ANALYSIS OF GENERAL CHARACTERISTICS OF TRANSMISSION ERROR IN HELICAL GEARS AND ITS EFFECTS ON GEAR NOISE AND VIBRATION

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ABSTRACT

In this thesis, a general model for the tooth meshing of gears is proposed; in which a quasi-infinite elastic model composed of springs with stiffness peculiar to the gear is incorporated. Also, the concept of potential gear noise, which is a noise to express directly the effect of tooth flank form of gear on the gear noise, is proposed and a sensory evaluation method is also proposed to evaluate sound level, noise quality and noise. The influence of tooth flank form deviation on transmission error is further investigated by using this model. The qualitative characteristic of the transmission error of gears with convex tooth flank form deviation is determined by the actual contact ratio and qualitative elements of gears; i.e. tooth flank form deviation and the distribution of stiffness. It can be concluded that the proposed sensory evaluation method of potential gear noise could enable gear designers to experience directly the effect of tooth flank form on the noise quality.

ABSTRAK

Thesis ini telah membincangkan model yang dicadangkan oleh penulis yang dapat mengenal ciri-ciri umum sepasang gear yang sedang mengalami ‘transmission error’. Juga, dengan menggunakan konsep ‘bunyi gear berpotensi’, di mana satu bunyi untuk menzahirkan kesan langsung dari permukaan bentuk gigi gear kepada bunyi gear, pengaruh bentuk gigi rusuk sisihan pada ‘transmission error’ disiasat dengan lebih teliti. Sifat-sifat kualitatif ‘transmission error’ dengan bentuk gigi rusuk sisihan yang bersifat cembung adalah berketentuan dilombong dengan nisbah hubungan sebenar dan unsur-unsur kualitatif gear, iaitu gigi rusuk bentuk penyelewengan dan pengagihan ketegangan. Dengan mengetahui sifat-sifat asas ‘transmission error’ sepasang gear melalui analisis nombor, kaedah ini membolehkan jurutera memahami kesan langsung gigi rusuk kepada pembentukan kualiti bunyi.

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"To my beloved family and supervisors, with gratitude for their inspiration, guidance, continuous support, and facilitation for me to be where I am today"

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Chapter 1

INTRODUCTION

1.1 Overview

In gear design, the most common type of tooth profile is the involute curve. It is used for the cylindrical spur and helical gears as well as for the conical gears like bevel, hypoid and spiral bevel gears. Some characteristics of involute (cylindrical) gears that have made them so unique are:

1. Uniform transmission of rotational motion, independent of small error in the center distance.
2. The sum of the tooth contact forces is constant and the direction of the total contact forces always acts in the same direction.

If the gears were perfectly rigid and no geometrical errors or modifications were present, the gears would transmit the rotational motion perfectly, which means that a constant speed at the input shaft would result in a constant speed at the output shaft. The assumption of zero friction leads to the understanding that the gears would transmit the torque perfectly, which means that a constant torque at the input shaft would result in a constant torque at the output shaft. No force variations would exist and hence no vibrations and no sound (noise) could be created. However, in reality, there are geometrical errors, deflections and friction present, and accordingly, gears sometimes create noise to such an extent that it becomes a problem.

In all types and sizes of gears, the main cause of gear vibration and noise can be attributed to gear tooth meshing dynamics, which is characterized by the transmission error. The transmission error can be defined as the deviation of gear angular position from its ideal position due to tooth profile and spacing error, and elastic deformation of the gear teeth and body. Its magnitude is of the order of several microns. This action produces gear tooth dynamic at mesh frequency of the gear. These forces excite coupled torsional/axial/transverse vibratory modes of the gear shafts and produce lateral and vertical displacements at the support bearing locations. Dynamic bearing forces are then generated due to the relative motions across the bearings in the radial direction. These in turn cause gear vibration and ultimately noise radiation from the gear systems.

The vibration and noise of gears used in power transmission have a strong effect on the evaluation of passenger cars; thus, many studies on gear vibration have been reported. The reduction of gear noise has been the main goal for automotive engineers who are seeking to improve the noise-vibration-and-harshness (NVH) performance of vehicles. The factors that affect gear vibrations are the gear dimensions, tooth flank modifications, the misalignment of shafts, applied loads and manufacturing errors. Several researches have claimed that the gear vibration is large when the actual contact ratio is close to an integer. Related studies have been carried out not only on spur and helical gears but also on hypoid gears. Some of the leading gear manufacturers have started utilizing these results in their designs.

