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A Study on the Attenuation of Flip-over Vibration in the Flat Blade Windshield Wiper

플랫 블레이드 윈드실드 와이퍼의 역전 진동 저감에 관한 연구

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Key Words : Windshield Wiper(윈드실드 와이퍼), Flip-over(플립오버), Flat Blade(플랫 블레이드), Contact Pressure(접촉압력), Blade Vibration(블레이드 진동)

ABSTRACT

This research introduces a new method to attenuate flip-over vibration generation in the flat blade windshield wiper by adjusting the contact pressure between the windshield glass and the blade. The knocking force in the flip-over action of the blade is decreased by inducing gradual tilting-over along the rubber strip of the blade. This gradual tilting-over is induced by introducing a non-uniform contact pressure distribution between the blade and windshield glass. The contact pressure distribution is adjusted by controlling the unloaded profile of the body spring in the blade using a procedure proposed in a previous study. Two blades, one blade designed to generate a uniform pressure distribution and the other designed to generate non-uniform pressure distribution, are developed using the procedure. Contact pressure distributions of the developed blades are measured using a special device and compared with the intended distributions confirming the similarities between the two groups. Vertical and lateral vibrations of the two blades are measured under realistic operating condition simulated by a wiper test rig. The vertical vibrations of the blade with non-uniform contact pressure are substantially smaller than corresponding vibrations of the blade with uniform contact pressure over the entire rubber strip.

요 약

플랫 블레이드 와이퍼의 블레이드의 누름압 분포를 조정하여 역전과정에서 발생되는 진동을 저감하는 방법을 제시하였다. 블레이드와 유리면 사이에 길이방향으로 불균일한 누름압 분포를 도입, 고무스트립에 점진적인 역전을 유도함으로써 역전과정에서 발생하는 충격력을 저감하였다. 블레이드 내의 바디스프링 형상을 이전 연구에서 제시된 방법을 통해 구해진 형태를 적용함으로써 누름압 분포를 조정하였다. 이 방법을 적용하여 전체 길이에 균일한 누름압과 불균일한 누름압을 발생시키는 두 종류의 블레이드를 개발한

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다음 누름압을 측정하여 확인하였다. 두 블레이드에서 발생하는 수직방향 및 횡방향 진동을 측정 비교한 결과, 불균일한 누름압을 가진 블레이드가 균일한 누름압의 블레이드에 비해 훨씬 작은 수직방향 진동을 나타냄을 확인하였다.

1. Introduction

The Windshield wiper that wipes out various contaminations such as rain, snow, dust, dirt from the automobile's windshield to ensure a clear field of vision is an indispensible system in the modern motor vehicle. However, the movements of a wiper blade on windshield glass often generate unwanted vibration and thus cause some annoying noises across different frequency ranges. Generally, vibration and noise in the wiper system are classified into three categories, i.e., squeal noise, chattering and flip-over noise(1). Flip-over noise, produced when the wiper reverses its moving direction, is an impact noise in the frequency range of 500 Hz or less(1). This type of vibration and noise cause audible annoyance to the driver or passengers. In the attempts to suppress this vibration, various approaches, i.e. modifying structures and properties of the wiper blade have been adopted(1).

Okura et al.(2) preformed a dynamic analysis of blade flip-over behavior using a 2-D model of a wiper system, and developed a spring-mass model of an arm and blade. Okura and Oya(3) extended their studies considering a complete three dimensional(3-D) model. Using the two models they showed that the reversal impact force could be reduced by modifying the maximum rubberneck rotational angle and the rubberneck rotational spring constant. Kotlarski(4) studied the effects of contact pressure on blade flip-over action, and concluded that blade flip-over process can be controlled by adjusting contact pressure distribution at lip of blade since lower contact pressure encourage rubber strip to flip-over.

