Research Article

Journal of Marine and Engineering Technology (JOINMET) 4(2), 54-63, 2024
Received: 12-Mar-2024 Accepted: 17-Dec-2024
Homepage: https://dergipark.org.tr/tr/pub/joinmet
https://doi.org/10.58771/joinmet.1595366

SAKARYA UNIVERSITY
OF APPLIED SCIENCES

Investigation of the Effects of Design Parameters on Tooth Profile Formation and Operating Performance in Cycloidal Reducers

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ABSTRACT

Cycloidal reducers have a unique and complex tooth profile design compared to conventional gear systems. Unlike standardized gear profiles, cycloidal reducers provide significant flexibility in design parameters such as module, profile modification coefficient, and eccentricity. However, these parameters interact in a complex manner, affecting both tooth profile formation and the overall performance of the reducer. Inaccuracies in selecting parameters may lead to problems such as excessive contact stress, gear deformation or reduced load transfer efficiency. This study aims to investigate the effects of design parameters on the formation of cycloidal tooth profiles and the operating performance of reducers. By analyzing the relationships and interactions between these parameters, the research provides a deeper understanding that will improve design processes, enhance performance, and contribute to future standardization efforts. The analysis results show that increasing the eccentricity (e) from 1.0 to 1.7 improves transmission efficiency by approximately 0.20% and contact efficiency by up to 8.00%. Conversely, an increase in the reference circle diameter (R_z) leads to a reduction in both transmission and contact efficiencies by approximately 0.2%, highlighting the critical impact of this parameter on performance optimization. In conclusion, eccentricity is identified as the design parameter with the highest impact on efficiency, emphasizing its critical importance in the design process.

Keywords: Cycloidal reducer, design parameters, cycloidal profile, efficiency.

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Sikloid Redüktörlerde Tasarım Parametrelerinin Diş Profili Oluşumu ve Çalışma Performansı Üzerindeki Etkilerinin İncelenmesi

ÖZET

Sikloid redüktörler, geleneksel dişli sistemlerine kıyasla benzersiz ve karmaşık bir diş profili tasarımına sahiptir. Standartlaştırılmış diş profillerinin aksine, sikloid redüktörler modül, profil modifikasyon katsayısı ve eksantriklik gibi tasarım parametrelerinde önemli bir esneklik sunar. Ancak, bu parametreler karmaşık bir şekilde etkileşime girerek hem diş profili oluşumunu hem de redüktörün genel performansını etkiler. Yanlış parametre seçimi, aşırı temas gerilmesi, dişli deformasyonu veya azalmış yük aktarım verimliliği gibi sorunlara yol açabilir. Bu çalışma, tasarım parametrelerinin sikloid diş profillerinin oluşumu ve redüktörlerin çalışma performansı üzerindeki etkilerini incelemeyi amaçlamaktadır. Bu parametreler arasındaki ilişkiler ve etkileşimler analiz edilerek, tasarım süreçlerini iyileştirecek, performansı artıracak ve gelecekteki standardizasyon çabalarına katkıda bulunacak daha derin bir anlayış sunulmaktadır. Analiz sonuçları, eksantriklik (e) değerinin 1.0'dan 1.7'ye artırılmasının iletim verimliliğini yaklaşık %0.20, temas verimliliğini ise %8.00'e kadar artırdığını göstermektedir. Buna karşın, referans çember çapındaki (R_z) artış, hem iletim hem de temas verimliliğinde yaklaşık %0.2 oranında düşüşe neden olmakta ve bu parametrenin performans optimizasyonundaki kritik etkisini vurgulamaktadır. Sonuç olarak, tasarım parametrelerinden verime en büyük etkisi olan parametrenin eksantriklik değeri olduğu ve tasarım sürecinde kritik bir öneme sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Sikloid redüktör, tasarım parametreleri, sikloid profil, verimlilik.

1 Introduction

Cycloidal reducers have garnered significant attention in the industry due to their unique operating principles and numerous advantages, including high reduction ratios, compact size, and outstanding efficiency. They are extensively used in industries requiring high transmission ratios, such as wind turbines, as well as in compact and precision-demanding applications like robotics and heavy machinery. Unlike traditional gear systems, which rely on standardized profiles defined by basic design parameters such as module and number of teeth, cycloidal reducers exhibit a more flexible and complex design structure. While this flexibility benefits performance optimization, it also introduces challenges in achieving standardization and robust design methodologies.