However, in these previous reports, the characteristics of transmission error are discussed on the basis of experiments and numerical analysis results for specific gear dimensions and tooth flank modification under specific loading conditions. Thus, it might be difficult to apply to other types of gears. General characteristics of transmission error that are valid for various types of gear dimensions and loading conditions have not yet been clarified theoretically.

1.2 Research Objectives

This study comprises of two main objectives that are closely related to the vibration and noise emitted from the gear meshing points:

1. The first part of the research work is an attempt to develop a model to analyze the general characteristics of the transmission error of gears. The model consists of a quasi-infinite elastic model employing a series of springs with stiffness specific to the gears. By using the developed model, further detailed analysis on the influence of the tooth flank form deviations on the general characteristics of transmission error is carried out.
2. To develop a computer program, which can consider the difference of tooth, flank form between each tooth and small irregularities on the tooth flank and generate the potential gear noise. By using the developed program, the effect of the surface finish methods on the vibrational performance can be investigated through the proposed sensory evaluation method.
3. To design and develop a test rig specifically for assessing the performance of micro-size gear with diameter below 1 mm. Using the developed test-rig, gear designer can obtain the qualitative and quantitative data on its meshing condition, failure, strength and lifetime.

1.3 Research Approach

The vibration/noise of power transmission gears is a serious problem for vehicles including automobiles, and therefore many studies on gear vibration have been reported. These studies, however, were carried out by investigation using numerical simulations in which gears with specific dimensions and tooth flank modifications under specific loading were considered. Therefore, the general characteristics of the transmission error of gears have not been clarified theoretically.

In this research, a general model for the tooth meshing of gears is proposed; in which a quasi-infinite elastic model composed of springs with stiffness peculiar to the gear is incorporated. The transmission error of gears is formulated by theoretical equations. An investigation on the factors affecting the general characteristics of transmission error is accomplished using the formulated equations. The qualitative characteristic of the transmission error of gears with convex tooth flank form deviation is determined by the actual contact ratio and qualitative elements of gears; i.e. tooth flank form deviation and the distribution of stiffness. Even if the amplitude of torque, the amount of tooth flank form deviation and other quantitative elements are not determined, the qualitative characteristic of transmission error can be derived. The peak-to-peak value of transmission error increases proportionately to the amount of tooth flank form deviation.

Under light load conditions such as highway cruising conditions, passenger car transmission systems tend to emit noise and vibration. In order to implement a smooth meshing condition, convex modification of the tooth flank form is normally applied to the gear, and therefore the contact pattern does not reach the tooth tips and side edges under light load conditions.

For the second part of this study, a simulation program to calculate the vibrational excitation that takes into account of the tooth meshing with elastic deformation under load is proposed. In order to generate vibrational characteristics that exhibit the attributes of actual gears, minute variations in the tooth flank form among teeth must be considered in the calculation. There are a number of surface finish methods for metal-based gears. Different surface finishing methods result in different tooth flank forms on the micrometer or submicrometer scale, although, the tooth flank form looks identical macroscopically. Such micrometer or submicrometer-order variations can affect the gear vibration. In the proposed simulation program, submicrometer-order variations in the tooth flank form between neighboring teeth can be considered and simulation can be performed using the actual measured tooth flank form data. The tooth flank form of gears manufactured using five different surface finish methods are measured by gear measuring instrument and are used as input data for the proposed program. Then, the proposed simulation program investigates the effect of surface finish method on the vibrational excitation under loading.

1.4 Thesis Organization

This thesis is organized as follows:

Chapter 1 provides an overview of the gear tooth flank form design to reduce vibration and noise, the research objective, the methodologies taken to achieve the research goals and summarize contents of five publications that collectively contributed toward achieving the research objectives.

Chapter 2 presents the literature review concerning the related fields of the transmission error, introduction and limitation of the design and development of the general model, indices used to evaluate gear noise in automotive industry and also the importance to develop gear test rig in order to measured the gear vibrational performance and its strength.

