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Designing a Strain Gauge Transducer for Dynamic Load Measurement in Cycling using numerical simulation

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Abstract

The aim of this work is to study the effect of a beam transducer's modal behaviour, suspended mass and system damping on the load measurement accuracy using base excitation, and to provide insight to engineers on the process of designing a strain gauge beam transducer to measure dynamic loads. Development and results for a simple beam transducer and an instrumented brake hood and seat post are presented. One of the main conclusions to be drawn from the results presented is that, in the case of base excitation, the transducer's first bending mode has no negative effect on the measurement accuracy.

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Keywords: *Strain gauge transducer; Dynamic loading; Cycling.*

1. Introduction

Load measurement, in situ and in the laboratory, plays a central role in the development of sports equipment. This is especially the case in cycling, where transducer development and load measurement have been very active research topics for the past few decades. Many transducers designed for measuring bicycle loads have been described in the literature: pedal dynamometers (Rowe et al. (1998), Drouet et al. (2008)) and instrumented stem,

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brake hood, hubs, seat posts and handlebars (Bolourchi and Hull (1985), Drouet and Champoux (2010, 2012), Vanwalleghem et al. (2013), Caya et al. (2012)).

Generally speaking, there are two types of loading when it comes to bicycle dynamic component loads: cyclist loading for propulsion and the loads induced by the road excitation. For propulsion, the cyclist applies time varying loads to the pedals, the handlebar and the saddle. This is a low frequency loading (under 3 Hz) along with the acknowledgement that a high pedalling cadence such as 120 RPM corresponds to only a 2 Hz excitation. The road excitation input forces are first transmitted to the tires and then to all of the connected bike components. For a road bike, the frequency content typically ranges from 2 Hz to 1000 Hz. Most of the energy is usually between 5-100 Hz (Lépine et al. (2013)). Proper static sensitivity calibration of transducers intended for measuring low frequency loads is generally sufficient to guarantee satisfactory measurement data. However, when measuring dynamic loads induced by the road (5 Hz and up), we need to take into account the effect of the transducer's vibrational behaviour on the measurement. In this context, designing a strain gauge transducer for dynamic load measurement presents additional challenges. During road induced excitation, the cyclist is considered to be a suspended mass leaning on a bicycle. This corresponds to what is called a base excitation condition in which a displacement under a system becomes the excitation; all the mass above it responds to the excitation.

Previous studies (Caya et al. (2012)), have investigated the influence of the transducer's stiffness on measurement accuracy in the context of base excitation. An ideal mass-spring-damper approach was used to compare the vibrational behaviour of an instrumented brake hood to that of its standard counterpart. Within the limits of this approach, it was shown that the transducer's stiffness has a direct and significant effect on measurement accuracy. However, the effect of the modal behaviour of the transducer itself and of two important parameters, the suspended mass and system damping, was not investigated.

The aim of this paper is twofold: (1) to study the effect of transducer's modal behaviour, suspended mass and system damping on the load measurement accuracy; (2) to provide additional insight to engineers on the process of designing a strain gauge transducer to measure dynamic loads. Because most of the strain gauge force transducers in the market or used on bicycles rely mainly on strain measurement associated with beam bending, the developments presented are specific to this type of structure and loading. As a relevant illustrative example, the cases of a simple beam transducer and of an instrumented brake hood and seat post are presented.

2. Methods

2.1. Simple beam transducer model

Using a free-sliding beam (Fig. 1) as a strain gauge transducer, measurements were taken of the force of interaction between the beam's right end and a suspended mass (*M*) attached to it. The beam is made of 6061-T6 aluminium. It is 0.3 m long with cross-sectional area dimensions of b = 25.4 mm and h = 4.8 mm. Using FEA and simulation software (SolidWorks Simulation, Dassault Systèmes, USA), a base acceleration excitation $a(t) = A_0 \sin(\omega t)$ is applied to this system with a frequency ranging from 0 to 200 Hz and a magnitude (A_0) of 1 "g" ($9.8\ \mathrm{m \cdot s^{-2}}$). The numerical calculations of the system's dynamic response allow us to determine the two following key parameters as function of frequency: (1) the strain field on the beam's surface; (2) the magnitude of the acceleration of the suspended mass along the *z*-axis, $A_{Mz}(\omega)$.