The contact pressure distribution in the wiper blade has been studied by many investigators(5~10). For example, Grenouillat and Leblanc(5) proposed analytical models for contact pressure distributions in the various types of wiper blades including the tournament type and flat blade type. Lee and Shin(6) numerically investigated contact pressure distribution in a wiper blade with experimental validation. Yoon and Kim(7) proposed a trial and error procedure using finite element models to obtain an optimized profile for a body spring that generates a uniform contact pressure distribution in flat blade wiper system. Song and Lee(8) proposed an analytical procedure to calculate body spring profile that generates the intended contact pressure distribution based on the principle of reciprocity. The results were compared with experimental data for verification. Kim et al.(9) and Kim and Park(10) introduced a blade pressure distribution measurement system using an array of piezoelectric sensors and measured the contact pressure distributions of various wiper blades.

This article attempts to attenuate vibration in the windshield glass caused by flip-over action in a flat blade wiper system. Knocking force due to blade reversal behavior is reduced by a gradual tilting-over of the rubber strip induced by an uneven contact pressure distribution at the tip of rubber strip. The contact pressure distribution is controlled by adjusting the initial(unloaded) profile of the body spring in the blade. Contact pressure distributions in the blade are experimentally investigated to verify the procedure. Also, blade vibrations during the flip-over process have been measured in the realistic conditions to verify the basic idea of this study.

The important assumptions for this study are as follows: (1) Frictions at the contact surfaces of any two adjacent components are negligible. (2)

The structural characteristics of the wiper blade are linear time-invariant. (3) The bending stiffness of flat wiper blade is mainly determined by the blade body spring and the contributions from other components are negligible. Major objectives of this study are as follows. (1) Introduce an analytical procedure to attenuate vibration and noise due to a flip-over action of the flat blade wiper system. (2) Investigate the effects of contact pressure distribution of flat wiper blade on knocking force due to the flip-over action. (3) Validate the proposed procedure measuring the contact pressure distribution and blade vibration in the realistic operating condition.

2. Flat blade type windshield wiper

Recently, various types of wiper blades such as flat blade and hybrid types as well as conventional tournament type have been developed and being used in the modern automotive industries with advancement in mechanical and material technologies.

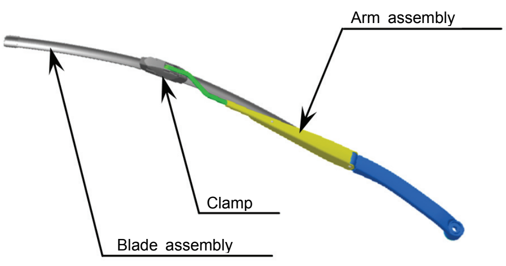


Fig. 1 A flat wiper arm and blade assembly

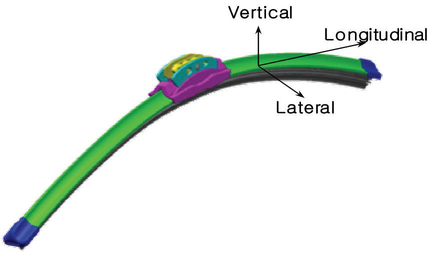


Fig. 2 A typical flat wiper blade and corresponding coordinate system

Due to the low cost, simple structure, and easy assemblage, flat blade wipers are gaining popularity in many kinds of automobiles.

A typical flat blade assembly connected to the wiper arm is shown in Fig. 1 along with a clamp that combines the blade assembly and arm. As shown in the figure, the flat wiper blade is one piece blade subjected to pressing force from the wiper arm at a center point. Force from the wiper arm that presses the blade against the windshield glass induces change in the blade profile(curvature) which in turn generates the contact pressure distribution on the tip of the rubber strip. So, the contact pressure distribution between the rubber strip and glass is determined by the transmitted pressing force and the structural characteristics of the blade assembly.

A typical flat wiper blade and corresponding coordinate system are explained in Fig. 2. As shown in the figure, the longitudinal axis is defined along the center line of the blade, lateral axis is normal to the mid-plane of the rubber strip, and vertical axis is normal to both the lateral and longitudinal axes.

