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METHOD FOR INVESTIGATION OF FRICTIONAL PROPERTIES AT IMPACT LOADING

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In the assessment of lubricant performance and also in various other contact applications it is of importance to know the frictional qualities of a surface. Under quasi-static conditions, normal and frictional forces are measured using force transducers but the task is more difficult when loads are transient. The experimental method presented in this paper is based on the analysis of propagating waves in a beam, due to an impact on the end surface. The impact is oblique and therefore a transverse as well as a normal force is generated. The normal force history is measured from the axial non-dispersive wave using strain gauges. Transverse force and bending moment both generate dispersive flexural waves. From the FFT of two transverse acceleration histories, the frictional force at the end of the rod is evaluated using beam theory. The relation between normal and frictional force histories displays the frictional properties at the impact. Preliminary results are presented.

1. INTRODUCTION

Simulation of complex physical and mechanical processes becomes easier to perform as computers and computer codes become more efficient. Reliable results generally demand detailed knowledge of the simulated event regarding material behaviour as well as the physical and mechanical processes involved. Knowledge of material parameters are often lacking, making the results of calculations less confident. In the field of friction and lubrication, the mechanical interaction of two surfaces and a lubricant is studied. The aim of the research in this field is to reduce energy loss and damage in machine elements such as bearings and gears. In such applications elasto-hydro-dynamic (EHD) lubrication is at hand which is characterised by high contact pressures, elastic deformation of the surfaces, lubricant compression and high shear rates. Investigation of EHD-lubrication involves experiments in which frictional properties evaluated from simultaneous normal and transverse forces are studied

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under impact conditions. From the results of such experiments quantitative information regarding lubricant properties can be gained and used in computer simulations.

Experiments on frictional properties of lubricants under different conditions regarding pressure and shear rate and with different methods have been reported by several authors. For example reference [1] used a spinning ball apparatus to investigate friction under slowly varying shear rates, reference [2] used inclined plate impact and reference [3] used high pressure viscosimetry. In none of these methods are the loading times and other conditions the same as those prevailing in practical EHD situations. Reference [4] used the impact of a spinning ball to investigate friction under transient conditions. References [5, 6] developed a test method utilising a steel ball impacting a flat lubricated surface. In these investigations the time-scale is representative for practical EHD situations, but the methods are not capable of recording the time histories of the forces during the impact.

In the present work, a method is suggested that is based on the principle of a steel ball impacting a flat surface and it allows the force histories in the contact to be measured during the impact. The method uses the theory of axial and flexural wave propagation in a straight beam for evaluation of normal and transverse transient forces at the flat end of the beam. The transverse force is obtained from two measured accelerations using spectral analysis. See, for example reference [7].

2. THEORETICAL BACKGROUND

Simultaneous normal and transverse transient forces due to an oblique impact on the end plane of a long rod are considered; see Figure 1. The transverse force, T, is a frictional force and its direction is therefore determined by the velocity vector of the impacting body. Assume that T is parallel to the co-ordinate z. The normal force N is compressive and parallel to the rods axis which is the x co-ordinate. The impact is assumed to be off-centre and therefore a bending moment will be generated. Its component in the y direction is $M = N{\cdot}e$. The transverse force T and the bending moment M generate a flexural wave in the x–

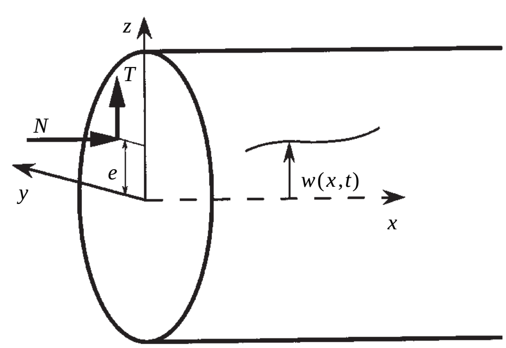

Figure 1. Normal and transverse forces due to an off-axis impact on the plane end of a rod with circular cross-section.

z plane described by the deflection $w(x, t)$ of the centre line of the beam. First order theory is used assuming no interaction between axial and lateral deformation. It is also assumed that a plane 1-D axial wave is generated by the normal force although it is more or less a point force. Furthermore, Euler–Bernoulli beam theory is used in the analysis of the flexural wave. This theory assumes that shear deformation as well as rotational inertia of the rod can be neglected.

