Abstract—Application of flexible structures has been significantly increased in industry and aerospace missions due to their contributions and unique advantages over the rigid counterparts. In this paper, vibration analysis of a flexible structure i.e., automobile wiper blade is investigated and controlled. The wiper generates unwanted noise and vibration during the wiping the rain and other particles on windshield which may cause annoying noise in different ranges of frequency. A two dimensional analytical modeled wiper blade whose model accuracy is verified by numerical studies in literature is considered in this study. Particle swarm optimization (PSO) is employed in alliance with input shaping (IS) technique in order to control or to attenuate the amplitude level of unwanted noise/vibration of the wiper blade.

Keywords—Input shaping, noise reduction, particle swarm optimization, wiper blade

I. INTRODUCTION

Since the automobiles have come to exist and used as daily transportation means the necessity and significance of a tool like wiper has been perceived in order to sweep the water, snow and mud from the automobile’s windshield. Various sorts of noise in different frequency ranges are generated due to vibration of wiper blade on windscreen. A low frequency sound known as beep noise whose range is nearly 100 Hz is focused in this study to be attenuated. In open literature it is evidenced that the vibration noise called chattering noise is due to deformation of wiper blade during the wiper turnover [1]-[3]. Control of motion and noise reduction of wiper blade can be carried out through manipulating and modifying the wiper physical structure and material used in wiper rubber ([2]-[4]) or suppress the vibration of wiper via various control approaches [5]-[7]. Knowing that a critical issue for designing a controller for a wiping system should be adequately simple to be implemented on microprocessors whose memory are small and compute slowly, input shaping (IS) as an effective feed-forward controller is chosen for noise reduction of flexible wiper blade [8]. Since Input shaping approach is highly dependent on system natural frequencies and damping ratios and meanwhile such accurate information of wiper blade may not be feasible in analytical study; a need to an optimizer is perceived in order to find the accurate time location of impulses. Particle swarm optimization (PSO) is a relatively new method compare to evolutionary algorithms and has been introduced by Kennedy and Eberhart [9] which utilized in several control problems [10], [11]. In this paper a PSO algorithm is employed together with IS controller to adjust the time location of input impulses and it is expected that it can attenuate the amplitude of unwanted noise of wiper blade during its operation.

II. WIPER BLADE ANALYTICAL MODELLING

In order to eliminate the uncertainties, noise and other unwanted vibration; the knowledge of wiper’s dynamic equation is an essential issue. Therefore, the mathematical model of a reversal rubber wiper blade in [12] is fully adopted. The parameters involved in a spring-mass model of wiper are shown in Fig. 1 and their corresponded values in this case study are listed in TABLE I. Also, detailed geometries of wiper blade structure is given in Fig. 2.

A. Zolfagharian, M.Z. Md. Zain, A. R. AbuBakar, and M. Hussein

Ali Zolfagharian is with Department of Applied Mechanic, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia; (e-mail: ali.zolfagharyan@gmail.com).
Mohd. Zarhamdy Md. Zain is with Department of systems and Control, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia; (e-mail: zarhamdy@fkm.utm.my).
Abd Rahim AbuBakar is with Department of Aeronautics and Automotive, Universiti Teknologi Malaysia; (e-mail: arahim@fkm.utm.my).
Mohamed Hussein is the Head of Control and Automation Panel at the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia; (e-mail: mohamed@fkm.utm.my)

Fig. 1 Spring-mass model wiper blade system [12]
In the present model of wiper blade five various circumstances may be occurred so those lead to five different groups of equation of motion \[12\]. In this study, it is assumed that rubber head and rubber shoulder are not touching each other and the blade lip and wind shield are in a slip condition. Based on Fig. 1 and Eqs(2), (3), the sum of forces in the x and y-directions can be stated as \[12\]:

\[
T_{\text{w}} = m_{x}(\ddot{x}_{w} + d) + c_{x}(\dot{x}_{w} + d) + y_{m}\tan\beta_{T} - \dot{x}_{T}) + k_{x}(x_{w} + d) + y_{m}\tan\beta_{T} - x_{T} + T_{\text{x}_0} = (-\sin\beta_{N}/\cos(\beta_{T} + \beta_{N}))T_{0} = 0
\]

\[
T_{\text{y}_0} = (\cos\beta_{N}/\cos(\beta_{T} + \beta_{N}))T_{0}
\]

While \(\beta_{T}\) is twist angle of blade tail.