Chapter 3 lists all the publication and the contribution of the author.

Chapter 4 discusses the overall conclusions by summarizing the findings in each publication and makes some recommendations for future work directions.

1.5 Summary of the publications

Publication I is the study on the characteristics of transmission error in automotive gears. The reduction of gear noise has been the main goal for automotive engineers who are seeking to improve the noise-vibration-and-harshness (NVH) performance of vehicles. The factors that affect gear vibrations are the gear dimensions, tooth flank modifications, the misalignment of shafts, applied loads and manufacturing errors. The results obtained in this study concludes that the qualitative characteristic of transmission error is determined by the qualitative elements of the gear under a constant actual contact ratio, and that the amplitude of transmission error is proportional to ridge curve curvature under a constant of actual contact ratio are derived not from numerical calculation by inputting the parameter values but from theoretical analysis based on the formulated equation. Therefore, the discussion on the characteristics of transmission error exhibits generality.

Publication II further investigates the effects of variations in tooth flank form on the characteristics of transmission error using developed model. The amount of ridge curve deviation strongly affects the peak-to-peak value of transmission error at peak positions. As the amount of ridge curve deviation decreases, so does the peak-to-peak value of transmission error. This indicates that bias-in tooth flank form modification is a preferable method to lower the peak-to-peak value of transmission error over a wide range of loading conditions. Conversely, the amount of ridge curve deviation has almost no effects on the actual contact ratio at the valley and peak positions of the transmission error. The actual contact ratio at the peak positions of the transmission error are narrowly concentrated and fall in the range from ‘integer’ to ‘integer+0.1’ for all peaks. This characteristic of the peaks is clearly a characteristic of gear transmission error. In order to reduce gear transmission error, tooth flank modification should be designed so that the actual contact ratio is not near an integer value.

Publication III developed a simulation program that enable to calculate the vibrational excitation under loading while considering the variations in the tooth flank form among the teeth of the gear and the small irregularity on the tooth flank. Using developed simulation program, the effect of surface finish method on the gear vibration and noise was analyzed. The effects of periodically changing profile and helix slope deviation among teeth on vibrational excitation were also investigated. In addition, the concept of potential gear noise, which is the noise obtained by converting the vibrational excitation into sound, and a sensory evaluation method based on the human auditory system were introduced in order to analyze directly the effect of tooth flank form on gear noise characteristics. The evaluation method in personal loudness level, noise quality and noise uncomfortness is proposed.

Publication IV primary objective is to design and develop a test rig specifically for micro-size gear. The essential functions needed for the test rig are considered and the instrument systems are fabricated. The second purpose of this paper is to clarify the characteristics of the failure mode of micro gears. For this research, steel micro gear, which is often used for micro geared motor, and metallic glass micro gear are investigated using developed test rig. Metallic glass is a novel material which has advantages in manufacturing micro parts. Based on the observation of sliding marks on the tooth flank, it is clarified that the meshing condition of a micro involute gear follows the meshing theory of an involute gear. Failure modes of SK4 micro gears and metallic glass micro gears are investigated. The experimental results indicated that SK4 micro gears suffer severe wear under unlubricated conditions that generate powderlike wear particles. On the other hand, flakelike wear particles appear in the metallic glass micro gear.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a literature review on the researches of general characteristics of transmission error and the effects of tooth flank form on the gear vibrational performance and noise. Due to the multidisciplinary nature of this topic, the literature review involved many different aspects. Initially, the development of numerical model to analyze the general characteristics of transmission error is reviewed. Then, the effects of tooth flank form variations on gear vibration and noise is presented. Finally, as the preliminary objective of validating all the presented theories, the design and development of a micro gear test rig is presented. Based on these reviews, an effective and thoroughly considered step of tooth gear design that incorporated in the early stage of tooth design was proposed.