The axial wave is ideally non-dispersive and therefore axial strain, ε, measured at a position along the rod represents the normal impact force, N, through the relation

$$N(t) = AE\varepsilon(t + t_0), \tag{1}$$

where A is the cross-sectional area of the rod, E is Young's modulus and t_0 is the travel time for the wave between the end and the cross-section where strain is measured.

The equation of motion in the transverse direction for an Euler–Bernoulli beam, free from distributed loads, is

$$EIw'''' + \rho A\ddot{w} = 0, \tag{2}$$

where $(')$ and $(\dot{})$ denote differentiation with respect to the x co-ordinate and time, respectively. Young's modulus E, area moment of inertia I, density ρ and cross-sectional area A are all constant along the beam. Equation (2) represents a dispersive mechanical system and Fourier-decomposition of the time dependent quantity w is introduced. A general harmonic wave solution of the form $w = C\mathrm{e}^{\mathrm{i}(kx + \omega t)}$ inserted in equation (2) yields the characteristic equation

$$k^4 - \alpha^4\omega^2 = 0, \tag{3}$$

where k is the wave number, ω is the angular frequency and $\alpha^4 = \rho A/EI$. Equation (3) has four solutions for the wave number k of which only two are physically acceptable for an initially quiescent semi-infinite ($x>0$) rod impacted at its end. The final expression for a harmonic component of the transverse displacement is therefore

$$w_h(x, t) = \hat{w}(x, \omega)\,\mathrm{e}^{\mathrm{i}\omega t} = [C_1(\omega)\,\mathrm{e}^{(-\mathrm{i}\alpha\sqrt{\omega})x} + C_2(\omega)\,\mathrm{e}^{(-\alpha\sqrt{\omega})x}]\,\mathrm{e}^{\mathrm{i}\omega t}, \tag{4}$$

where $C_1(\omega)$ and $C_2(\omega)$ are complex constants. The first term in equation (4), having an imaginary wave number, represents a harmonic wave, travelling in the x direction, while the second term having a real wave number represents a non-propagating vibration or a so called evanescent solution. The expression within brackets in equation (4) is the Fourier transform $\hat{w}(x,\omega)$ of the transverse displacement $w(x,t)$. Using the well known relations between transverse displacement and bending moment, shear force and acceleration respectively it is straightforward to derive (from equation (4)) the expressions

$$\hat{M} = EI\hat{w}''(0, \omega) = EI(\alpha\sqrt{\omega})^2[-C_1 + C_2],$$

$$\hat{T} = EI\hat{w}'''(0, \omega) = EI(\alpha\sqrt{\omega})^3[iC_1 + C_2],$$

$$\hat{a}_1 = -\omega^2\hat{w}(x_1, \omega) = -\omega^2[C_1\,\mathrm{e}^{-\mathrm{i}\alpha\sqrt{\omega}x_1} + C_2\,\mathrm{e}^{-\alpha\sqrt{\omega}x_1}] \tag{5}$$

$$\hat{a}_2 = -\omega^2\hat{w}(x_2, \omega) = -\omega^2[C_1\,\mathrm{e}^{-\mathrm{i}\alpha\sqrt{\omega}x_2} + C_2\,\mathrm{e}^{-\alpha\sqrt{\omega}x_2}],$$

from which the complex constants C_1 and C_2 can be eliminated. Thus, from the Fourier transforms of the two measured acceleration histories $a_1(t)$ and $a_2(t)$ in the z direction at two positions x_1 and x_2, the Fourier transforms of the bending moment and the transverse force caused by the impact can be determined. It is convenient to choose $x_1 = 0$ and from the expressions in equations (5), elimination of C_1 and C_2 gives

$$\hat{M} = \frac{EI\alpha^2}{\omega(n-m)}[2\hat{a}_2 - (n+m)\hat{a}_1], \tag{6}$$

$$\hat{T} = \frac{-EI\alpha^3}{\sqrt{\omega}(n-m)}[(i+1)\hat{a}_2 - (in+m)\hat{a}_1], \tag{7}$$

where $n = \mathrm{e}^{-\alpha\sqrt{\omega}x_2}$ and $m = \mathrm{e}^{-\alpha\sqrt{\omega x_2}}$, for the two quantities (M and T) that generate the flexural wave in the beam. The time functions are easily found by inverse Fourier transformation of equations (6) and (7). $T(t)$ is the desired time history of the frictional force caused by the oblique impact.