In the present model of wiper blade five various circumstances may be occurred so those lead to five different groups of equation of motion \[12\]. In this study, it is assumed that rubber head and rubber shoulder are not touching each other and the blade lip and wind shield are in a slip condition. Based on Fig. 1 and Eqs(2), (3), the sum of forces in the x and y-directions can be stated as \[12\]:

\[
m_{x}(\ddot{x}_{w} + d) + c_{x}(\dot{x}_{w} + d) + y_{m}\tan\beta_{T} - \dot{x}_{T}) + k_{x}(x_{w} + d) + y_{m}\tan\beta_{T} - x_{T} + T_{\text{x}_0} = (-\sin\beta_{N}/\cos(\beta_{T} + \beta_{N}))T_{0} = 0
\]

\[
m_{y}(\ddot{y}_{m} + c_{y}(\dot{y}_{m} - \{(\beta_{G} - \theta_{c}\sin\theta)x_{m} - l_{o}\beta_{d}\cos\theta\}) + c_{y}(l(\beta_{G}((1 + 1/K))\cos\theta - (\beta_{G}/K)\sin\theta)) + (y_{m}\tan\beta_{T} - y_{m} + k_{x}(x_{w} + l(\sin\theta + \beta_{d}/K)\cos\theta + y_{m}\tan\beta_{T} - x_{T})\tan\beta_{T}) - [k_{y}(y_{m} - y_{N}) + (\cos\beta_{N}/\cos(\beta_{T} - \beta_{N}))T_{0}]
\]

\[
+ (\cos\beta_{N}/\cos(\beta_{T} - \beta_{N}))T_{0}
\]

\[
(5)
\]

III. INPUT SHAPING

Input shaping’s mathematic derivation for two-impulse sequence can be obtained by a second order system as following.

The residual vibration resulted from a series of impulses utilized in the system can be derived as \[8\]:

\[
V(\omega, \xi) = \exp(-\xi\omega_{n}\sqrt{(\sum_{i=1}^{N} P_i(\omega, \xi))^2 + (\sum_{i=1}^{N} Q_i(\omega, \xi))^2}}
\]

\[
P_i = A_i\exp(-\xi\omega_{i}\sin\phi_i)
\]

\[
Q_i = A_i\exp(-\xi\omega_{i}\sin\phi_i)
\]

\[
(6)
\]

\[
\phi_i = \omega_{d}\xi_i
\]

\[
\omega_{d} = 2\pi f_{n}\sqrt{1 - \xi^2}
\]

Where \(A_i\) is amplitude, \(i\) represents the time of the impulses and \(n\) is the number of impulses in the impulse sequence and \(f_{n}\) and \(\xi\) are \(n\)th natural frequency and damping ratio of system respectively.

In order to achieve the zero residual vibration; the amplitude of a sequence of two impulses and their time location should be determined by solving (6) alongside some premises which should be taken into account to obtain non-trivial solutions as \[13\], \[14\]:

\[
A_1 = 1/1 + G, t_1 = 0
\]

\[
A_2 = G/1 + G, t_2 = Td/2
\]

Where \(G = \exp(-\xi\sqrt{1 - \xi^2})\) and \(Td = 2\pi/\omega_{d}\) is damped period of system.

IV. PARTICLE SWARM OPTIMIZATION

PSO has a population base algorithm in which some initial solutions are chosen which called particles. Each particle is
represented with its position and velocity. In first step, the algorithm is initialized with a number of random particles. The term dimension is defined as the number of decision maker in the problem; it means a problem with two variables corresponds to a two dimensions problem in particle swarm. Arbitrary appointed particles surf through the dimension(s) space of problem to look for the new solutions. Like other optimization methods a fitness function is defined that can calculate the certain objective of problem.

