Design and Evaluation of Haptic Interface Systems for Motorbike Application Using Multibody Modelling

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Abstract— **In this paper, the design and the evaluation of haptic HMI systems for motorbike are presented. The final goal of designing haptic interfaces is to set a communication between the rider and the motorbike increasing the rider safety. The designed systems have been evaluated through simulation using MSC Adams®. Considering the possibility of a future realization of the simulation tested system, the haptic HMI devices have been designed taking into consideration a wide number of specific requirements. Starting from the state of the art, a preliminary study has been done in order to determine the design requirements. Three solutions have then been modelled: the Haptic Brake Lever, the Haptic Handle and the Haptic Knob. Each of the models has been tuned through simulations to convey the optimal haptic feedback to the rider, in terms of amplitude and frequency. In the end, the three solutions have been compared basing on safety, feedback perceivability, design and mechanical efficiency. The best solution will be realized and tested on a real motorbike during future work.**

I. INTRODUCTION

The object of this paper is to design different interaction systems implementing a vehicle-to-rider communication through an haptic feedback generated by a human machine interface (HMI) installed on a motorbike. The systems are targeted to increase the safety level of a motorcycle.

In the last decade, the research interest in two wheels vehicles has been driven by two main features [1]. On one hand, motorcycles are means for personal mobility with a low environmental impact due to the relatively low weight, and they seem to be extremely promising for the development of electric vehicles. On the other hand, they are responsible for about 20% of road accidents due to a relatively low level of safety. Thus, many different safety systems have been designed such as the Curve Warning systems [2], the Intersection Support System [3] and the Navigation and Routh Guidance [4]. However, every safety system able to identify potential dangerous situations must also be capable of warning the rider. Thus, HMI devices could be a key factor in safety systems for two wheels vehicles, since fully reliable safety systems has to be coupled with highly efficient HMI devices in order to stimulate fast and correct reaction of the rider [5].

The development of different HMI devices for motorbike application can be found in literature. Each solution is capable to exploit different sensorial channel in order to convey a feedback to the driver : visual, audio and haptic. Visual interface systems are more suitable to be installed on automobiles rather than on motorbikes due to safety reasons. In [4], a navigation and route guidance software based on different HMIs, a visual display and a smart helmet, is evaluated. Smart helmet feedback could be acoustic or haptic. Results of a field test shown that the smart helmet, based on audio and haptic feedback, was the most preferred and was perceived as safer. On the contrary the visual display on motorbikes must be avoided in order not to be distracting. In [5] a system to increase the safety level of a motorcycle based on an audio interaction located at helmet level is proposed. Audio feedback through the smart helmet allows a hands free vehicle to rider communication increasing the driving safety respect to the considered visual HMI. However, these audio/visual interfaces are not suitable for motorcyclists, since they require their visual and auditory channels to maintain awareness of the environment around them.

That is the reason why, in the last decade, different haptic HMI systems have been designed in order to provide a vehicle to rider communication system that is both safe and perceivable by the rider. They differ both in the positioning of the haptic interface and in the way of generating the feedback.

Regarding the position of the interface systems, most of the haptic HMI founded in literature are installed on the handlebar: in [6] an intelligent Curve Warning system is proposed; it gives the riders support when negotiating a curve. Haptic feedback was provided using two alternative rider interfaces: a force feedback throttle and a haptic glove. In the first setup, the alert is transmitted to the rider through a force feedback generated by a system placed inside the the gas-throttle handle. If the rider speed is too high, the stiffness of the throttle increases, generating a resistance torque. A similar solution is studied in [7], where a motorbike is equipped a with a haptic throttle grip that is externally connected to a motor by gear. This throttle grip can output haptic signals to the rider by controlling the motor. The critical point in those systems is that they produce a warning that is intrusive, since it affects a component of the vehicle control, the throttle. Therefore, this could have possible negative effects on the riding behaviour and the acceptance by the motorcyclist.

