ARTICLE IN PRESS

Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Analysis of the behavior of a wiper blade around the reversal in consideration of dynamic and static friction

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ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
28 December 2016
Accepted 10 January 2017
Handling Editor: L.G. Tham

Keywords:
Dynamic friction
Static friction
Slack variable method
Set-valued problem
Wiper blade

ABSTRACT

Reducing noise generated by automobile windshield wipers during reversals is a desirable feature. For this purpose, details of the behavior of the wiper blade need to be ascertained. In this study, we present theoretical and experimental clarification of this behavior during reversals. Using simulation algorithms to consider exactly the effects of dynamic and static friction, we determined theoretical predictions for the vibrational response caused by friction and the response frequency and compared these results with experimental ones obtained from a mock-up incorporating an actual wiper blade. We introduce an analytical link model with two degrees of freedom and consider two types of states at the blade tip. In the stick and the slip states, static friction and dynamic friction, respectively, act on the blade tip. In the theoretical approach, the static friction is expressed by a set-valued function. The transition between the two states is repeated and an evaluation of an exact transition time leads to an accurate prediction of the behavior of the wiper system. In the analysis, the slack variable method is used to find the exact transition time. Assuming low blade speeds during reversal, a parameter study indicates that the blade tip transitions between slip and stick states and the frequency of the vibration caused by this transitions is close to the natural frequency of the neck of the wiper blade. The theoretical predictions are in good agreement with experimental observations.

1. Introduction

Recently, noise reduction in windshield wipers is attracting much attention as a means to lower noise within car cabins and improve driver and passenger comfort. To reduce noise from windshield wipers, a detailed understanding of the dynamics of the wiper blades is required. Squeal noises are high-pitched sounds having frequencies of around 1000 Hz. Reversal noise is an impact sound having a frequency of 500 Hz or less. Many studies on the dynamics of a wiper blade have been conducted for the purpose of reducing both these types of noise and improving wiping performance.

The characterization of the friction between wiper blade and swept surface has an important role in the analysis of the dynamics involved. In their experiments, Koenen and Sanon [1] examined the friction acting on the wiper blade and derived the coefficient of dynamic friction under various conditions. In dry conditions, the coefficient of dynamic friction decreases as temperature increases. In wet conditions, the value of this coefficient of friction decreases with increasing velocity

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http://dx.doi.org/10.1016/j.jsv.2017.01.018

Please cite this article as: M. Unno, et al., Analysis of the behavior of a wiper blade around the reversal in consideration of dynamic and static friction, *Journal of Sound and Vibration* (2017), http://dx.doi.org/10.1016/j.jsv.2017.01.018

between 0 and 0.5–0.7 m/s and also with a load applied to the wiper blade. In addition, they observed a tacky environment if the water evaporates and showed that the coefficient of friction approaches a level higher than that in dry conditions. Deleau et al. [2] experimentally investigated the relationship between friction and wiping performance using various elastomer specimens and showed that in wet conditions, three different friction regimes can be defined. In the boundary regime at low sliding velocities, friction remains high but lower than that in dry conditions. In the mixed regime at intermediate velocities, the coefficient of friction decreases as the velocity increases because a thin water film forms in the contact area. In the partially lubricated regime at high velocities, friction is low. Bódai et al. [3] investigated the effect of load and velocity on dynamic friction through experimental and numerical analysis. First, the effect of wiper blade geometry on the coefficient of friction was investigated by using 2D FE model. The contact area changes depending on the coefficient of friction. Further, at low loads, the relation of normal and friction forces is approximately linear, but above 25 N/m nonlinear. Finally, it was clarified that the characteristics of coefficient of friction cannot be explained by the hydrodynamic effect but by thin film lubrication.

The cause of noise from the wiper blade is friction-induced vibration. Several studies have investigated this source of wiper-blade noise. Goto et al. [4] experimentally clarified that the squealing noise is generated before and after reversal. Using the finite-element method, they established the vibration mode and introduced a simplified model for analyzing blade vibrations. Using the equations of motion, methods to reduce blade noise have been proposed such as the appropriate selection of rubber materials to increase damping and changing the configurations of the wiper blade to optimize blade stiffness. Reddyhoff et al. [5] experimentally showed that there are two frequency components in friction-induced noise during sliding, one near 1000 Hz and the other between 2000 and 2500 Hz. From the analytical results using the finite-element method, these frequencies coincide with the eigenfrequencies of the first two bending modes of the blade. The presence of water in contact with the wiper modulates the frequency and amplitude by effectively adding mass to the vibrating system. As a result, they suggest approaches to reduce the friction-induced noise such as improving wettability of the swept surface by applying a coating, modifying the negative rate of change in the coefficient of dynamic friction by changing the stiffness and geometry of the wiper blade, and increasing the material damping of the wiper blade material. Min et al. [6] experimentally investigated the contribution of the windscreen waviness to the generation of squeal noise. After continuous duty, the coefficient of friction becomes larger than 1. The waviness of the swept surfaces induce the variation of the sliding velocity of the wiper blade and the coefficient of friction. When the coefficient of friction is larger than 1, the squeal noise is generated with decreasing coefficient of friction and increasing sliding velocity.

The above-mentioned studies dealt only with instances when the wiper moves unilaterally. To understand the mechanism that generates noise in detail, the behavior of the wiper blade during reversals needs to be analyzed. Okura et al. [7] constructed an analytical model dealing with the entire wiper system consisting of motor, link, arm, and wiper blade. They simulated the dynamic characteristics of the system during reversal and showed the generation of impulsive forces, which contribute significantly to the noise from the wiper system. They also showed that it can be reduced by modifying some parameters of the wiper system. However, this study did not mention the behavior of the wiper blade when the impulsive force is generated. Sugita et al. [8] investigated the behavior of the wiper blade during reversal, observing in experiments that the blade tip comes actually to rest. They introduced a set-valued function to model the static friction and conducted a bifurcation analysis. In particular, their analysis showed that when the compression force is near the buckling point, the blade can reverse even if friction is small. In addition, they revealed that the normal force, which increases sharply during reversal, contributes to reversal noise. Introduced a link model with two degrees-of-freedom (2DOF) consisting of a rigid bar, Lancioni et al. [9] considered three types of states: free-flight that occurs when the blade tip is detached from the swept surface, slip state that occurs when the blade tip is moving but in contact with the surface, and stick state that the blade tip is at rest. The static friction force in the stick state is considered as a set-valued function. They showed that slip-stick vibration occurs with a frequency of 500 Hz in the low-speed region near reversal and that the complex vibration combining stick, slip and free-flight states can occur with large attack angles. They also showed a large increase in the normal force near reversal. In this study, however, the exact timing of the state transitions is not considered and experiments were not conducted.

Encountering the exact timing of the state transitions is important because in nonlinear systems a slight discrepancy in transition times results in a much different prediction of the behavior. In this study, we examined both slip and stick states with regard to the exact transition time obtained using the slack variable method. Furthermore, we conducted experiments and compared the results with those from simulations. Below, we introduce a 2DOF analytical link model [8,10,11] and separately model the dynamic and static friction associated with the slip and stick states, respectively. In particular, the static friction force is expressed by a set-valued function. Using the slack variable method, we find the exact transition times of the state. We establish a simulation algorithm that treats the two types of states and the exact transition time and theoretically clarify the dynamics of the wiper blade near reversals. The vibration of the wiper blade contains two frequency components: 78 Hz and around 500 Hz. These frequencies correspond to the natural frequencies of the head and the neck of the blade, respectively. Furthermore, we conducted experiments and confirmed that the result is in good agreement with an experimental observation using an actual wiper blade.

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