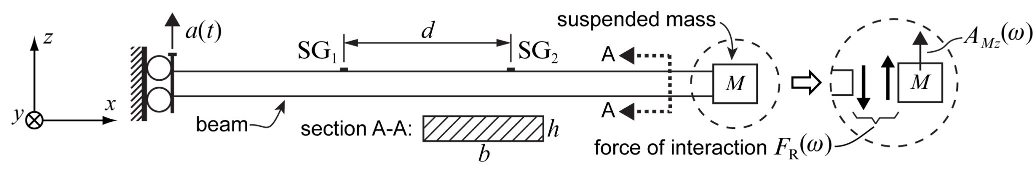

Fig. 1. Simple beam transducer model and boundary conditions. The detailed view (inside the dotted circle) shows (1) the force of interaction between the beam and the suspended mass (*M*); (2) the magnitude of the acceleration of the suspended mass along the *z*-axis, $A_{Mz}(\omega)$.

To assess the effect of this transducer's vibrational behaviour on the force measurement accuracy, two forces will be compared for a given base excitation frequency range: (1) $F_{\mathrm{R}}(\omega)$: the real force of interaction between the beam and the suspended mass; (2) $F_{\mathrm{SG}}(\omega)$: the estimation of $F_{\mathrm{R}}(\omega)$ as it would be measured if the beam was actually used as a strain gauge (SG) force transducer.

To simulate measurement with strain gauges in a Wheatstone half-bridge configuration, two positions, SG_1 and SG_2, are selected along the x-axis (d = 76.2 mm) and halfway across the beam's width. The difference between the normal strain along the x-axis (obtained from the beam's strain field) at these two positions allows us to calculate $F_{\mathrm{SG}}(\omega)$ using traditional strength of materials formulas (Craig (2000)). Using Newton's second law, the real force of interaction between the beam and the suspended mass is calculated as follows: $F_{\mathrm{R}}(\omega) = MA_{Mz}(\omega)$. Because of the vibrational behaviour of the beam, the beam transducer measurement accuracy is expected to be impaired. $F_{\mathrm{R}}(\omega)$ being the true value of the force of interaction, the measurement error (in %) on $F_{\mathrm{R}}(\omega)$ is given by (1).

$$E(\omega) = 100\left[F_{\mathrm{SG}}(\omega) - F_{\mathrm{R}}(\omega)\right] / F_{\mathrm{R}}(\omega) \tag{1}$$

2.2. Instrumented seat post and brake hood

Using FEA and simulation software, the effect of transducer's vibrational behaviour on the measurement accuracy was determined for instrumented seat post and brake hood (Fig. 2) used for bicycle vibrational transmissibility assessment purposes.

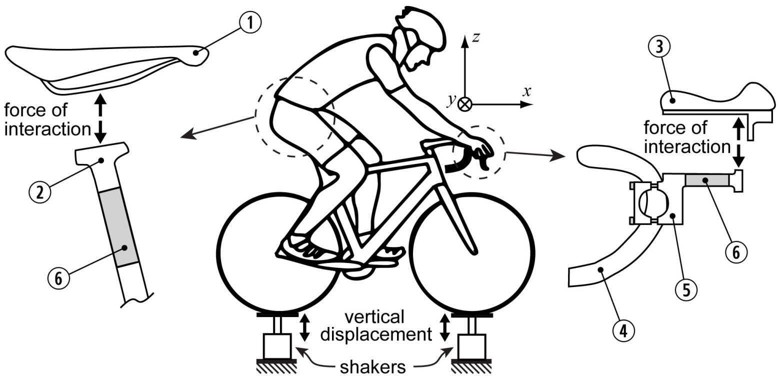

Fig. 2. Road simulator equipped with two shakers for bicycle vibrational transmissibility assessment. The bicycle is equipped with an instrumented seat post and two instrumented brake hoods. 1-saddle; 2-seat post; 3-hand rest; 4-handlebar; 5-brake hood body; 6-strain gauges area.