A small number of solutions are based on special haptic HMI systems that are wearable by the driver. In the second setup of [6], the HMI is incorporated in the right glove. The glove is equipped with electronics and vibration motors and transmits the warning signal by vibration applied to the riders wrist. In [8] a haptic interface system called HaptiMoto

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is introduced: it consists of a tactile vest with adjustable straps to fit different users. It is equipped with an electronic controller that controls three vibrational tactors located on the vest. Although those solutions are probably the most perceivable because the HMI is directly worn by the driver, they have the strong disadvantage that are not embedded into the motorbike.

Haptic HMI systems differ also in the way of producing the feedback: as already said, in [6] and in [7] the HMI devices generated a resistance torque that opposites the driver torque on the throttle. Resistance torque amplitude is proportional to the warning emergency. Others, like the haptic gloves, the smart helmet or the Haptimoto wearable vest, produce feedbacks that are perceivable by the driver as a vibration of a part of the equipment. In [9] some experimental and numerical investigations have been reported to evaluate the possibility to adopt a drive assistant system on motorcycles, based on mechanical vibrations of the handlebar grip. This problem is very difficult to solve because the driver should distinguish the warning vibrating signal from those coming from the engine or due to other causes occurring during operation. The results of the study proved that it is possible to generate a feedback through a vibration of the handlebar grip but no applications of this idea have been found in literature.

On the other hand, in [10] the development of an haptic HMI device to communicate information/warnings to the rider based on pressure variation under the rider hand is suggested. The mechanical solution consists of an external micro-motor connected to a cam shaft through a flexible shaft. The cam shaft actuates sequentially the moving elements, giving the sensation of a moving wave towards the external part of the handle. It is to notice that the micro-motor and the control unit are positioned away from the handle whereas the cam shaft is inside resulting in a low efficient solution in terms of mechanical power.

The aim of this paper is to design different innovative Haptic HMI devices for motorbike starting from the current state of the art. The modelled solutions differs from the previous works because they are both fully embedded into the motorbike handlebar and generate an haptic feedback that does not directly affect the motorbike riding. Thus, they do not require the rider to wear special equipment such as gloves or vests. They are based on micromotors that are directly placed on the brake lever or inside the handlebar avoiding the use of any external trasmission resulting in highly efficient solutions. The haptic feedback is based on mechanical vibration of the handlebar grip. Handlebar vibrations due to the engine are considered and studied. Frequency and amplitude of the feedback are then set in order to make the haptic feedback distinguishable from the vibration coming from the engine.

The remainder of the paper is organized as follow: in Sect. II the problem is defined and design requirements are listed; in Sect. III three different innovative Haptic HMI devices for motorbike application are designed and simulated using MSC Adams®; in Sect.IV solutions are evaluated and compared each other in order to determine the best one; in Sect.V conclusions are drawn and future directions are briethly announced.

II. Problem statement and requirements

The aim of this paper is to design and evaluate different haptic HMI systems in order to establish a communication between the motorbike and the rider. Haptic interfaces are designed in order to increase the rider safety on the motorbike. The designed systems have been evaluated through simulation using MSC Adams®. Considering the possibility of a future realization of the simulation tested system, the haptic HMI devices have to be designed taking into consideration a wide number of specific requirements:

Firstly, the alert must be distinguishable from vibrations due to other sources that are maily the engine, the wheels unbalance, the road roughness etc. Among all the sources, the engine is the primary cause of vibration on a motorbike. Engine vibration are characterized by a wide range of possible frequencies from 10 to 500 Hz. A preliminary study has been done in order to analyze the nominal vibrations of the motorcycle to understand how to design the haptic actuator. Three accelerometers have been installed at the end of the left knob of a Ducati Panigale 1199. Thus accelerations of the three main axes are measured. The aim of this preliminary test is to determine, if exists, a possible relationship beetween the engine rotational frequency (rpm) and the accelerations generated on the knob. A frequency sweep from 10 Hz (600 Rpm) to 187 Hz (11120Rpm) has been imposed to the engine. Vibrations on the rotary knob are strictly correlated to the engine rotational frequency. Measured acceleration frequencies on the three axes are multiple armonics of the engine rotation frequency. As an example, in Fig. 1 the spectrogram of the vibration along axis x generated by the motor is reported. It is clearly visible that three main armonics of 374, 748 and 934 Hz are generated. They correspond respectively to two, four and five times