The performance and durability of cycloidal reducers depend significantly on the design of the cycloidal tooth profile. Critical design parameters such as module, profile modification coefficient, and eccentricity interact in a complex manner, influencing key factors such as contact stress distribution, load transfer efficiency, and overall operational reliability. Improper selection of these parameters can result in critical issues such as gear deformation, excessive wear on contact surfaces, and reduced transmission efficiency. Consequently, a comprehensive understanding of the relationships among these design parameters and their effects on both tooth profile formation and operational performance is crucial.

Previous studies have emphasized the importance of precise design and optimization of cycloidal reducers. For instance, the geometry and dynamic behavior of modified cycloidal reducers with epitrochoidal tooth profiles have been analyzed to improve manufacturability and performance, with specific focus on the influence of the tooth thickness ratio and raceway parameters on efficiency and stiffness (Li et al., 2020). Other studies have investigated the effects of manufacturing deviations and elastic deformations on load distribution in mismatched cycloid-pin gear pairs, offering insights into contact stress and transmission error characteristics (Li et al., 2022). Additionally, research has explored the wear mechanisms of cycloidal drives by examining changes in tooth profiles and operational parameters to enhance durability and reliability (Xu, 2019). Structural parameter studies have also shown significant improvements in transmission efficiency and contact stress distribution through the application of multi-objective optimization techniques (Huang, 2020).

Despite these advances, a comprehensive analysis of the interplay between design parameters and their impact on both tooth profile formation and operational performance of cycloidal reducers remains limited. Existing studies often focus on specific aspects, such as wear mechanisms or load distribution, without integrating these findings into a holistic framework. This gap underscores the need for more systematic research.

In the context of cycloidal reducers, parameters such as module, profile modification coefficient, and eccentricity should be studied not only individually but also in terms of their interactions. For example, eccentricity directly influences the gear contact ratio, altering the dynamic load distribution, while the module determines gear dimensions, thereby affecting load-carrying capacity and contact stiffness (Tsai et al., 2017). Furthermore, profile modification enables the optimization of critical performance factors such as surface wear and vibration (Li et al., 2018).

Studies on cycloidal reducer profiles have particularly focused on minimizing backlash, a critical criterion in precision reducers. To this end, various mathematical models have been developed to address potential errors arising from modification values and manufacturing methods. Alipiev (1988) provided a mathematical model explaining the effects of module and modification values on cycloidal disk geometry and analyzed the relationships among these parameters in detail. Uzun (2019) extended Alipiev’s model, analyzing the impact of the Profile Correction Factor on load distribution, determining that its effects on force distribution were non-linear, with an optimal distribution observed at a value of 0.8.

The inability to standardize parameters such as module, modification values, modification coefficient, and profile correction factor in cycloidal disk profile generation allows for design flexibility but complicates profile determination. Mathematical models leveraging transformations in Cartesian coordinate systems have facilitated the definition of these parameters. These models consider factors such as pin radius, the radius of the reference circle where pins are located, the number of pins, and eccentricity. Modification operations are generally conducted by altering either the pin radius or the radius of the reference circle (Li et al., 2020; Lin et al., 2014; Ren et al., 2017; Xu et al., 2019; Yan & Lai, 2002).

Given the critical sensitivity of design parameters, optimization algorithms have been employed to address these challenges. For instance, Korkmaz et al. (2024) optimized profile parameters within specified boundary conditions, while Que et al. (2023) aimed to enhance efficiency through optimization processes, enabling informed decision-making regarding design parameters (Korkmaz et al., 2024; Que et al., 2023). Hu et al. (2020) proposed a method termed “elastic error compensation,” designed to reduce sensitivity to potential gaps in the system, reporting significant improvements in contact performance through profile modifications.

This study aims to investigate the effects of critical design parameters on the tooth profile formation and operating performance of cycloidal reducers. By analyzing the complex interactions among these parameters, the research seeks to provide valuable insights for optimizing design processes and improving performance. Additionally, the findings are expected to contribute to efforts to standardize cycloidal reducer designs, ensuring their applicability and reliability across diverse engineering applications.