These transducers measure, for a frequency range of 0 to 100 Hz, the vertical (along the z-axis) force of interaction between the seat post and saddle, and between the brake hood body and the hand rest. They are fitted to a road bicycle which is tested using a laboratory road simulator. In this laboratory setup, a cyclist is seated in a resting position on the bicycle with his hands on the brake hoods. Two shakers apply a vertical displacement excitation to the bicycle's tires. The force of interaction at the seat post and at the brake hood is measured using a total of eight (two full Wheatstone bridges) and four strain gauges (one full Wheatstone bridge) respectively.

3. Results

3.1. Simple beam transducer model – Suspended mass effect

With no suspended mass (M = 0 kg), the real force of interaction is zero at any frequency ($F_{\mathrm{R}}(\omega) = 0$ N, $\forall\omega$). However because of the beam's mass and modal behaviour, $F_{\mathrm{SG}}(\omega)$ is not zero and varies with the frequency as shown in Fig. 3. With a suspended mass of 0.5 kg, $F_{\mathrm{R}}(\omega)$ and $F_{\mathrm{SG}}(\omega)$ are close to one another up to around 20 Hz (Fig. 3), between the first (point *B*) and second bending modes (point *C*). This particular behaviour is a fundamental characteristic of this type of system (i.e. beam with suspended mass and vertical base excitation).

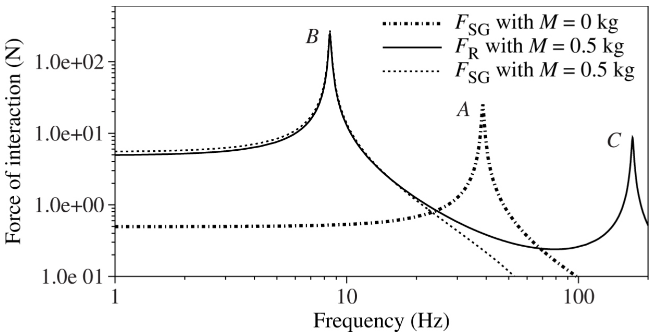

Fig. 3. Force of interaction for the simple beam transducer with suspended mass values of 0 and 0.5 kg.

To help further understand the effect of the suspended mass of on $F_{\mathrm{R}}(\omega)$ and $F_{\mathrm{SG}}(\omega)$, the system's vibrational response for M values of 0.5, 1, 2 and 5 kg was computed. Results for $F_{\mathrm{R}}(\omega)$ and $F_{\mathrm{SG}}(\omega)$ are presented on Fig. 4a. In Fig. 4b, the measurement error $E(\omega)$ is reduced with an increase in the suspended mass. This can be explained by the fact that part of the transducer's own mass can be considered as suspended and therefore has a reduced effect on $F_{\mathrm{SG}}(\omega)$ for higher suspended mass values.

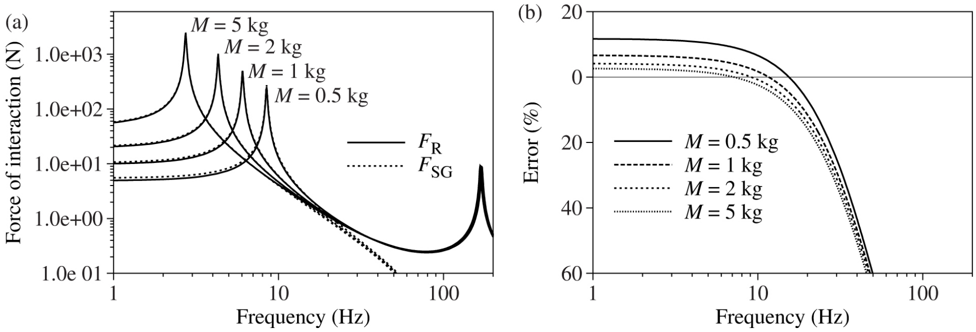

Fig. 4. Force of interaction (a) and measurement error (b) for the simple beam transducer with suspended mass values of 0.5, 1, 2 and 5 kg.