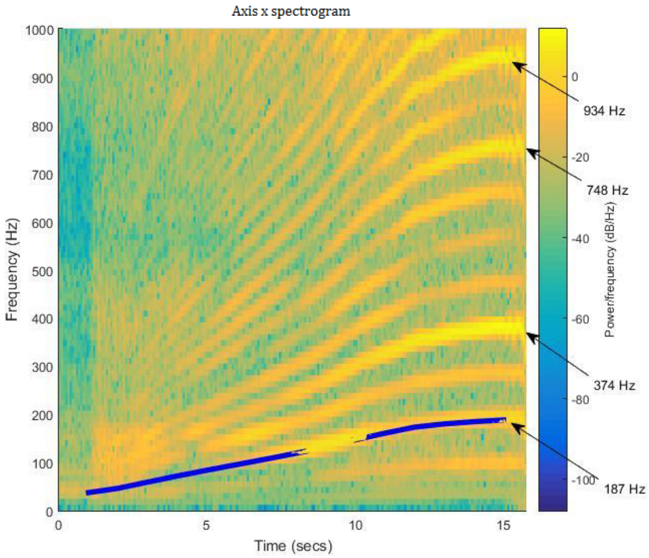

Fig. 1. Spectrogram of the vibration along axis x generated by the motor.

the input frequency. Thus, generated accelerations on the knob are equal or faster in terms of frequency respect to the engine rotational speed. This result leads to a first conclusion: the haptic actuator must be designed in order to generate a feedback with a frequency strictly lower than the minimum engine rotational speed of 600 rpm, which corresponds to 10 Hz.

Further analysis of the spectrograms have then demonstrated that the engine vibrations on axes x and y are nearly two times greater than the ones on z axis. Thus z axis, that corresponds to the vertical direction, has to be preferably chosen as the direction of the haptic actuation because it is less affected by the engine vibrations.

Beside the first requirement, the haptic feedback must be perceivable by the rider. Thus, the working method is to design different haptic devices that generate a feedback whose frequency is lower than 10Hz in order to avoid interferences with engine vibrations. The exact frequency value is chosen in order to have the most perceivable feedback. The resulting amplitude is then controlled; desidered amplitude range is 0.5 to 2 mm. It has been arbitrarly set considering both rider safety and the minimum skin mechanoreceptors resolutions [11].

Last requirement is to design HMI devices that are highly efficient. Designing highly efficient devices means that most of the micromotor input power is trasferred to the handlebar grip. The mechanical efficiency is defined as:

$$\eta = \frac{P_{output}}{P_{input}} \qquad (1)$$

where P_{output} and P_{input} are the mechanical output and input power respectively. The higher η is, the more perceivable the haptic feedback is supposed to be. Moreover, high values of η allow to select smaller micromotor and supply battery sizes resulting in less bulky devices.

III. DESIGN AND SIMULATION

Once the requirements have been clearly defined, three different haptic HMIs have been modelled in Adams®, where a wide number of multibody simulations can be performed in order to study the system dynamics. Each of the models have been tuned to convey the optimal haptic feedback to the rider, in term of amplitude and frequency. In the end, it is necessary to briefly verify if the designed solutions are really achievable. Starting from the requested torque and speed, a motor dimensioning is quickly reported.

A. The Haptic Brake Lever

The first solution is based on an ERM motor placed on the brake lever, as shown in Fig.2. An ERM motor is composed of a standard micro-motor and a eccentric rotary mass (m_{ERM}) connected to its shaft; The ERM rotation generates a centrifugal force that makes the entire brake lever oscillate. Thus the lever vibrates with a frequency f and an amplitude A. The lever displacement is directly proportional to the ERM whereas it is inversely proportional to the lever mass. It means that the bigger the ERM is, the more perceivable the feedback is. Standard ERM values go from 1g to 10g. Right size of the ERM is determined through simulation.

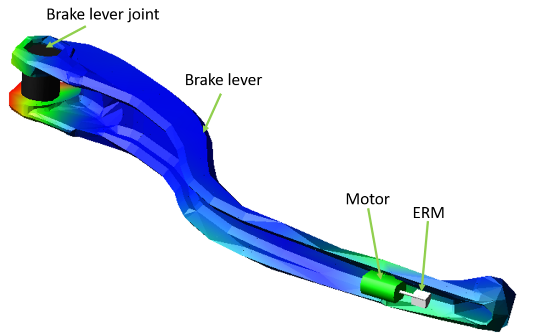

Fig. 2. Multibody model of the haptic brake lever.