2 Design Parameters in Cycloid Reducers

There are two different methods used for the design of cycloidal reducers. The first method involves the profile design based on the module and profile modification coefficient. The second method focuses on the disk profile derived by tracing the contact points between the disk and the pins. To examine the effects of design parameters on the profile, it is necessary to evaluate these two methods separately. In the evaluation of the methods, the commonly accepted configuration in studies has been adopted, where the number of lobes in the disk (z_1) is 39, and the pin count (z_2) is 40.

Figure 1 shows the conceptual cycloid disk design that will form the basis of the study (Korkmaz, 2024). The distribution of pins around the disk is also defined.

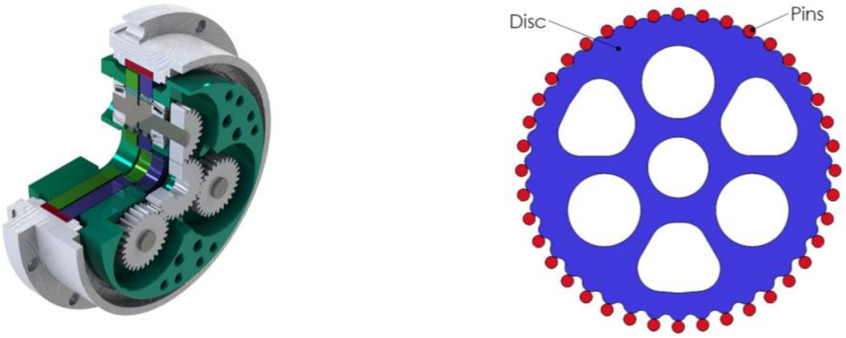


Figure 1: Design of the cycloidal reducer disc and pins

2.1 Parameters of Profile Equations Based on Module and Modification Coefficient

In this method, the cycloidal profile is determined by interrelated parameters: module (m), modification coefficient (x), and profile smoothing factor (r_c^*). The method is based on modeling the cycloidal profile formed by the rolling motion of a circle with a radius of (radius of r_c) on a reference circle without slipping (Alipiev, 1988). The value of is calculated as shown in Equation (1) by multiplying the radius correction coefficient (r_c*) of the profile-generating circle with the module value (Korkmaz, 2024):

$$r_c=r_c^*\times m \tag{1}$$

The r_c^* value is taken as 1 in the definitions found in the literature (Alipiev, 1988a).

Another design parameter, the eccentricity (e) is equal to half of the module value (Alipiev, 1998a).

$$e=m/2 \tag{2}$$

The dimensions of the cycloidal gear and the form of the cycloidal profile are determined based on the parameters provided in Equation (3):

$$\begin{cases} x=\frac{m}{2}\left[(z_1+1)\sin(t)-(1-x)\sin((z_1+1)t)+\frac{2r_c^*[(1-x)\sin((z_1+1)t)-\sin(t)]}{\sqrt{1-2(1-x)\cos(z_1t)+(1-x)^2}}\right] \\ y=\frac{m}{2}\left[(z_1+1)\cos(t)-(1-x)\cos((z_1+1)t)+\frac{2r_c^*[(1-x)\cos((z_1+1)t)-\cos(t)]}{\sqrt{1-2(1-x)\cos(z_1t)+(1-x)^2}}\right] \end{cases} \tag{3}$$

2.2 Parameters of Profile Equations Based on the Contact Point Between the Disk and Pins

In this method, the mathematical expression of the path resulting from the relative displacement at the contact point between the pin and the cycloidal profile is utilized. Both the number of parameters and their interrelation are fewer compared to the method based on the modification coefficient. The equation used for this method is provided in Equation (4) (Korkmaz, 2024).

$$R_p(\theta_1)=\begin{bmatrix} r_z\frac{K_1}{\sqrt{1+K_1^2-2K_1\cos\theta_1}}\sin\theta_1 \\ R_z-r_z\frac{(1-K_1\cos\theta_1)}{\sqrt{1+K_1^2-2K_1\cos\theta_1}} \\ 0 \\ 1 \end{bmatrix} \tag{4}$$

Here, R_z represents the radius of the pin reference circle, r_z denotes the pin radius, and K_1 refers to the modification value. The modification value is calculated as shown in Equation (5):

$$K_1=\frac{e\times z_2}{R_z} \tag{5}$$

As seen in Equations (2) and (3), the parameters in this method are, respectively, eccentricity (e), the radius of the pin reference circle (R_z), and the pin radius (r_z).