3. EXPERIMENTS

3.1. SET-UP

In Figure 2 the experimental set-up is shown. A cylindrical steel rod (SIS 1650) with diameter 16 mm and length 5 m hangs vertically with its lower end free. Normal and transverse forces from an off axis impact on the lower end surface generate longitudinal and flexural waves in the rod. Both the transverse force and the bending moment contribute to the flexural wave if the impact is not in the centre of the cross-section.

At a position 100 mm from the end of the rod a pair of strain gauges, coupled in a Wheatstone-bridge for bending suppression, measures the axial strain history. After amplification this signal is recorded and used to calculate the normal impact force $N(t)$ according to equation (1).

Lateral acceleration in the direction of the frictional force (z direction) is measured at two positions using identical piezoelectric accelerometers (B&K 4393). One accelerometer is located as close to the end as possible and the other at a position 33.5 mm along the rod. Two identical charge amplifiers (B&K 2635) are used and the signals are recorded by a transient recorder (YOKOGAWA DL4100) using a sampling rate of one sample per microsecond

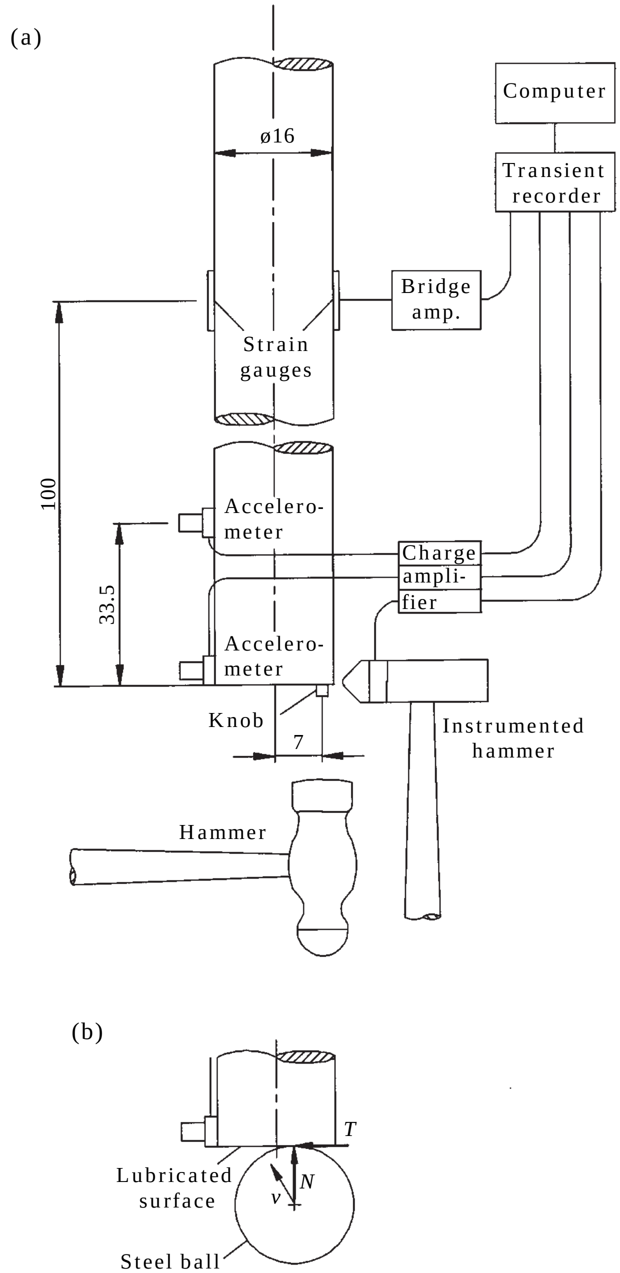

Figure 2. Experimental set-up: (a) for calibration and (b) for impact measurement.

and a record length of 10 000 samples. The software MATLAB 5.0 is used for data analysis including a 10 000 point FFT and inverse FFT. The moment and the transverse force at the end of the rod are calculated from the measured accelerations according to equations (6) and (7).