Dimensional limits need also to be investigated. ERM motor must be fixed to a plan and sufficiently wide surface; moreover, ERM motor and supply cables have to be easily installed and must not come in touch with the pilot hand. Thus, lever internal side has been chosen as possible selectable position. Maximum allowable space dimension is 22x11x7mm. As visible in Fig. 2, a standard motorbike lever has been modelled using Adams®. The brake lever is then modelled as a finite elements body. In such a way, the brake lever is able to deform if stressed by the ERM motor rotation. ERM motor has been modelled directly into Adams® because of its simple geometry. The designed system has two degrees of freedom: ERM rotation around the motor shaft and lever rotation around its axis. A torsional spring has been added to the lever rotational joint to reproduce the real lever behavior. Rider hand pressure on the lever has been modelled as the sum of two components: a stationary pressure of 50N, due to the rider hand weight, and a dynamic pressure, due to the braking action, from 50 to 800N depending of the braking intensity [10].

Once the model is completed, simulation can be performed. As a preliminary test, the ERM has been set to 10g and a 0 to 10Hz frequency sweep has been imposed as input to the ERM rotational speed. The first task is to detemine if one or more system resonances are present in this frequency range. As desired, one perceivable system resonance is visible around 3Hz in Fig. 3. Thus, further simulations have been performed with an ERM rotational frequency at 3 Hz. Different values of ERM from 1 to 10 g has been tested to observe their influence of the feedback amplitude. Fig. 4 shows that there is a 0,8mm lever displacement corresponding to an ERM of 10g rotating with a frequency of 3Hz.

From the simulation, some conclusions are derived:

- Feedback amplitude maximum value is reached with a ERM rotational speed of 3 Hz. The feedback frequency is compatible with the requirements . Thus, 3Hz is the chosen feedback frequency;
- Centrifugal force F is directly proportional to the ERM

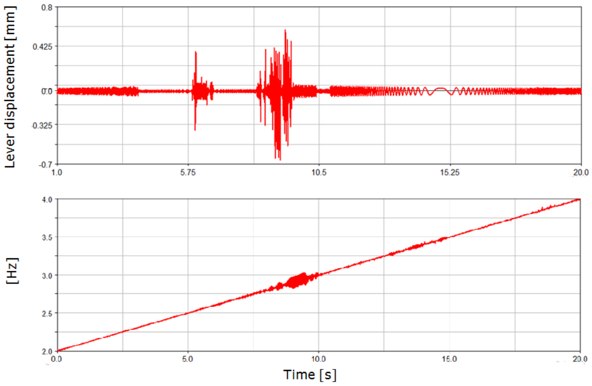

Fig. 3. Resonance frequency analysis for Haptic brake lever system.

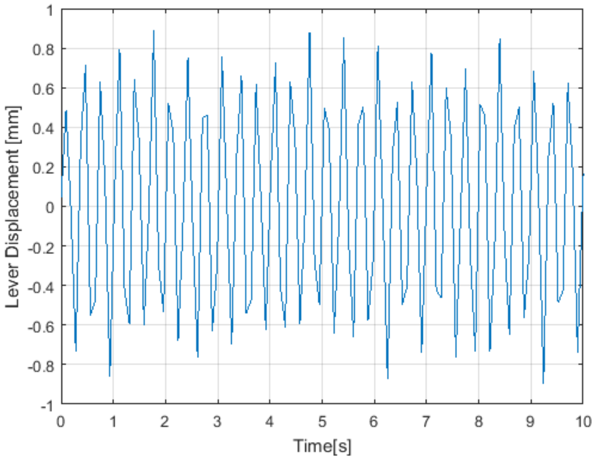

Fig. 4. Lever displacement with f=3Hz and ERM=10g.

mass m_{ERM} so, the more m_{ERM} increases, the more the feedback is perceivable. Thus, a ERM of 10g is chosen.