2.3 Effects of Parameters on Efficiency

In cycloidal reducers, efficiency calculations are defined based on the contact region between the disk and the pins, and they are directly influenced by design parameters. The transmission efficiency (η_x) defined for cycloidal reducers is provided in Equation (6):

$$\eta_x=1-[(R_z-\Delta R_z)-(r_z-\Delta r_z)]\frac{4\mu}{k1\times z_1\times(R_z-\Delta R_z)\pi} \tag{6}$$

In addition to the given design parameters, ΔR_z is used to account for potential deviations in the reference circle, and Δr_z represents elastic deformations in the pins. These factors are included in the calculations. Furthermore, the coefficient of friction (μ) has also been incorporated, which is assumed to be 0.075 due to the high lubrication level of the system (Gao et al., 2024).

Also, cycloidal reducers have contact efficiency. An increase in gear contact efficiency indicates reduced wear and clearance during engagement and the transmission of motion and power between the cycloidal profile and pins. Therefore, it is highly significant for performance. Contact efficiency is calculated using Equation (8):

$$\eta=\frac{\eta_x}{1+z_1(1-\eta_x)} \tag{7}$$

3 Results and Discussion

The effect of the profile modification coefficient on performance in the method based on the modification coefficient was evaluated by Uzun (Uzun, 2019). The study indicated that a decrease in the profile modification coefficient leads to a reduction in the reaction forces occurring in the disk, which in turn results in a decrease in efficiency. The profile changes resulting from the application of design parameters are illustrated in Figure 2.