The cross-sectional structure of a typical flat wiper blade is explained in Fig. 3. As one can see in the figure, all components of the flat blade are assembled in a very simple way, inserting one component into another. At the bottom of the blade, a rubber strip is assembled. The strip actually

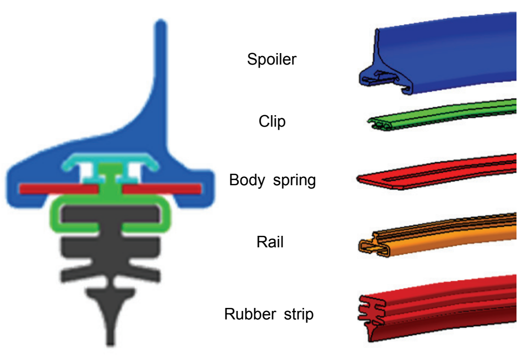


Fig. 3 Composition of a typical flat wiper blade

contacts the glass for cleaning action, and generates flip-over action during the change in the moving direction of the wiper. On the top of the rubber strip a rail is inserted to connect the blade rubber strip to the body spring with the aid of a clip. The body spring transmits pressing force from the wiper arm to the rubber strip and generates the intended contact pressure distribution through change in its own curvature. So, the distribution of contact pressure between the windshield glass and the wiper rubber blade is controlled by the bending shape of the body spring in the blade.

3. Flip-over action of the wiper blade

During the wiping process, the wiper blade moves back and forth laterally to its longitudinal span by a motor-driven wiper arm connected to the wiper blade, and generates the contact pressure against the window. The wiper blade has an elongated wiper strip that can be placed against the windshield screen and an elongated spring-elastic carrying element. The element has a connecting unit for the wiper arm and is disposed parallel to the longitudinal axis of the wiper strip to distribute contact pressure over the entire wiper strip.

The posture of a wiper blade during the wiping action and various forces acting on the blade are explained in Fig. 4. As shown in the figure, the

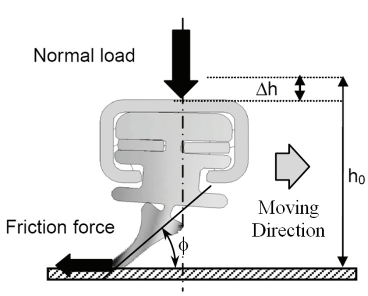


Fig. 4 Configuration of flat blade assembly in the drag position to right

tip of the rubber strip follows the center line of the blade. This drag position is natural considering the wiping mechanism of the blade, and also essential for effective and low noise operation of the wiper system. During the cleaning operation, the wiper blade changes its direction of movement at its uppermost and lowermost positions. It is quite conceivable that the deformation shape of the rubber strip abruptly flips over from one drag position to the other when the wiper blade reverses its working direction. In this process, all the elements in the blade, as well as the rubber strip, change their shapes interacting with the wiper arm that presses the blade against the windshield glass.

3.1 Mechanism for flip-over vibration

As explained in the previous section, the wiping action of the blade is performed by friction between the windshield glass and the rubber strip. Also, the contact pressure necessary for the wiping action is generated by pressing force from the wiper arm. The friction accompanied by the pressure deforms the rubber strip into the drag position shown in Fig. 4. In this process, the cross-section of the blade changes its configuration as shown in Fig. 5. As one can imagine from the figure, whole section of the blade is lifted in the first stage and lowered in the next stage. In this process, a knocking force is exerted on the windshield glass by the blade in these movements.

3.2 Effects of flip-over action

As one can imagine from Fig. 5, abrupt lifts and downs of blade and arm assembly take place during the flip-over action. These abrupt lifts and downs, especially downs motions, inevitably generate periodic knockings of the arm and blade assembly on the glass that generate unavoidable impact vibration in the windshield glass. This vibration in the glass, in sequence, causes undesirable interior noise that hurts comfort of driver