Feedback frequency and ERM has then been chosed from the multibody simulation. However, some studies are required to determine the right motor size. Motor nominal torque must be greater than the required torque, as calculated in eq. 2.

$$C_n > C_{required} = F \cdot e = m_{ERM} \cdot e^2 \cdot \omega^2 \qquad (2)$$

The selected motor is a 12x24 mm micro-motor that fits with the allowable space on the brake lever. Motor nominal torque in 32Nmm at a rotational frequency of 3Hz. Then, it is possible to calculate the mechanical efficiency η of the designed system as follow:

$$\eta = \frac{P_{output}}{P_{input}} = \frac{m_{lever} \cdot a_{lever} \cdot v_{lever}}{C_{mot} \cdot \omega_{mot}} \qquad (3)$$

Where m_{lever} is the lever mass and v_{lever} and a_{lever} are respectively the velocity and the acceleration of the lever along z axis. C_{mot} is the motor torque and ω_{mot} is the motor speed. Their values are derived from the simulation. Thus, the mechanical efficiency is calculated and its value is 13%

B. The Haptic Handle

The second solution is based on a rotary motor placed inside the handlebar. A cam shaft is connected to the end of the motor. During motor rotation, the cams come in contact with two or more moving elements specially stuck in the handlebar. Thus, the radial movements of the elements deform the knob resulting in a pressure variation on the pilot hand. A multibody model of the designed system is shown in Fig. 5. The green parts are the cams connected to the motor shaft whereas the yellow ones are the elements that deform the knob. The resulting model has two DOF: motor rotation around the handlebar axis and the radial movemements of the deforming elements. Two contact forces are modelled properly: the contact between the cams and the elements and the one between the elements and the knob. Contact parameters have been set properly considering the material of the involved parts. The knob has then been modelled as a finite element deformable part. Knob deformation generates a pulsating pressure variation that represents the haptic feedback trasmitted to the rider hand. To end the modelling phase, rider seizure force on the knob has to be considered: two radial forces of 100N are introduced to reproduce a uniform seizure action. As for the Haptic Brake Lever, a 0 to 10Hz frequency sweep has been imposed as input to the micromotor rotational speed. Results of this preliminary simulation are similar to the ones in 3; thus, a rotational frequency of 3Hz has been selected. The resulting contact force between one of the moving elements and the knob is then derived through simulation. The contact force is supposed to be nearly zero when the element is not actuated by the cam shaft. On the other hand, every time that the cams force the elements to radially move toward the knob, the contact force increases immediately resulting in a maximum value of deformation force of 12N that corresponds to a knob displacement of around 1mm. In Fig.6 the knob displacement is reported. Thus the torque requested to the motor during element-knob contacts has been derived from the simulation.

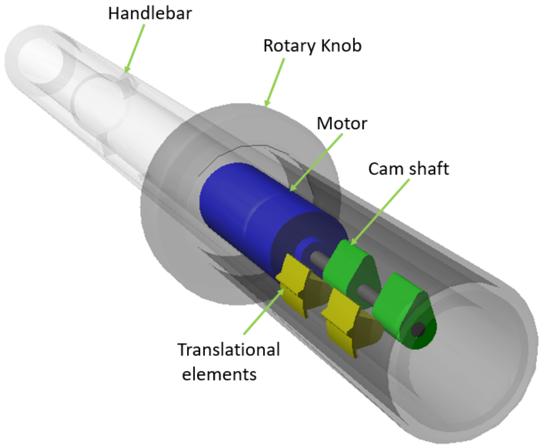

Fig. 5. Haptic Handle multibody model.

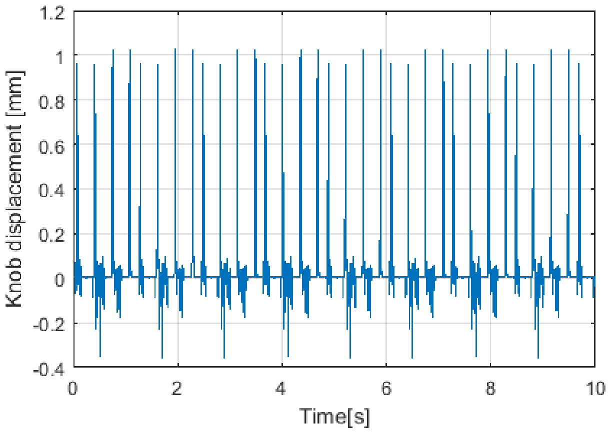

Fig. 6. Haptic Handle grip diplacement with f=3Hz.