3.2. Simple beam transducer model – Damping effect

The system's damping effect was investigated by computing the system's vibrational response for a suspended mass of 5 kg and for modal damping ratio values of 0.01, 0.05 and 0.1. Results (Fig. 5 and 6) show that the increase in damping reduces the measurement error, $E(\omega)$, before and up to a certain frequency after the first bending mode. Above that frequency, the error increases drastically. When comparing results for damping ratio values of 0.05 and 0.1 to results for a damping ratio value of 0.01, this frequency is 5.7 Hz and 3.6 Hz respectively.

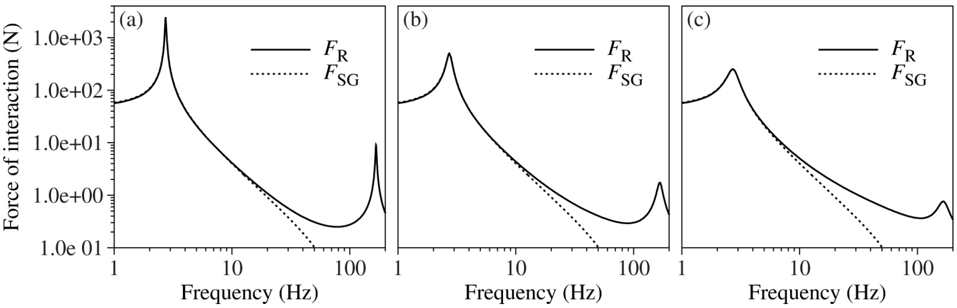

Fig. 5. Force of interaction for the simple beam transducer with suspended mass of 5 kg for modal damping ratio values of (a) 0.01, (b) 0.05 and (c) 0.1.

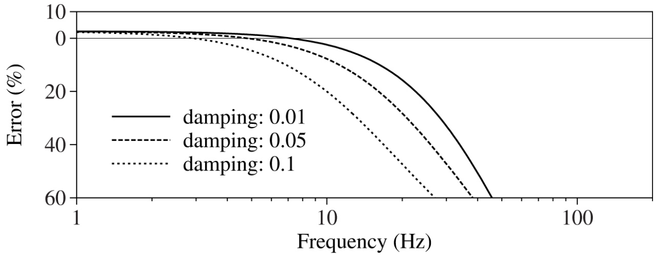

Fig. 6. Measurement error for the simple beam transducer with suspended mass of 5 kg for modal damping ratio values of 0.01, 0.05 and 0.1.

3.3. Instrumented seat post and brake hood

Results for $F_R(\omega)$ and $F_{SG}(\omega)$ for the seat post (M = 30 kg; modal damping ratio: 0.05) and the brake hood (M = 5 kg; modal damping ratio: 0.05) are shown in Fig. 7. For both transducers, $F_{SG}(\omega)$ remains close to $F_R(\omega)$ up to around 500 Hz. The maximum measurement error within the transducers' operational frequency range (0 to 100 Hz) is 0.13% and 2.6% for the seat post and brake hood respectively. Point *A* (Fig. 7) corresponds to the brake hood's first bending mode. Contrary to the simple beam and the brake hood, the seat post is subjected to both transverse and longitudinal excitations because it is inclined relative to the *z*-axis at a 17° angle. Both bending and axial modes of the seat post therefore have a significant influence on the force of interaction measurement. This influence can be observed in Fig. 7 where points *B* and *C* correspond to the first bending mode and the first axial mode respectively.

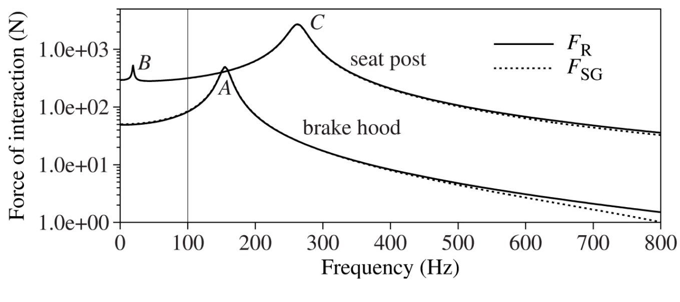

Fig. 7. Force of interaction for the instrumented seat post and brake hood (frequency range: 0 to 800 Hz). The vertical line at 100 Hz corresponds to the upper limit of the operational frequency range of these transducers when they are used for bicycle vibrational transmissibility assessment.