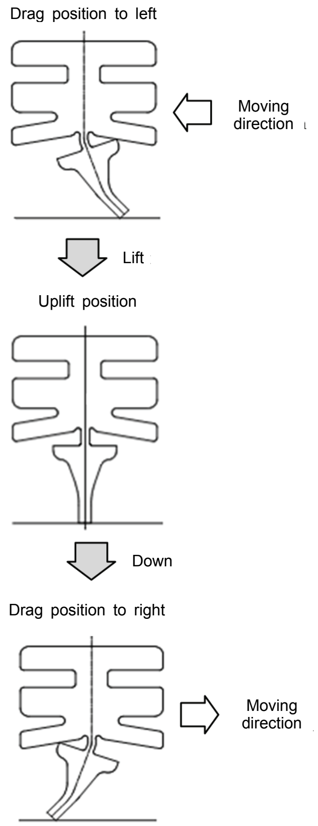


Fig. 5 Movement of the blade rubber strip during a flip-over process

and passenger(s). Consequently, flipping-over of the blade at the uppermost and lowermost positions generates periodic knocking force that causes unpleasant windshield glass vibration and interior noise. As one can infer form above, knocking force in the flip-over action is determined by the interaction between blade and glass as well as pressing force from wiper arm.

4. Control of flip-over vibration and noise

4.1 Control of flip-over action

As explained in the previous chapter, the knocking force of the blade on the windshield glass is determined by interaction between the blade and glass as well as pressing force transmitted from the wiper arm. For instance, knocking force and associated vibration and noise can be attenuated by reducing the pressing force transmitted from the wiper arm which can be easily controlled by adjusting the characteristics of the spring in the arm. However a reduced pressing force might cause deterioration of wiping ability due to globally decreased contact pressure at the tip of the rubber blade. In addition, flip-over vibration can be controlled by regulating the tilting-over behavior of rubber strip in the wiper blade. It is conceivable that the total knocking force from the wiper system in the flip-over action would be maximized if the entire rubber strip tilts-over at the same time. In this case, knocking vibration in the windshield glass and associated interior noise in flip-over behavior are also maximized. So, it is possible to attenuate flip-over noise and vibration by initiating the tilting-over of the blade from one or two positions then gradually spreads to the whole blade strip.

4.2 Effect of contact pressure distribution on flip-over vibration

The relation between contact pressure and flip-over action was studied in the previous study(4). According to the study, the impedance to the blade tilting-over behavior of a flat blade is proportional to the contact pressure at the tip of the rubber strip. So, the uniform pressure distribution over the entire wiper blade length causes the wiper strip to abruptly flip over along its entire span from its one drag position into the other when the wiper blade reverses its working direction.

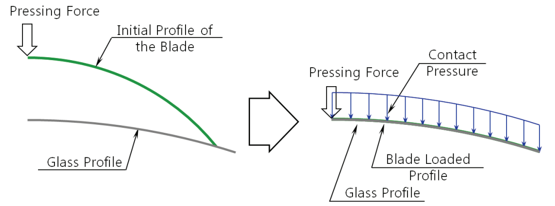
If the contact pressure between the rubber strip and glass decreases, the drag angle of the rubber strip the angle between the center line of the rubber strip and glass(in Fig. 4) - increases. A greater drag angle in the rubber strip leads steeper drag posture in the wiper lip which encourages the tilting-over process in the wiping direction reversal positions of the wiper blade. Thus, if the contact pressure distribution is not uniform along the rubber strip of the blade, a steeper drag position of the wiper lip is produced in the region of the relatively small contact pressure. Consequently, tilting-over behavior of the blade lip initiates there and then continues in the region that has greater contact pressure. This prevents the abrupt snapping over of the entire wiper blade strip and the unpleasant knocking vibration and noise associated with it.

4.3 Control of contact pressure distribution in the flat wiper blade

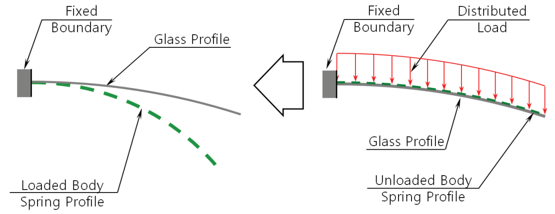
Mechanisms for the generation of contact pressure between the wiper strip and glass depend on the overall structures of the wiper system. For example, in conventional tournament type blades, pressing points of the supporting steel structure determine the contact pressure distribution at the rubber blade tip. On the other hand, in the case of flat wiper blade, contact pressure distribution is controlled by adjusting the profile of the body spring in the blade before contact(8).

In addition, the proper unloaded profile of a body spring can be obtained by applying a distributed load that is identical to the intended contact pressure on the convex side of a body spring having an initial profile which is identical to the windshield glass profile(8).