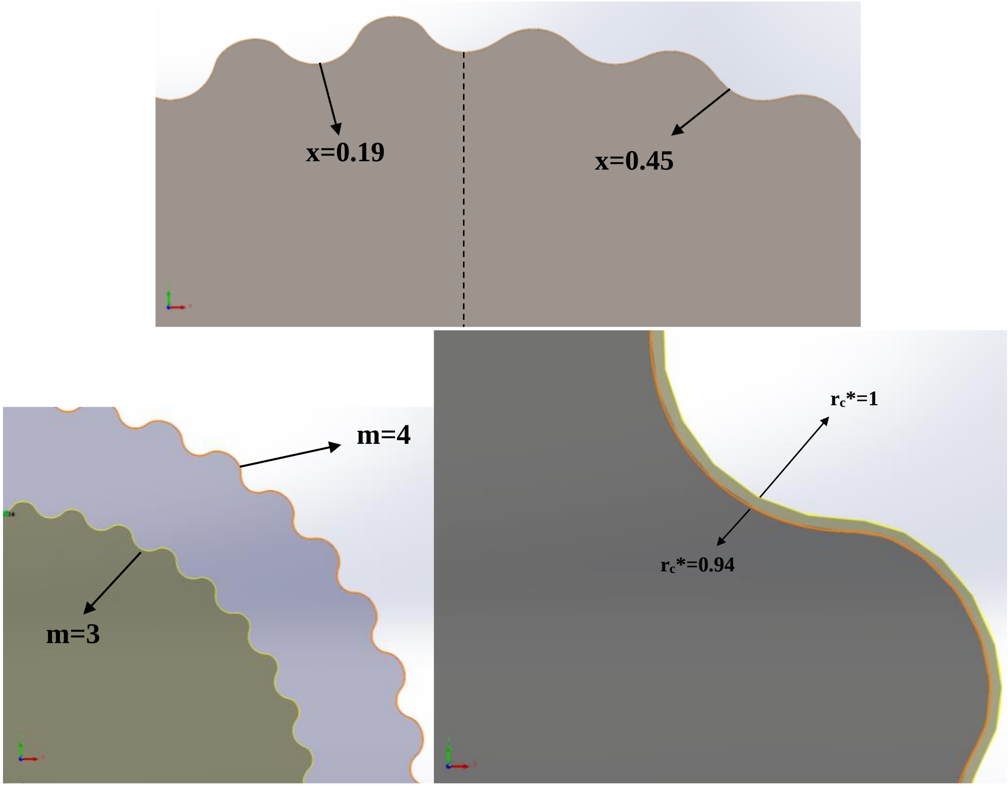
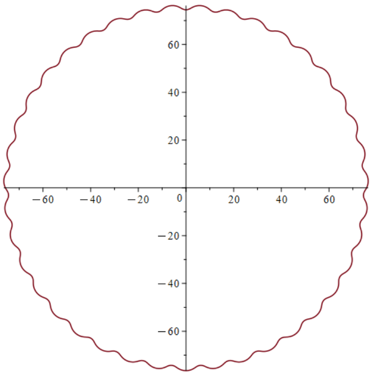
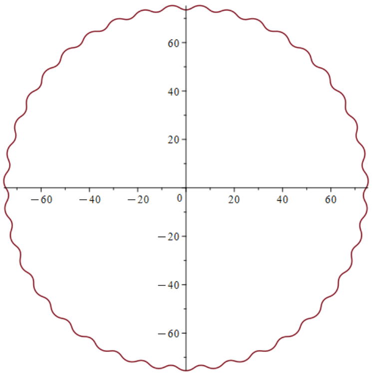
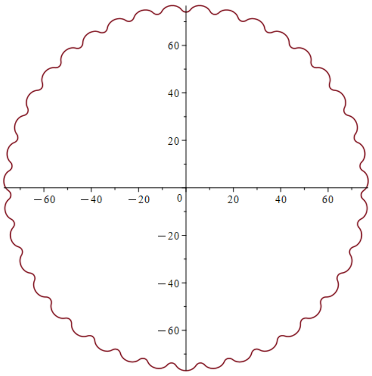
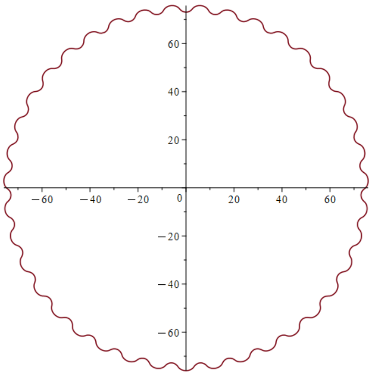
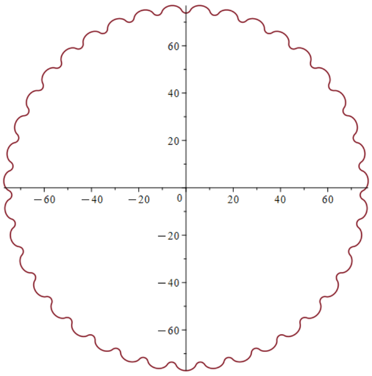
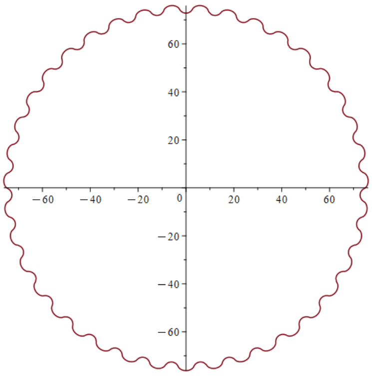
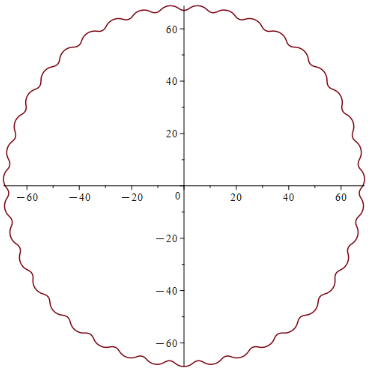
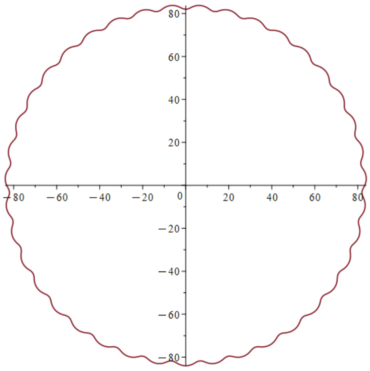
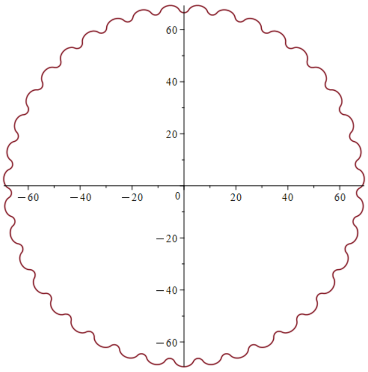
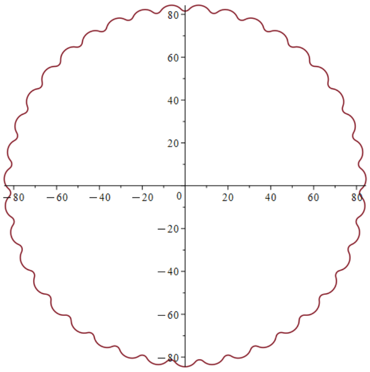