After initializing the nominee particles, PSO’s construction factor algorithm updates all the initial velocities and positions at each epoch as follow [15]:

\[ V_i^{t+1} = K \left[ V_i^t + C_1 U_1 (p_i - X_i^t) + C_2 U_2 (p_g - X_i^t) \right] \]  

(8)

Where K is named the constriction factor and defined as follow:

\[ K = \frac{2}{2 - \sqrt{\varphi^2 - 4\varphi}} \]

\[ \varphi = C_1 + C_2 > 4 \]  

(9)

K should be assigned a value between zero and one in order to convergence of algorithm. As it has been formulated K is ultimately a function of \( C_1 \) and \( C_2 \) that named self-recognition component and coefficient of the social component respectively and both are positive constants. \( X_i \) and \( V_i \) are the vectors of position and velocity of \( i \)th particle respectively. \( p_i \) is the best position of previous fitness value of \( i \)th particle. \( p_g \) represents the fittest particle among the all fitness values in the swarm. \( U_1 \) and \( U_2 \) are random numbers in the range of [0, 1].

For more comprehending the process of algorithm it can be supposed that the new velocity of each particle are comprised of three components which navigate the particle toward its best position, the global best position in previous level and same direction of last particle velocity. The best personal (pbest) and global (gbest) particles are acted like two attraction points which draw the particle somewhat toward themselves (Fig. 3).

Finally, new position of each particle is calculated as:

\[ X_i^{t+1} = X_i^t + V_i^{t+1} \]

(10)

In this study PSO is assigned as a fast and relatively accurate optimization algorithm to find the best time location of input impulses so that reduce unwanted noise of wiper blade (Fig. 4).

V. RESULTS AND DISCUSSIONS

In this section simulation of wiper blade are presented in the x and y directions. These simulation results are verified by numerical and experimental results that already existed in the open literature [16].

A double switch bang-bang velocity (Fig. 5) is considered as input of amplitude 0.2 m/s in system at time interval of 10 seconds.

The behavior of wiper blade in the x and y- direction with the unshaped bang-bang velocity input in time domain and frequency domain are illustrated in Fig. 6 and Fig. 7 in which the maximum amount of end point acceleration in x and y-direction are 4.8 m/s² and 1.9 m/s² and the highest power spectrum density (PSD) of end point acceleration in frequency domain are \( 23.1 \times 10^{-3} (m/s^2 \times m/s^2)/Hz \) at 97.5 Hz and \( 3.34 \times 10^{-3} (m/s^2 \times m/s^2)/Hz \) at 126.35 Hz respectively.

The earlier result has proved a closed correlation between the analytical results and numerical results in which the maximum amplitude of wiper vibration in the x and y-direction occurred at 99.08 Hz and 137.46 Hz respectively.
A PSO algorithm is applied on the path of bang-bang input in this stage to find the most appropriate time location of input shaper impulses as well as their amplitude which strongly dependent on the natural frequencies and the damping ratios of the system. The area under graph of wiper lip acceleration in terms of time is determined as an objective function to be minimized by means of PSO.

Acceleration constants of PSO algorithm is taken as equalled to $2.08$ for both $C_1$ and $C_2$ and the construction factor is calculated as constant value of $-0.67$ subsequently. In Fig. 8 and Fig. 9 the convergence of PSO algorithm with 8 particles and particles’ dynamic to find the closest values of frequencies and damping ratios to actual ones are illustrated.

It is shown that the first and second natural frequencies of system are obtained at 15.079 Hz and 28.3729 Hz respectively after 6 epochs of PSO algorithm. So, the optimized time location and amplitude of shaper impulses have been obtained and after convolving with bang-bang input has been sent into wiper system (Fig. 10).