2.2 Analysis of General Characteristics of Transmission Error

There have been number of reports deal with the effects of vibration and noise of gears in power transmission to the quality of car cabin. One of the main goals of gear designer is to have a quiet and durable gear meshing condition. Normally, parameters that affect gear vibrations are the gear dimensions, tooth flank modifications, the misalignment of shafts, applied loads and manufacturing errors. In efforts to investigate the effects of these factors, several promising methods of predicting transmission errors have been developed by (Litvin et al., 1994), (Umeyama, 1998), (Kahraman et al., 1999) and (Sundaresan et al., 1994). Studies have been carried out on various types of gears using various methods of behavior modeling. For instance, it has been reported that the vibration performance of a helical gear upon the convex modification of the tooth flank form is related to the actual contact ratio, that is, the ratio between the lengths of the actual contact pattern in the direction of the line of action and that of the normal pitch. Several studies claimed that the gear vibration is large when the actual contact ratio is close to an integer. Moreover, previous investigations have been carried out not only on spur and helical gears but also on hypoid gears.

However, from these researches, the characteristics of transmission error are derived from experiments and numerical analysis based on specific gear dimensions. (Maatar et al., 1997) succeeded in deducing a simple expression of normalized transmission error of narrow-faced helical gears and the characteristics of transmission error were investigated. Their method is effective for narrow-faced helical gears. However, it might be difficult to apply to other types of gears. General characteristics of transmission error that are valid for various types of gear dimensions and loading conditions have not yet been clarified theoretically.

In the automotive industry, gear transmission error remains as one of the most challenging issues. For that reason, a large amount of research has been conducted on the characteristics of motion of helical and hypoid gears with convex tooth flank form deviation. Significant contributions to the understanding of gear transmission error and tooth modifications have been achieved through important numerical analysis and experimental investigations by (Houser et al., 1998), (Velex et al., 1999), (Kubo et al., 1988), (Litvin et al., 1997), (Kahraman et al., 1992) and other researchers. As a result, the relationship between the actual contact ratio and gear transmission error has been clarified. The actual contact ratio means the contact ratio in which tooth flank forms deviation (modification) and elastic deformation due to load are considered. However, in these reports, the characteristics of gear transmission error have not been clearly elucidated. Moreover, the relationship between tooth flank form and transmission error remains unclear.

2.3 Effects of Tooth Flank Form on Gear Vibration and Noise

In today's gear manufacturing technology, several types of errors exist from manufacturing tolerances and variances and this could lead to fluctuation of transmitted load, thus creating vibration in the gear box via gear shafts and bearings, and finally it is amplified by the gear housing. The estimation of the noise level emitted from the vibrating structure is an important step in the design and development of a high quality gearbox. Thus, prior studies have yielded a vast literature on variety of analytical models for gear vibration and noise in order to reduce gear noise significantly. (Sabot & Perret, 2001) tried to correlate gearbox-radiated noise with structural parametric excitation, which is a function of gear geometric errors and tooth deflection. Other models take into account of the dynamic behavior of the driveline that corresponds to excitation amplification and so lead to gear noise. Although some of the general characteristics of gear noise in automotive transmissions have been identified, there is no specific study to explain the correlation between the audibility of gear noise and human hearing system in the presence of background noise.

For car cabin acoustic performance, other noises co-exist with the gear noise, i.e. engine noise, windy noise and road noise should aslo be considered. Generally, the sound level of gear noise is smaller than the other noises. Therefore, even if the gear noise exists, human ears are not able to detect it in some cases. In other words, although gear noise exists, it becomes non-issue if human ears are unable to detect those gear noises. In this research, this situation is called an audibility of gear noise under the existence of background noise. It is important to be noted that tooth flank form of gear with micrometer order has crucial influences on the characteristics of the gear noise emitted. Therefore, it could affect the audibility of the gear noise.

Assessment of gear noise by means of sound level is common in industrial world, which is based on the magnitude of sound pressure emitted and the minimum audible level of human hearing system as a function of frequency. However, it is difficult to evaluate the audibility of gear noise under background noise using sound level method. Even if the gear noises from drive-train systems have an identical sound pressure, yet differences in audibility of the gear noise still occurred in some cases. However, there is no report on gear noise evaluation method that is based on human hearing system as the first preference up to date.

Vibrational excitation is widely used to assess gear noise and vibration quality. (Rautert & Kollmann, 2001) presented a computer simulation of the force generated in gear meshing and the resulting noise radiation. (Barthod et al., 2002) studied the effect of different gearbox configurations on the gearbox rattle phenomenon while assuming a constant value of tooth meshing stiffness.