Figure 2: Effects of parameters on profile and disk dimensions in the first method

The effects of changes in eccentricity and pin radius on the disk profile in the second method are presented in Table 1. The table shows that variations in eccentricity significantly influence the disk height. On the other hand, changes in pin radius do not cause substantial alterations to the disk profile.

Table 1: Effects of parameters on profile and disk dimensions in the second method

 e = 1; r_z = 2; R_z = 77.5 **A**	 e = 1; r_z = 3; R_z = 77.5 **B**	 e = 1.5; r_z = 2; R_z = 77.5 **C**
 e = 1.5; r_z = 3; R_z = 77.5 **D**	 e = 1.7; r_z = 2; R_z = 77.5 **E**	 e = 1.7; r_z = 3; R_z = 77.5 **F**
 e = 1; r_z = 2; R_z = 70 **G**	 e = 1; r_z = 2; R_z = 85 **H**	 e = 1.5; r_z = 2; R_z = 70 **I**



e = 1.5; r_z = 2; R_z = 85

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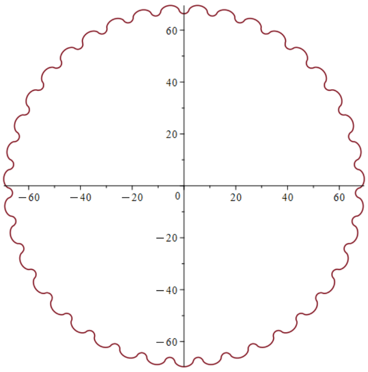

e = 1.7; r_z = 2; R_z = 70

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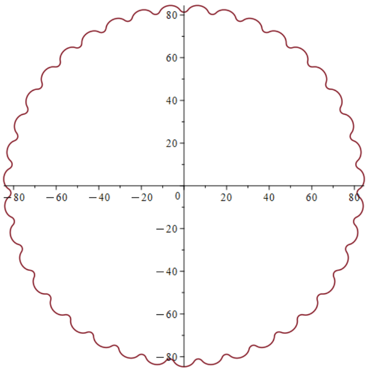

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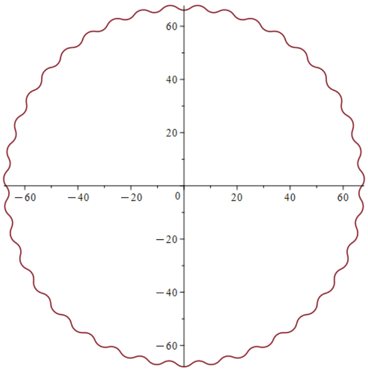
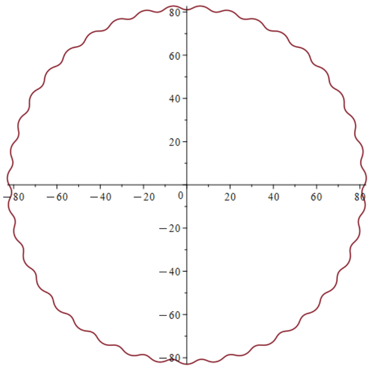


e = 1; r_z = 3; R_z = 70

M



e = 1; r_z = 3; R_z = 85

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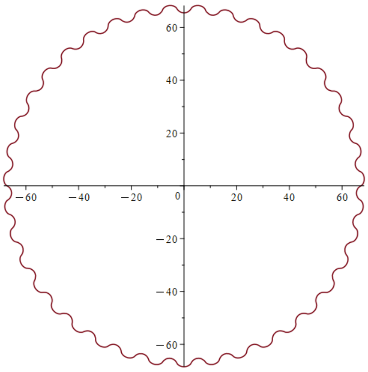