Stick-slip condition is a phenomenon caused via interactions between rubber blade and windshield in the x-direction. The oscillation of wiper blade during the stick-slip situation causes more unwanted noise. From Fig. 11 it can be seen that the stick-slip behavior of current wiper blade has reduced significantly by applying the PSO in collaboration with IS compare to free of controller input. Jump condition is a phenomenon that happens when rubber blade leave the windshield surface during the movement in y-direction. This effect leads to adverse consequences like annoying noise and discomfort vision for driver and occupants. From Fig. 12 the jump duration of the wiper blade has been shortened to 0.075 seconds.
Fig. 10 Convolved input resulted from PSO+IS

Fig. 11 slip-stick situation in x- direction

Fig. 12 Jump condition in y- direction

Fig. 13 PSD of end point acceleration response in x- direction

Fig. 14 end point acceleration in x- direction

Fig. 15 Displacement of Wiper Lip in Time Domain

Fig. 16 Acceleration of Wiper Lip in Time Domain

Fig. 17 Power Spectral Density of Wiper Lip Acceleration

Fig. 18 Input Shaping Impulse (Velocity versus Time)

Fig. 19 Frequency (Hz)

Fig. 20 Magnitude (m/sec/sec)*(m/sec/sec)/Hz

Fig. 21 Power Spectral Density of Wiper Lip Acceleration

Fig. 22 Frequency (Hz)

Fig. 23 Magnitude (m/sec/sec)*(m/sec/sec)/Hz

Fig. 24 Input Shaping Impulse (Velocity versus Time)

Fig. 25 Time (seconds)

Fig. 26 Displacement (m)

Fig. 27 Acceleration (m/sec/sec)

Fig. 28 Time (seconds)

Fig. 29 Displacement (m)

Fig. 30 Acceleration (m/sec/sec)

Fig. 31 Input Shaping Impulse (Velocity versus Time)

Fig. 32 Time (seconds)

Fig. 33 Displacement (m)

Fig. 34 Acceleration (m/sec/sec)

Fig. 35 Input Shaping Impulse (Velocity versus Time)

Fig. 36 Time (seconds)

Fig. 37 Displacement (m)

Fig. 38 Acceleration (m/sec/sec)

Fig. 39 Input Shaping Impulse (Velocity versus Time)

Fig. 40 Time (seconds)

Fig. 41 Displacement (m)

Fig. 42 Acceleration (m/sec/sec)

Fig. 43 Input Shaping Impulse (Velocity versus Time)

Fig. 44 Time (seconds)

Fig. 45 Displacement (m)

Fig. 46 Acceleration (m/sec/sec)

Fig. 47 Input Shaping Impulse (Velocity versus Time)

Fig. 48 Time (seconds)

Fig. 49 Displacement (m)

Fig. 50 Acceleration (m/sec/sec)

Fig. 51 Input Shaping Impulse (Velocity versus Time)

Fig. 52 Time (seconds)

Fig. 53 Displacement (m)

Fig. 54 Acceleration (m/sec/sec)

Fig. 55 Input Shaping Impulse (Velocity versus Time)

Fig. 56 Time (seconds)

Fig. 57 Displacement (m)

Fig. 58 Acceleration (m/sec/sec)

Fig. 59 Input Shaping Impulse (Velocity versus Time)

Fig. 60 Time (seconds)

Fig. 61 Displacement (m)

Fig. 62 Acceleration (m/sec/sec)

Fig. 63 Input Shaping Impulse (Velocity versus Time)

Fig. 64 Time (seconds)

Fig. 65 Displacement (m)

Fig. 66 Acceleration (m/sec/sec)

Fig. 67 Input Shaping Impulse (Velocity versus Time)

Fig. 68 Time (seconds)

Fig. 69 Displacement (m)

Fig. 70 Acceleration (m/sec/sec)

Fig. 71 Input Shaping Impulse (Velocity versus Time)

Fig. 72 Time (seconds)

Fig. 73 Displacement (m)

Fig. 74 Acceleration (m/sec/sec)

Fig. 75 Input Shaping Impulse (Velocity versus Time)

Fig. 76 Time (seconds)

Fig. 77 Displacement (m)

Fig. 78 Acceleration (m/sec/sec)

Fig. 79 Input Shaping Impulse (Velocity versus Time)

Fig. 80 Time (seconds)

Fig. 81 Displacement (m)

Fig. 82 Acceleration (m/sec/sec)