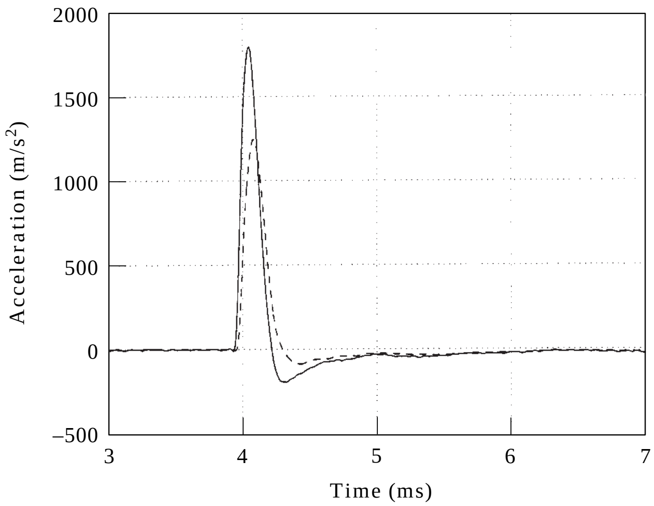

Figure 3. Measured acceleration signals: —, a_1 ($x = 0$); - - -, a_2 ($x = 33{\cdot}5$).

3.2. MEASUREMENTS AND RESULTS

An instrumented hammer is used for verification of the evaluation procedure. The impact force from the hammer is measured with a piezoelectric force transducer (B&K 8200) mounted in the head of the hammer. The sensitivity of the transducer, taken from the manufacturers calibration chart, is 4 pC/N and the signal from the hammer is amplified (B&K 2635) and recorded. A transverse impact at a point diametrically opposite the accelerometers (Figure 2(a) is suitable for verification of the evaluation model, equation (7). The two measured acceleration histories from a transverse impact by the instrumented hammer are shown in Figure 3 and it is noted that there is a difference in the histories due to the different positions of the accelerometers. In Figure 4 measured and evaluated

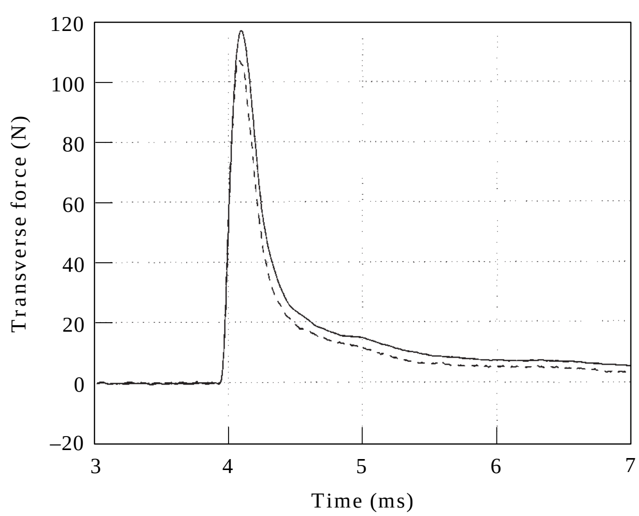

Figure 4. Measured and evaluated transverse force: —, evaluated; - - -, measured.

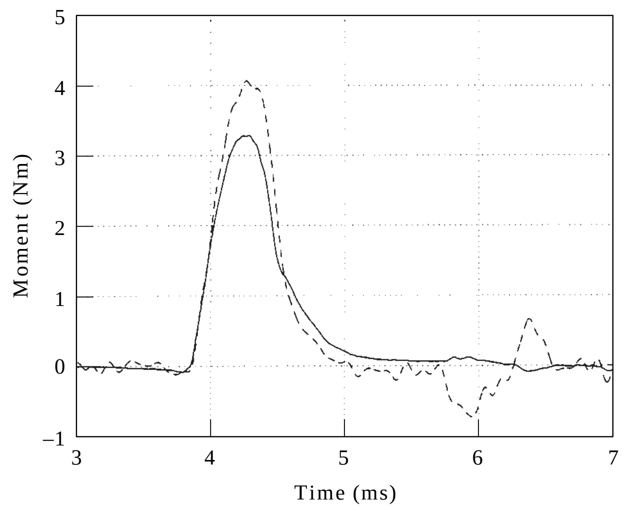

Figure 5. Measured ($N{\cdot}e$)and evaluated bending moment: —, evaluated; - - -, measured.

force histories are shown. The shape of the curves representing measured and evaluated transverse forces show good coincidence but their levels differ slightly.