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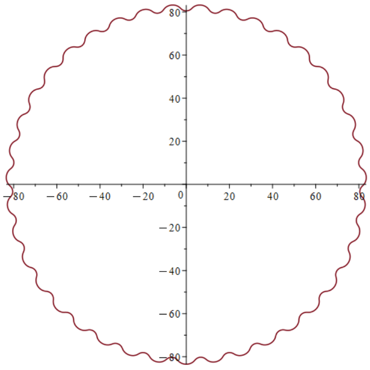

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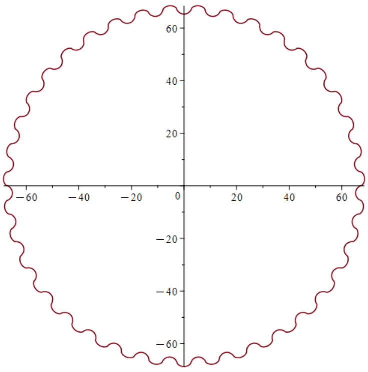

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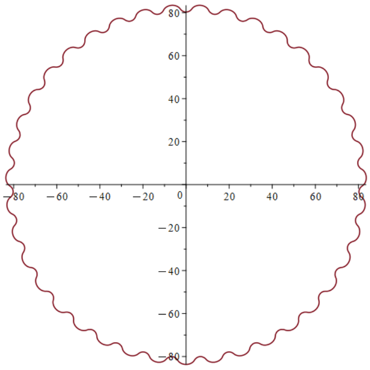

e = 1.7; r_z = 3; R_z = 85

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As seen in Figure 3, changes in design parameters such as eccentricity and pin radius have a minimal effect on transmission efficiency. However, while variations in pin radius have a minor impact on contact efficiency, an increase in the eccentricity parameter results in an improvement in efficiency. This indicates that eccentricity is the most critical parameter in cycloidal reducers. Additionally, it is observed that as the reference circle diameter increases, both contact efficiency and transmission efficiency decrease.