Fig. 83 Input Shaping Impulse (Velocity versus Time)

Fig. 84 Time (seconds)

Fig. 85 Displacement (m)

Fig. 86 Acceleration (m/sec/sec)

Fig. 87 Input Shaping Impulse (Velocity versus Time)

Fig. 88 Time (seconds)

Fig. 89 Displacement (m)

Fig. 90 Acceleration (m/sec/sec)

Fig. 91 Input Shaping Impulse (Velocity versus Time)

Fig. 92 Time (seconds)

Fig. 93 Displacement (m)

Fig. 94 Acceleration (m/sec/sec)

Fig. 95 Input Shaping Impulse (Velocity versus Time)

Fig. 96 Time (seconds)

Fig. 97 Displacement (m)

Fig. 98 Acceleration (m/sec/sec)

Fig. 99 Input Shaping Impulse (Velocity versus Time)

Fig. 100 Time (seconds)

Fig. 101 Displacement (m)

Fig. 102 Acceleration (m/sec/sec)

Fig. 103 Input Shaping Impulse (Velocity versus Time)

Fig. 104 Time (seconds)

Fig. 105 Displacement (m)

Fig. 106 Acceleration (m/sec/sec)

Fig. 107 Input Shaping Impulse (Velocity versus Time)

Fig. 108 Time (seconds)

Fig. 109 Displacement (m)

Fig. 110 Acceleration (m/sec/sec)

Fig. 111 Input Shaping Impulse (Velocity versus Time)

Fig. 112 Time (seconds)

Fig. 113 Displacement (m)

Fig. 114 Acceleration (m/sec/sec)

Fig. 115 Input Shaping Impulse (Velocity versus Time)

Fig. 116 Time (seconds)

Fig. 117 Displacement (m)

Fig. 118 Acceleration (m/sec/sec)

Fig. 119 Input Shaping Impulse (Velocity versus Time)

Fig. 120 Time (seconds)

Fig. 121 Displacement (m)

Fig. 122 Acceleration (m/sec/sec)

Fig. 123 Input Shaping Impulse (Velocity versus Time)

Fig. 124 Time (seconds)

Fig. 125 Displacement (m)

Fig. 126 Acceleration (m/sec/sec)

Fig. 127 Input Shaping Impulse (Velocity versus Time)

Fig. 128 Time (seconds)

Fig. 129 Displacement (m)

Fig. 130 Acceleration (m/sec/sec)

Fig. 131 Input Shaping Impulse (Velocity versus Time)

Fig. 132 Time (seconds)

Fig. 133 Displacement (m)

Fig. 134 Acceleration (m/sec/sec)

Fig. 135 Input Shaping Impulse (Velocity versus Time)

Fig. 136 Time (seconds)

Fig. 137 Displacement (m)

Fig. 138 Acceleration (m/sec/sec)

Fig. 139 Input Shaping Impulse (Velocity versus Time)

Fig. 140 Time (seconds)

Fig. 141 Displacement (m)

Fig. 142 Acceleration (m/sec/sec)

Fig. 143 Input Shaping Impulse (Velocity versus Time)

Fig. 144 Time (seconds)

Fig. 145 Displacement (m)

Fig. 146 Acceleration (m/sec/sec)

Fig. 147 Input Shaping Impulse (Velocity versus Time)

Fig. 148 Time (seconds)

Fig. 149 Displacement (m)

Fig. 150 Acceleration (m/sec/sec)

Fig. 151 Input Shaping Impulse (Velocity versus Time)

Fig. 152 Time (seconds)

Fig. 153 Displacement (m)

Fig. 154 Acceleration (m/sec/sec)
VI. CONCLUSION

In this study particle swarm optimization method as a fast and accurate population based optimization method is fully utilized to determine the most suitable time location of input shaping impulses so that unwanted noise of automobile wiper blade known as beep noise in both x and y- directions can be reduced significantly. Furthermore, the stick-slip and jump condition which represent the oscillation behavior of wiper blade in time domain for the x and y- direction have been improved using the PSO in associating with IS controller.

REFERENCES