4. Discussion

One of the main conclusions to be drawn from the results presented in this paper is that, in the case of base excitation, the first bending mode has no negative effect on the measurement accuracy. This conclusion may come as some surprise because one of the conventional rules of transducer design is to have a first natural frequency high enough to avoid any dynamic amplification. A study of the first bending mode shape for the simple beam reveals that this shape is analogous to the deformed shape of this beam when it is loaded with a vertical force at the right end. The strain field in both cases is also analogous, and the measurement error, $E(\omega)$, is thus expected to remain relatively small for frequencies below the first bending mode frequency and even in the vicinity of this mode.

The results presented in this paper and those from Caya et al. (2012) allow us to provide the following hints regarding the design of strain gauge transducers to measure dynamic loads in cycling during base excitation.

- Transducer stiffness: The stiffness of the transducer (ex.: instrumented seat post, brake hood or stem) must be as close as possible to that of the standard counterpart it replaces. Fabricating a stiff transducer to push away the first bending mode frequency from the upper limit of the operational frequency range is a design misconception (Caya et al. (2012)).
- Damping: Damping can be a two-edged knife. An increase in damping will be beneficial to the measurement accuracy at frequencies below the first bending mode frequency but detrimental to the measurement accuracy starting at some point between the first and second bending modes.
- Suspended mass vs transducer’s mass: The higher the value of the suspended mass relative to the transducer’s mass, the better the measurement accuracy at any frequency – at least up to the second bending mode.

FEA and simulation software used to predict the effect of a transducer’s vibrational behaviour on measurement accuracy have proved to be valuable tools in the design of the instrumented seat post and brake hood presented in this paper. Both were built and experimentally validated using an impedance head and suspended masses. Future work should focus on other mode types and strain gauge configurations such as the torsion mode in relation to torque measurement.

5. Conclusion

In this study, we have demonstrated that in the case of a base excitation, the transducer’s modal behaviour, the suspended mass and the system’s damping may have a significant effect upon load measurement accuracy. This effect should not be overlooked when designing transducers. We have also shown that the transducer’s first bending mode has no negative effect on the measurement accuracy.

References

Rowe T., Hull, M.L., Wang, E.L., 1998. A Pedal Dynamometer for Off-Road Bicycling. J. Biomech. Eng. 120, 160-164.

Drouet, J.-M, Champoux, Y., Dorel, S., 2008. Development of multi-platform instrumented force pedals for track cycling. In: Estivalet, M., Brisson, P. (Ed.), The Engineering of Sport 7. Springer, Paris, 263-271.

Bolourchi, F., Hull, M.L., 1985. Measurement of Rider Induced Loads During Simulated Bicycling. Int. J. Sport Biomech. 1, 308-329.

Drouet, J.-M., Champoux, Y., 2010. A novel dynamometric hubset stem design to measure wheel loads in road cycling. In: Sabo, A., Kafka, P., Litzenberger, S., Sabo, C. (Ed.), The Engineering of Sports 8, Procedia Engineering 2. Elsevier, 2925-2930.

Drouet, J.-M., Champoux, Y., 2012. Development of a three-load component instrumented stem for road cycling. In: Drane, P. (Ed.), Engineering of Sports Conference 2012, Procedia Engineering 34. Elsevier, 502-507.

Vanwalleghem, J., De Baere, I., Loccufier, M., Van Paepegem, W., 2013. Sensor design for outdoor racing bicycle field testing for human vibration comfort evaluation. Meas. Sci. Technol. 24.

Craig, R.R. Jr, 2000. Mechanics of materials (2nd Ed.). John Wiley & Sons, New York, USA.

Caya, A., Champoux, Y., Drouet, J.-M., 2012. Dynamic behaviour and measurement accuracy of a bicycle brake hood force transducer. In: Drane, P. (Ed.), Engineering of Sports Conference 2012, Procedia Engineering 34. Elsevier, 526-531.

Lépine, J., Champoux, Y. and Drouet, J.-M., 2013. A Laboratory Excitation Technique to Test Road Bike Vibration Transmission. Experimental Techniques. doi: 10.1111/ext.12058