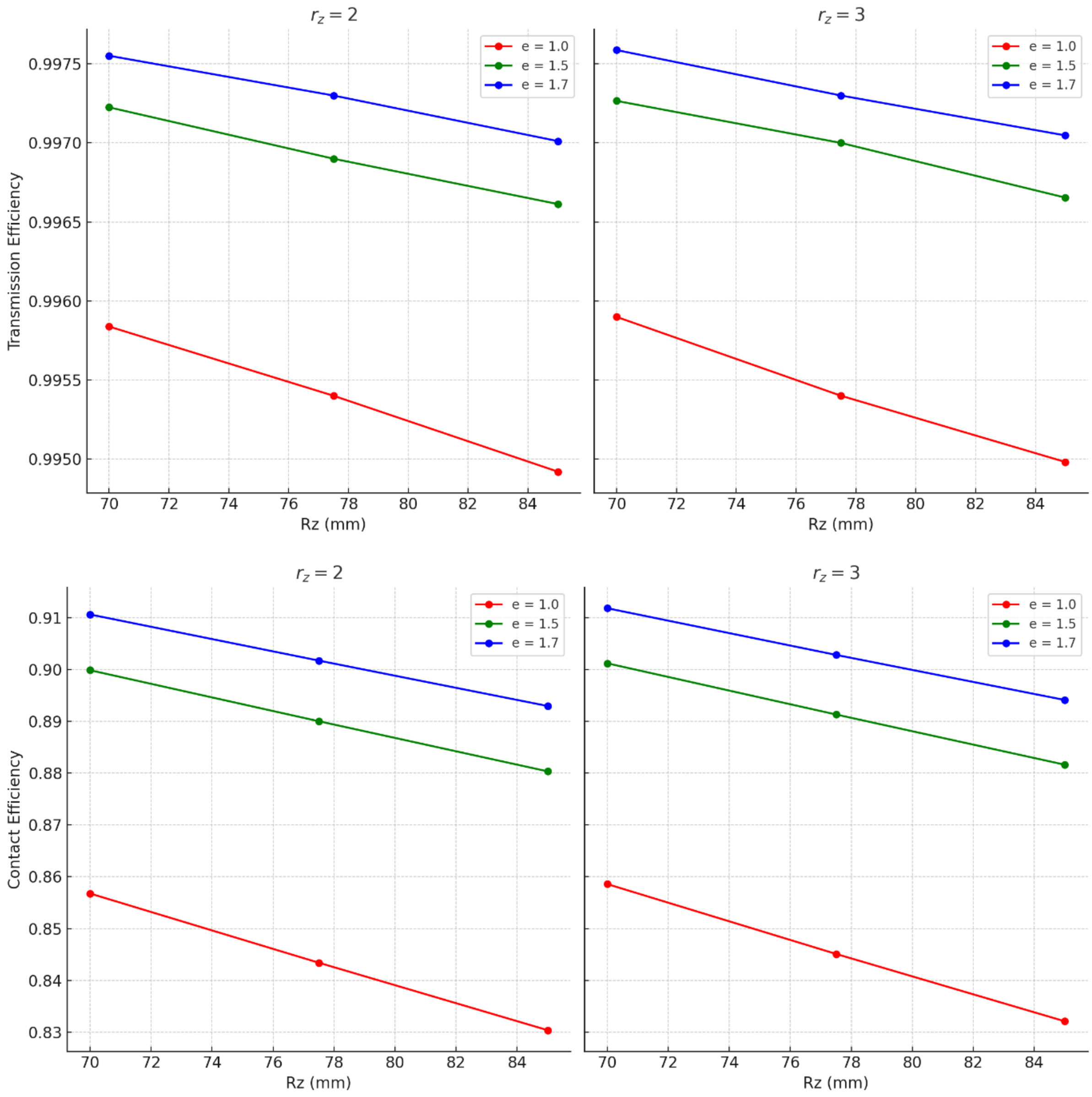

Figure 3: Comparison of transmission and contact efficiency

The results indicate that changes in pin radius (r_z=2 mm and r_z=3 mm) have a negligible effect on transmission efficiency. In contrast, eccentricity (e) plays a more prominent role. For fixed pin radius values, an increase in eccentricity from e=1.0 to e=1.7 leads to a slight improvement in transmission efficiency across all reference circle diameters (R_z). However, as R_z increases, a marginal decline in transmission efficiency is observed, irrespective of the values of e and r_z.

Contact efficiency shows a similar dependence on the design parameters. Higher eccentricity values consistently enhance contact efficiency, with e=1.7 yielding significantly better results compared to e=1.0. This improvement reflects better engagement and interaction between the cycloidal profile and pins. Conversely, an increase in R_z results in a reduction in contact efficiency, likely due to increased clearances or misalignment, which adversely impact power and motion transmission.

Among the analyzed parameters, eccentricity emerges as the most influential in determining both transmission and contact efficiency. Higher eccentricity values not only improve efficiency but also contribute to smoother engagement, reducing wear and enhancing durability. In comparison, variations in pin radius have a minor impact, highlighting the secondary role of r_z in optimizing performance.

In conclusion, while both R_z and r_z influence efficiency, eccentricity stands out as the critical parameter for improving the performance of cycloidal reducers. These findings underscore the importance of optimizing e and carefully selecting R_z to balance efficiency and reliability in cycloidal reducer designs.

4 Conclusion

This study investigated the effects of critical design parameters on tooth profile formation and operational performance of cycloidal reducers. The findings revealed that parameters such as eccentricity, pin radius, and modification coefficient have varying degrees of impact on both profile geometry and operational efficiency. Among these, eccentricity emerged as the most influential parameter that significantly affects both contact and transmission efficiency.

The analysis showed that although changes in pin radius have minimal impact on efficiency, eccentricity plays a critical role in optimizing performance. Additionally, the study showed that although beneficial for smoother transitions in profiles, increasing modification coefficients can lead to increased wear and decreased efficiency due to higher reaction forces. These insights highlight the importance of careful parameter selection to balance durability and performance.

The results of this research contribute to a deeper understanding of the interaction between design parameters in cycloidal reducers, paving the way for improved optimization strategies. Future work should focus on integrating these findings into standard design frameworks and exploring advanced optimization algorithms to further enhance the reliability and applicability of cycloidal reducers in various engineering applications.

5 Declarations

5.1 Competing Interests

There is no conflict of interest in this study.

5.2 Authors’ Contributions

Furkan Korkmaz: Contributions have been made in conducting the literature review for the article, formulating ideas or hypotheses for the study, planning the materials and methods necessary to reach the conclusions, organizing the data, and performing comparisons with the developed models.

Ahmet Kolip: Contributions have been made in developing ideas or hypotheses for the article, planning the materials and methods to achieve the results, logically explaining and presenting the findings, and revising the manuscript before submission not only for grammar and spelling but also for intellectual content.

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