This procedure is briefly summarized in Fig. 6. The mechanism for contact pressure generation in the wiper blade due to the pressing force from the arm is illustrated in Fig. 6(a). As explained in the figure, the transmitted pressing force changes the profile of the blade into that of the glass. This profile change generates contact pressure in the tip of rubber strip according to the deflection angle of the blade at this position. The procedure to calculate the profile of the body spring that generates the intended contact pressure distribution is explained in Fig. 6(b). The body spring clamped at the



(a) Contact mechanism



(b) Profile calculation

Fig. 6 Calculation of the profile of a body spring based on the contact mechanism of the flat wiper blade

center of the span with a distributed load identical to the intended contact pressure on the convex side can be idealized as a cantilever beam fixed at one end with an initial profile as explained in Fig. 6. The deflection angle at the given location $\gamma(x)$ in the body spring due to the distributed load is calculated from the bending moment at that location using following Equation(11).

$$\gamma(x) = \int_0^x \frac{M(x)}{EI} dx \qquad (1)$$

Here, E is Young's modulus, I is the area moment of inertia of the body spring. A deformed profile of the body spring that is identical to the profile of the completed body spring can be calculated based on the deflection angle $\gamma(x)$ calculated using Eq. (1). The whole spring is divided into a large number of infinitesimal elements. The displacement in each element of the body spring can be calculated based on the configuration given in Fig. 7. In the figure, Δl is the length of the infinitesimal segment of the body spring, θ_i is the angle of the ith segment of the body spring due to the initial profile, γ_i is deflection angle seg-

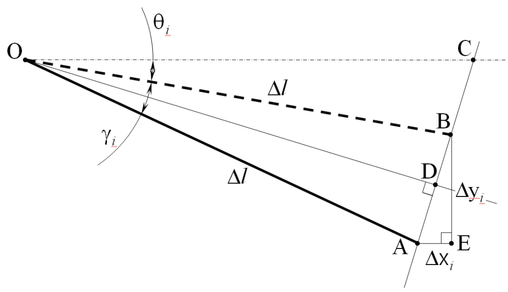


Fig. 7 Displacements in the *i*th segment of the body spring

ment i due to the applied load, Δx_i and Δy_i are relative displacements in the x and y directions at the right side with respect to left end of the element i. Since the length of line AB is $2\Delta l \sin(\gamma_i/2)$ and ODC and AEC are similar to each other, Δx_i and Δy_i can be calculated using following equations.

$$\Delta x_i = 2\Delta l\, sin\left(\frac{\gamma_i}{2}\right) sin\left(\theta_i + \frac{\gamma_i}{2}\right)$$
$$\Delta y_i = 2\Delta l\, sin\left(\frac{\gamma_i}{2}\right) cos\left(\theta_i + \frac{\gamma_i}{2}\right) \quad (2)$$

The final profile of the body spring can be obtained by simultaneously considering the initial profile and the displacements calculated above.

5. Validation study

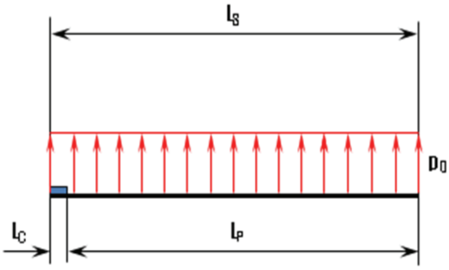
5.1 Modifying contact pressure distribution

As explained in Section 3, the knocking force and associated vibration and noise related to the flip-over action of the blade can be attenuated if the tilting-over of the rubber strip initiates at specific region(s) and then spreads to the entire region of the blade. So it is necessary to introduce uneven contact pressure distribution along the span of the blade. Also, since the windshield glass profile has smaller curvature at the right and left sides, the blade rubber strip cannot have sufficient contact at the lowermost wiper position when the contact pressure of the wiper strip against the window is greater in its center section than at the two end sections. Therefore, the contact pressure of the wiper strip against the window is optimized to be substantially greater in its two end sections than in the center section. Since contact pressure in the center region is significantly less than in the two end regions, tilting-over of the strip is expected to initiate in the center area then spread to the both ends of the blade. In addition, deterioration in wiping performance at the end sections of windshield screen due to the sharp decrease in the curvature could be compensated by this type of pressure distribution.

