular plate's internal energy, sphere kinetic energy, and plate tip displacement in the x-direction. At a rotational speed of 6000 rpm, the plate exhibited the highest internal energy and minimal tip displacement after the sphere rebounded. For nickel material, the results show excellent absorption of the sphere's kinetic energy and reduced plate tip displacement, making nickel a promising material for designing aircraft blades due to its superior energy absorption and stability.

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"ديناميكيات تأثير الألواح الدوارة: تقييم تأثيرات المواد والسرعة في تصميم شفرات الطائرات"

إعداد الباحث:

محمد العبيد

معهد تدريب البناء، الهيئة العامة للتعليم التطبيقي والتدريب، الكويت

الملخص:

تبحث هذه الدراسة في الاستجابة الديناميكية لصفائح دائرية دوارة تتأثر بكرة صلبة، مع تطبيقات محتملة في فهم ضربات الطيور على شفرات ضاغط الطائرات المحورية. باستخدام LS-DYNA للمحاكاة، يتم فحص العلاقات بين الطاقة الداخلية للوحة، والطاقة الحركية للكرة، وإزاحة طرف اللوحة تحت سرعات دوران ومواد مختلفة. الهدف هو تقييم فعالية المواد المختلفة وسرعات الدوران في تعزيز مقاومة التأثير واستقرار اللوحة، مما يوفر رؤى حول التصميم الأمثل لشفرات الطائرات. من خلال التحليل المقارن، يهدف هذا البحث إلى تحديد العوامل الرئيسية التي تؤثر على امتصاص الطاقة وسلوك التشوه في الصفائح الدوارة، وبالتالي المساهمة في تحسين السلامة والأداء في هندسة الطيران.

الكلمات المفتاحية: ديناميكيات التأثير، الصفائح الدوارة، محاكاةLS-DYNA ، مواد الطيران.