However, the simulation programs used in these studies assume that all of the gear teeth have an identical form. In actuality, vibrational excitation is influenced by minute variations, on the order of micrometers, of the tooth flank form among the teeth. As such, it is impossible to simulate an actual operating condition using existing simulation programs that assume identical tooth flank forms. In the present study, a novel simulation program is proposed that incorporates the variation of tooth flank form among the gear teeth caused by manufacturing errors. The present approach offers a more faithful representation of the properties of an actual gear.

2.4 Design & Development of a Test Rig

In the stage of gear design, the basic experimental data on meshing condition, failure, strength and lifetime of gear are needed. For a normal-size gear, those data have been compiled through the existing gear test rigs. For instance, (Kubo et al., 2000), (FZG et al., 2003) and other researchers are dealing with considerable amount of research for gear failure modes, strength and lifetime of normal-size gear using e.g. power-absorption type or power-recirculating type of gear test rig. In order to put micro gears into practical use for industrial field, a prior understanding of the characteristics of micro gear in terms of meshing condition, failure modes, strength and its lifetime need to be established.

In the field of micro precision engineering, there are a number of existing research works to develop manufacturing technologies of micro gears e.g. micropowder injection moulding (μPIM) and high precision die-casting method that have been assisted in mass production. Tecpha uses wire type of electric discharge machining (EDM) to develop non-circular type of micro gears. Also, (Namiki Precision et al., 2002) have produced metal micro gears integrated into a micro geared motor using conventional gear cutting technology. The LIGA technology, a combination of lithography, electroforming and replication processes, can be used for the cost effective fabrication of high precision micro gear from polymeric materials. For example, (Faulhaber Group, 2002) have used high performance polymer that has considerable strength to commercialized three-staged planetary gear system. In micro-electromechanical systems (MEMS), micro gears are being fabricated from silicon by means of surface processing technology, using dry deep etching and sacrificial layer techniques. More recently, some of the authors have produced micro geared motor of diameter 1.5 mm using metallic glass, which consists of one-body structure of sun, carrier and pins manufactured through net-shape process without assembly.

There is also a possibility of the fact that the micro-geometry of the micro gear is not as good as the normal-size gear due to its higher ratio between the gear dimensions and its micro-geometry dimensions compared to normal-size gear. Thus, it is strongly believed that the meshing condition, failure and strength characteristics of micro gear are different from those of the normal-size gear and most of the experimental data on normal-size gear cannot be applied to the micro gear. To obtain qualitative and quantitative data on the meshing condition, failure, strength and lifetime of micro gear, a test rig specifically designed for micro-size gear is needed. However, in the field of micro gear, there is no test rig available in the market and no research work on the strength of micro gear is reported up to the present. In addition, it is commonly believed that to design a micro gear test rig by downsizing the existing test rig of a normal-size gear would be inappropriate.

2.5 Conclusion

The literature review presented in this chapter has contributed to several dimensions of the research. The importance of tooth gear design in early stage to minimize the vibration and noise of gear powered transmission system is crucial. There are numbers of researches attempt to minimize the gear transmission error through tooth flank form design. In the conventional simulation or using the finite element method, by providing the gear dimensions and running condition, it is possible to calculate the transmission error of specific gears under specific conditions. However, it is impossible to discuss the general characteristics of transmission error by using the current method. From this viewpoint, we can show the significant advantage of the proposed method.

Chapter 3

PUBLICATIONS

3.1 List of Publications

In this chapter, the author listed the published articles. The following five ISI-research papers are collectively contributed toward achieving the research scope:

1. Edzrol Niza Mohamad, Masaharu Komori, Hiroaki Murakami, Aizoh Kubo, and Suping Fang, Analysis of General Characteristics of Transmission Error of Gears With Convex Modification of Tooth Flank Form Considering Elastic Deformation Under Load, Journal of Mechanical Design, Vol. 131, Issue 6, 061015, 2009-6, (9 pages).
2. Edzrol Niza Mohamad, Masaharu Komori*, Hiroaki Murakami, Aizoh Kubo, and Suping Fang, Effect of Convex Tooth Flank Form Deviation on the Characteristics of Transmission Error of Gears Considering Elastic Deformation, Journal of Mechanical Design, Vol. 132, Issue 10, 101005-1--11, 2010-10, (11 pages).
3. Edzrol Niza MOHAMAD, Masaharu KOMORI*, Shigeki MATSUMURA, Chanat RATANASUMAWONG, Masanori YAMASHITA, Takushi NOMURA, Haruo HOUJOH and Aizoh KUBO, Effect of Variations in Tooth Flank Form Among Teeth on Gear Vibration and an Sensory Evaluation Method Using Potential Gear Noise, Journal of Advanced Mechanical Design, Systems, and Manufacturing, No.6 Vol.4, 1166-1181, (Release Date: October 8, 2010), (16 pages).
4. M.E. Niza, M. Komori*, T. Nomura, I. Yamaji, N. Nishiyama, M. Ishida, Y.Shimizu, Test rig for micro gear and experimental analysis on the meshing condition and failure characteristics of steel micro involute gear and metallic glass one, Mechanism and Machine Theory, Vol.45, 1797-1812, 2010-(In Press)(Available online 15 September 2010), (16 pages), doi:10.1016/j.mechmachtheory.2010.08.008
5. 小森雅晴・E. Niza MOHAMAD・野村拓史・山路伊和夫・西山信行・石田央・清水幸 春，マイクロギヤの損傷・強度評価試験装置の開発(試験装置の構想・構築と金属 ガラス製 マイクロギヤの評価)，日本機械学会論文集（C 編），74 巻 742 号，（2008 年 6 月），pp.1601-1608

Chapter 4

CONCLUSIONS

This chapter summarizes the publications findings and their contributions to the knowledge of the area.

4.1 Summary and Conclusions

1. The first part of the research analyzes the gear tooth design in order to establish the general characteristics of transmission error. Further investigation on the effects of tooth flank form deviation on the gear transmission error has been carried out.
2. The second part of the study investigates the effects of tooth flank form deviation to the gear noise. This could enable gear designers to experience directly the effect of tooth flank form on the noise quality and it is an effective means in the initial stage of gear design.
3. The third part focuses on the design & development of a micro gear test-rig which enable gear engineers to clarify the general characteristics of the failure modes and its transmission errors in the stage of gear tooth design.

Publication I :The theoretical analysis of the characteristics of gear transmission error was carried out and the following conclusions were obtained:

(1) The actual contact ratio and qualitative elements of the gear such as the tooth flank form deviation and the distribution of stiffness determine the qualitative characteristic of the transmission error of a gear with convex tooth flank form

deviation. Even if the amplitude of the torque, the amount of tooth flank form deviation and other quantitative elements are not determined, the qualitative characteristic of the transmission error can be derived.

(2) The peak-to-peak value of transmission error increases proportionally to the amount of tooth flank form deviation. Hence, under a large change in the actual contact ratio, e.g., a large change in the operating torque, fundamentally, keeping the amount of the tooth flank form deviation as low as possible is an effective method of lowering the gear vibration.

Publication II : In this report, using a formulation for gear transmission error based on a general model for meshing conditions, the characteristics of transmission error and the effect of tooth flank form deviation were analyzed. From the results, the following conclusions were drawn:

1. The amount of deviation of the ridge curve strongly affects the amplitude of the transmission error at peak positions. As the amount of deviation of the ridge curve decreases, so does the amplitude of the transmission error. This indicates that bias-in tooth flank form modification is a preferable method to lower the amplitude of the transmission error over a wide range of loading conditions. Conversely, the amount of deviation of the ridge curve has almost no effect on the actual contact ratio at the valley and peak positions of the transmission error.
2. The width of the apex of the ridge curve has a strong effect on, not only the amplitude of the transmission error, but also the actual contact ratio at the valley positions of the transmission error. The actual contact ratio corresponding to the valleys decreases as the width of the apex of the ridge curve increases. The effect of the width of the apex of the ridge curve on the amplitude of the transmission

error at peak positions differs for each peak. For the case of a ridge curve having a wide apex; the peaks with larger actual contact ratio values could have larger amplitudes of the transmission error than that of smaller actual contact ratio. This is significant and differs from previously reported results.