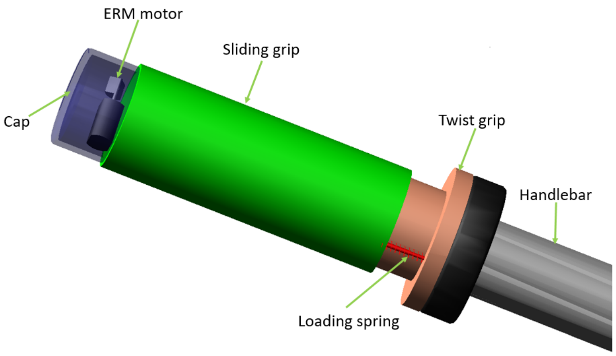

Fig. 7. Multibody model of ERM motor in the cap solution.

A130Nmm torque is requested to the motor so that one element can deform the knob with a frequency of 3 Hz. Thus, a torque of 260Nmm is required for two moving elements. A commercial micromotor with a maximum torque of 298Nmm at 200rpm (around 3Hz) has been found. Thus, the solution is determined feasible. Mechanical efficiency of the present HMI device is expressed below.

$$\eta = \frac{P_{output}}{P_{input}} = \frac{F_{def} \cdot v_{def}}{C_{mot} \cdot \omega_{mot}} \tag{4}$$

Note that the input power is the same of the previous solution whereas the output power has been defined as the power connected to the lever deformation. The average value of the mechanical efficiency is 25%.

C. *The Haptic knob*

The haptic feedbacks generated by the two previous modelled HMIs systems propagates radially from the feedback source. The ERM motor installed on the brake lever makes the lever oscillate mainly in vertical direction, whereas the haptic HMIs inside the handlebar produces a pressure variation that propagates radially to the pilot hand. The task of the third solution is to design a haptic HMI device that actuates the grip in the longitudinal direction, so that the grip can slide back and forth. A multibody model of the designed solution has been created using Adams®, as shown in Fig.7: the grip is composed by an outer cylinder, called *Sliding Grip*, and an inner cylinder, called *Twist Grip*. The *Twist Grip* is fixed to the rotary knob whereas the *Sliding Grip* is held in place by a spring. The *Sliding Grip* can slide back and forth longitudinally on the twist grip. All the other dofs of the outer cylinder are prevented by mechanical joints. The longitudinal movement is actuated by an ERM motor placed inside the cap of the handlebar. Note that the rotation of the ERM motor makes the *Sliding Grip* oscillate back and forth on the *Twist Grip* while the *Loading spring*, that links the outer and the inner parts, generates an opposite force. This result in a periodically haptic signal that propagates longitudinally on the grip. The input of the model is the motor frequency rotation in Hz and the measured output is the knob longitudinal displacement in mm. As for the previous solutions, rider pressure on the knob has been taken in consideration. The frequency of the motor and the size of the ERM are the tuning parameters to be set in order to generate an Haptic feedback which is both perceivable and safety. Desired values corresponds to a feedback frequency lower than 10 Hz and amplitude around 1mm. As for the Haptic Brake Lever, a preliminary simulation has been performed: a 0 to 10 Hz frequency sweep has been imposed. A frequency of 3Hz has been chosen accordingly to the previous solutions. On the other hand, simulations of different ERM sizes show that the heavier is the ERM the bigger the feedback amplitude is. Accordingly to the simulation results an eccentric mass of 3g has been chosen. A suitable ERM motor with an eccentric mass of 3g has been found on the market and selected for this application. The motor has a nominal torque of 3.2Nmm at a frequency of 3Hz. The corresponding longitudinal displacement is visible in Fig. 8. In the end, mechanical efficiency is calculated from