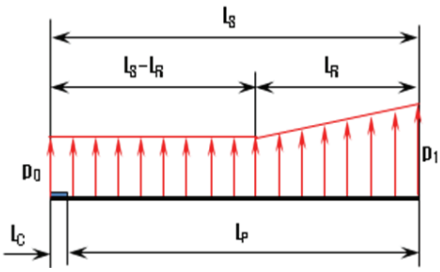
For the comparative study, a blade designed to develop uniform pressure over the entire blade span is simultaneously investigated. Blade I is designed to develop uniform pressure(p_0=10 gf/cm) over the entire blade span as shown in Fig. 8(a) and blade II is designed to generate larger pressure(p_1=15 gf/cm) in two end regions than the pressure(p_0=10 gf/cm) of the middle as shown in Fig. 8(b).

Geometric dimensions and material properties of the blade I and II are provided in Table 1. As shown in the table, two blades are made of the same material and have identical geometric configurations except LR.

The final profiles of the two body springs, spring I(for the blade I) and spring II(for the blade II), are calculated using the procedure given in Section 3.2 along with the simplification of blade assembly as body spring rail based on the results of the previous studies(8). The curvature of the windshield screen is assumed to be single value 4000 mm which is average of radii of curvature for various windshield screens at the several locations(8). Calculated profiles of Spring I and II are compared with each other in Fig. 9 where the difference of the two profiles are clearly shown. Calculated profile for Spring II has much smaller curvature than that of Spring I in the center region.



(a) Uniform



(b) Uneven(uniform+ramp)[8]

Fig. 8 Intended contact pressure distributions

Table 1 Blade dimensions and body spring material properties

Dimension or property		Blade I	Blade II
Total spring length(mm)	$2L_S$	650.0	←
Clip length(mm)	$2L_C$	25.0	←
Deformable length(mm)	L_P	312.5	←
Ramp load length(mm)	L_R	–	100.0
Spring thickness(mm)	t	0.8	←
Spring width(mm)	b	14.0	←
Young's modulus(Gpa)	E	17000	←
Poisson's ratio	ν	0.29	←

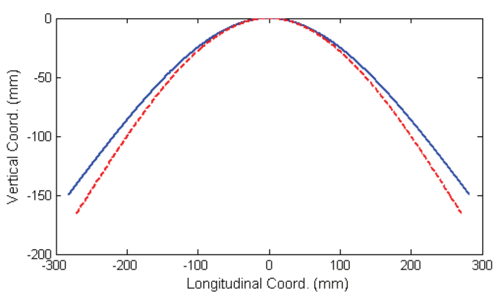


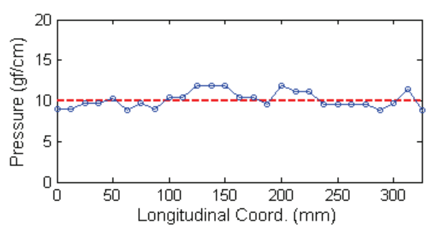
Fig. 9 The calculated profiles of the spring rails, key: ──, spring I; - - -, spring II[8]

5.2 Measurement of contact pressure distribution

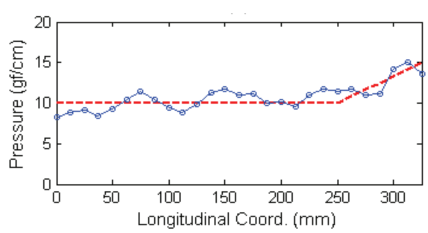
Contact pressure distributions of the two blades are measured with contact pressure measuring equipment using piezo-electric sensors. The results are compared with each other in Fig. 10. As shown in the figure, the pressure distribution for blade I is almost constant over the total span of the blade. On the other hand, in blade II, pressure at the right end of the blade is greater by about 50 % than the pressure in the center area. In both cases measured contact pressure distribution match the intended pressure distribution reasonably well over the entire blade. Therefore, it can be concluded that the procedure explained in Section 5.1 has sufficient accuracy in obtaining the body spring profile for the intended contact pressure distribution.