3. The influence of the curve on the contact line on the transmission error is smaller than that of the ridge curve. As the curve on the contact line becomes sharper at the apex, the amplitude of the transmission error at the peaks reduces.
4. For Valley 1 (minimum actual contact ratio) the frequency distribution for the actual contact ratio at the valley is quite wide. However, for other valleys it is concentrated in the range from 'integer+0.4' to 'integer+0.8'. The actual contact ratio at the peak positions of the transmission error are narrowly concentrated and fall in the range from 'integer' to 'integer+0.1' for all peaks. This characteristic of the peaks is clearly a characteristic of gear transmission error. In order to reduce gear vibration, tooth flank modification should be designed so that the actual contact ratio is not near an integer value.

Publication III : In this study, an approach that focuses on the audibility of gear noise under the existence of background noise is proposed. In addition, the effects of surface finish methods and periodical and random changes of tooth flank form on the audibility are investigated. The results obtained in this study are summarized below:

(1) The result shows that the tooth flank form of all types of surface finish methods may look identical in macroscopic level but the differences exist in the audibility. Generally, shaving-processed gear is known for its poor performance in gear noise. However, in this study it is revealed that gear noise of shaving-processed gear is more difficult to be detected when compared to grinding-processed gear.

(2) When periodical changes occur in the pressure angle deviation and helix angle deviation, these changes have little impact on the audibility evaluation result. However, in the case of random changes, the gear noise becomes harder to be detected as the random changes increase. In other words, it can be concluded that the evaluation of gear noise shows better result in terms of audibility with the increase in random change of tooth flank form.

(3) From these results, it is clear that differences may occur in the audibility evaluation of the gears even though the gears realize identical sound level, in other words, e.g. the cases where two different types of surface finish methods have identical sound level. This result indicates that the quality inspection of gear noise based on the threshold value of different sound level is necessary if the surface finish methods are different.

In the conventional evaluation method, evaluation of gear noise focuses more on the sound level. Fewer studies have been conducted on the qualitative terms of the gear noise. The proposed evaluation method that is based on the easiness of the gear noise to be detected can be seen as a new approach in the sound quality evaluation.

Publication IV : A micro gear test rig has been successfully designed and fabricated. Investigation on the failure mode and meshing condition of SK4 and metallic glass micro gears are performed using proposed test rig. The conclusions are summarized as follows:

1. One-sided support structure of large diameter gear shaft and ball bearing with preload is proposed as an appropriate support method of micro gear in terms of stiffness and rotational accuracy. Measurement method of gear assembly condition is proposed by using laser displacement sensor and XY stage. Relative

position and posture of the drive and driven gears are estimated through fitting the theoretical 3-D form into the measured one. Gear support base integrated with magnetic base is presented, which has advantages in multi degree of freedom (DOF) adjustment and high stiffness. For the in-situ observation system, a high power stereomicroscope integrated with digital camera is introduced, which enables the observation of the gear tooth condition without disassembling the gear parts.

2. Under no lubricated condition, SK4 micro gear has shown severe tooth failure by wear. Wear particles in the form of very fine powder like are accumulated in the tooth bottom, tooth side and tooth flank. The dominant failure mode was the wear near the gear tooth tip and gear tooth height gradually shows decrement. On the other hand, for the metallic glass micro gear, the overall gear tooth failure was less significant. Apparently, wear particles in the form of flake like are observed to have peeled off from the tooth flank surface.

In SEM images, sliding marks on the tooth flank surface were observed. The direction of the sliding marks on the metallic glass micro gear follows the theory of an involute gear.

4.2 Future Work

This research has proposed a very promising method to analyze the characteristics of transmission error during early stage of gear tooth design and also incorporate a new method of evaluating the gear noise under meshing condition using potential gear noise as one of the indices. Future works could include an approach to design of gear tooth flank form based on analysis considering variations in tooth flank form and virtual noise evaluation. There are also variations of effects of tooth flank form on the characteristics of transmission error that could be investigated using the developed general model.

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大水　昭寿　歯面形状精度にばらつきがある歯車のギアノイズ評価に関する研究。