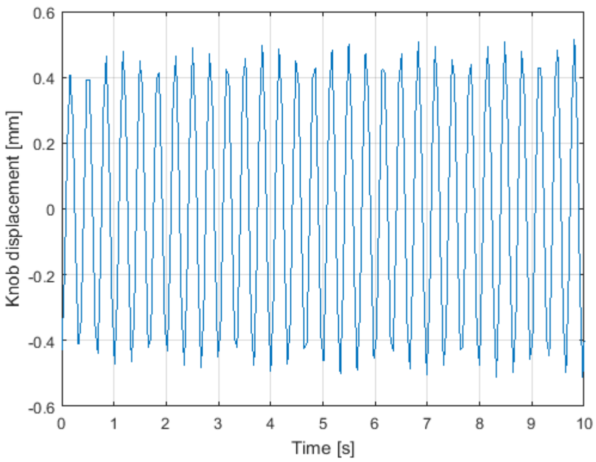

Fig. 8. Knob disp. with f=3Hz and ERM=3g.

the following equation:

$$\eta = \frac{P_{output}}{P_{input}} = \frac{m_{knob} \cdot a_{knob} \cdot v_{knob}}{C_{mot} \cdot \omega_{mot}} \tag{5}$$

Take care that a_{lever} and v_{lever} are now the acceleration and the velocity of the twist grip in longitudinal direction. mechanical efficiency is the calculated and the average value is 18%

IV. PERFORMANCE EVALUTATION AND COMPARISON

Three innovative haptic HMI devices has been multibody modelled using MSC Adams®: the Haptic Brake Lever, the Haptic Handle and the Haptic Knob. Design parameters have been tuned following the requirements descripted in section II. A comparison of the three solutions is then needed in terms of perceivability, safety, mechanical efficiency and design. Main features of each proposed solutions are summarized in the table I: All the three solutions are supposed to be perceivable in theory because they all generate a feedback with a frequency equal to 3Hz lower than the limit of 10Hz. Thus, they all should avoid interferences with the vibration generated by the engine. However, some practical considerations are easy to derive. The Haptic Lever has the strong disadvange to be perceivable only if the rider has his fingers on the lever. Thus, it is possible to conclude that the Haptic Brake Lever is not the optimal one in terms of perceivability during all riding conditions. The Haptic Knob could have some percivability problems when the rider is approaching a curve. The twist grip could come in contact with the external or internal mechanical limit due to the forces generated during the curve. This could prevent the motor to generate the feedback. On the other hand, the Haptic Handle results to be the more perceivable feedback because it is not influenced by any riding condition. The driver perceives a pressure variation on the palm of his hand resulting in a totally safe haptic feedback that does not affect negatively the rider's guide.

TABLE I

DESIGNED HMIS SUMMARY

HMI position	feedback	f [Hz]	η[%]
brake lever	Radial vibration	3Hz	6.5%
Handlebar	radial pressure variation	3Hz	13%
knob	longitudinal vibration	3Hz	18%

Regarding the mechanical efficiency, the Haptic Knob has the highest value. It means that less power is needed to produce the same haptic feedback. On the other hand, The Haptic Lever has the lower mechanical efficiency. This is due to the nature of the solution. The feedback is based on the elastic deformation of the entire lever generating a vibration. This solution, altough it is easy to design and implement, it is inefficient if compared with the others. To sum up the Haptic Knob has the best mechanical efficiency but its safety needs some experimental tests; the Haptic Brake Lever has the simpliest design but it is strongly inefficient. Thus , The Haptic Handle has been chosen as the optimal solution to be tested on a real prototype in future.

V. CONCLUSIONS

To sum up, starting from the state of the art, a preliminary test on a real motorbike has been done in order to determine the design requirements. Test results show that the haptic feedback must have a frequency strictly lower than the minimum engine rotational speed of 600 rpm, which corresponds to 10 Hz. Thus, three solutions have been modelled and simulated using MSC Adams®: the Haptic Brake Lever, the Haptic Handle and the Haptic Knob. . Each of the models have been tuned to convey the optimal haptic feedback to the rider, in terms of amplitude and frequency. In the end, the three solutions have been compared basing on safety, feedback perceivability, design and mechanical efficiency. The Haptic Handle has been chosen as the best solution; future direcitons will be to realize a prototipe of the chosen solution and test it on a real motorbike.

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