5.3 Measurement of flip-over vibration

Vertical and lateral vibrations of the blades described in Section 5.1 are measured in the wiper blade test rig that simulates realistic operating conditions. The test rig is composed of a windshield screen, a wiper motor, an arm assembly,



(a) Blade I



(b) Blade II

Fig. 10 Measured contact pressure distributions, key: ─∘─, measured; - - --, intended[8] a blade assembly, and linkages that are identical to those of a real automobile. During the test, water is sprayed on the screen to obtain realistic friction characteristics between the rubber strip and the glass, thereby simulating a rainy environment. One accelerometer (accelerometer 1) is attached at center of the blade(region I in Fig. 12) in the vertical direction and two accelerometers(accelerometers 2 and 3) are attached at the far end of the blade(region II in Fig. 12) in the vertical and lateral directions.

Amplitudes of vibrations in the vertical direction measured at region I and II of the two blades are compared each other in Fig. 13 where the differences in the amplitudes are clearly shown. As one can see in the figure, vertical vibration of the blade with uniform contact pressure distribution(blade I) is about 25 % greater than that of the blade with uneven contact pressure distribution(blade II). Lateral vibrations at the far ends of two blades are compared each other in Fig. 14. As shown in the figures, lateral vibrations

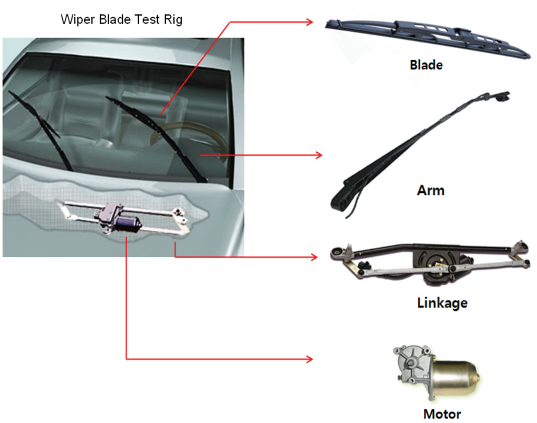


Fig. 11 The composition of a typical wiper blade test rig

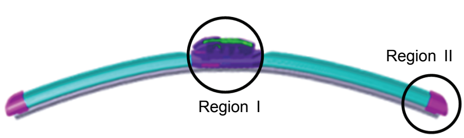
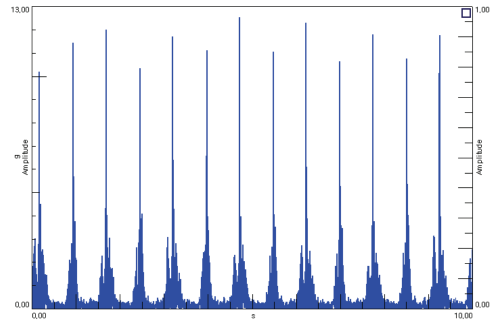
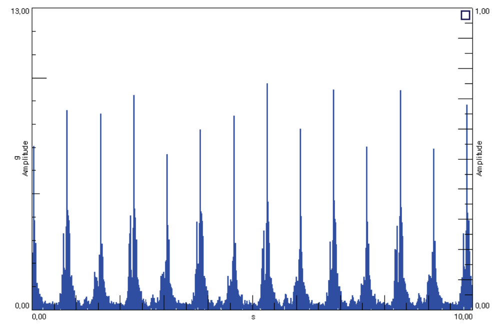


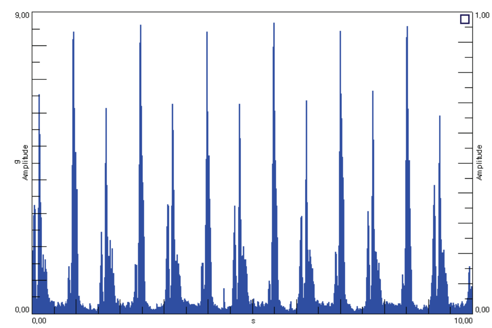
Fig. 12 Positions of accelerometers



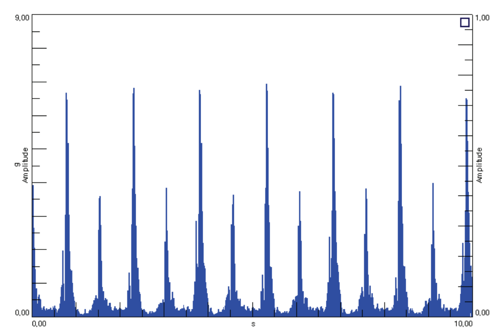
(a) Region I of blade I



(b) Region I of blade II

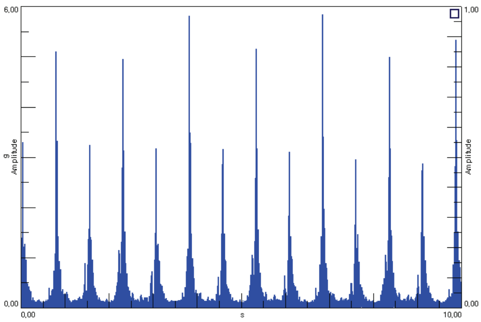


(c) Region II of blade I

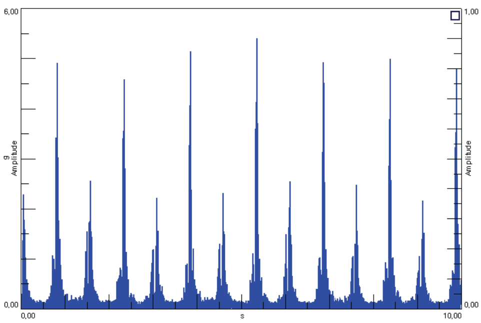


(d) Region II of blade II

Fig. 13 Vertical vibrations of two blades in the region I and II



(a) Blade I



(b) Blade Ⅱ

Fig. 14 Lateral vibrations of two blades in the region II

of the two blades are almost identical to each other regardless of the contact pressure distribution. This result is reasonable considering the flip-over mechanism of the blades in which vertical excitation is generated by abrupt up and down motion of the blade assembly. Therefore, it can be concluded that lateral excitation is not generated in blade flip-over process and consequently lateral vibration of the flat wiper and consequently lateral vibration of the flat wiper blade is little affected by the flip-over action in the blade.

6. Concluding remarks

A method to alleviate the flip-over vibration in the windshield glass due to the blade reversal action of the flat type blade wiper system is introduced. Drag angle variation along the blade length has been controlled to prevent the simultaneous flip-over of the entire rubber strip. The contact pressure distribution at the tip of the rubber strip, which determines the drag angle has been optimized to initiate rubber strip flip-over action at the center region of the blade then propagate to the both ends by introducing greater pressure in the two end regions than the center region. For the comparative study, vibration in this modified blade has been compared with that of the original flat wiper blade with uniform contact pressure distribution.

The intended contact pressure distributions have been obtained by adjusting the profile of the body spring in the blade using the procedure introduced in a previous study. The contact pressure of the flat blades which are assembled with the body springs developed above have been measured and compared with intended distribution confirming that developed blades have proper characteristics.

The proposed method has been experimentally verified by measuring blade vibration utilizing a wiper blade test rig that simulates the realistic operating conditions. Two sample blades have been developed and tested: an original blade with uniform contact pressure over the entire rubber strip, and a modified blade with 50 % greater pressure at both ends than at the center. According to the results, the modified blade generates much smaller vertical vibration than the original blade. On the other hand, lateral vibrations of the two blades are almost same regardless of the contact pressure distribution.

It can be concluded that blade vibrations in a flat blade wiper system due to the flip-over process can be attenuated by the uneven contact pressure distribution that can be achieved by adjusting the profile of the body spring in the blade. Vehicle interior noise is also expected to be attenuated by the modified contact pressure distribution, accordingly.

Future studies include the optimization procedure for the contact pressure distribution between blade rubber strip and windshield glass. In addition, variations in the vehicle interior noise due to the blade vibration caused by the modified contact pressure distribution should be included in the study.

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