In order to verify also the calculated end moment, an experiment was performed where a small knob, placed 7 mm from the centre of the rod, was impacted in the axial direction by a hard strike from an ordinary hammer (Figure 2(a)). The instrumented hammer could not be used because the required force was beyond its capacity (the hammer was however used to calibrate the strain gauges that measure axial force). With known eccentricity, the applied end moment is given by the axial force history. The moment is also evaluated according to equation (6), and in Figure 5 the two time histories are shown. The difference in shape and level is larger than it is for the transverse force.

A preliminary experiment regarding friction at impact on the flat, ground and polished end surface of the rod was also performed in order to verify the potential of the method. A 50-mm steel ball from a roller bearing was used to impact the surface at an oblique angle (Figure 2(b)). The ball was held by hand and the impact was directed in the z direction. The normal force history was measured by the strain gauges and the transverse force was evaluated from the accelerometer signals. Thus, simultaneous normal and transverse force histories were determined and the frictional properties during the impact could be studied. Results for a non-lubricated and a lubricated surface are presented in Figure 6. Transverse force is plotted versus normal force for an impact with dry and clean surfaces and for an impact where the flat surface is lubricated with a grease (Mobilith SHC 460). The contact time is about 300 μs, for the impacts. It is obvious from the graphs, that the relation between the transverse and normal force depends on the surface condition. Also it is observed that, for the dry contact, the frictional coefficient defined as the quotient between transverse and normal force appears to vary during the impact. However, this has to be investigated in a series of repeated experiments and is the subject for future work.

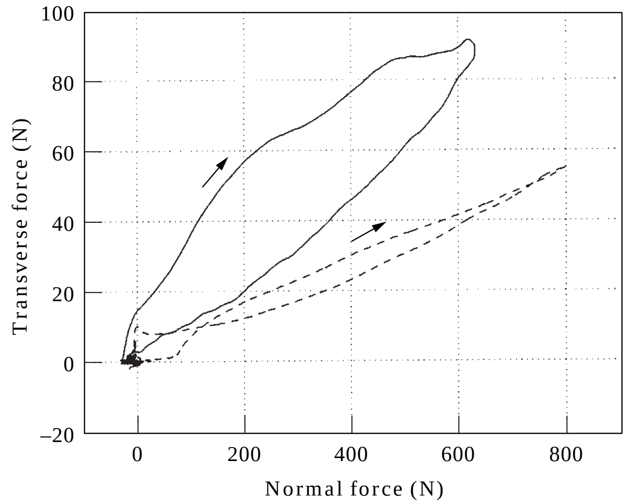

Figure 6. Transverse versus normal force during a dry and a lubricated impact: —, dry impact; - - -, lubricated impact. The arrows indicate increasing time.

4. DISCUSSION AND CONCLUSIONS

Theoretical background and preliminary experimental verification is presented for a method that allows simultaneous measurement of transverse and normal forces due to impact on the end of a straight beam. Also the end moment due to off axis impact can be calculated, but is only of secondary interest. The method is based on the relation between transverse accelerations of points along the beam, and the generating quantities at the impacted end.

The transverse equation of motion according to Euler–Bernoulli beam theory has been used in the analysis. Accordingly neither shear deformation nor rotational inertia of the beam is considered, and it is believed that at least rotational inertia is of importance because of the high frequency components generated by an impact. Also the inertia of the accelerometers is neglected in the evaluation model at present. Both these effects can be included in the model.

The intention is to use the method for friction investigations and it is therefore important that the transverse force can be measured accurately. It is observed from Figure 4 that the form of the calculated force history agrees well with that of the measured. A rigorous calibration of the instrumented hammer could not be performed, and therefore the disagreement in the levels of about 10% may not be significant.

A bending moment at the end of the rod is generated if the impact is not perfectly centred, which contributes to the flexural motion. Cancellation of this contribution is essential for an accurate evaluation of the transverse force, while the moment in itself is not of primary interest. The curves in Figure 5 show that the form of the predicted moment history agrees well with the measured one but that the level is some 20% lower. A source of error is that the accelerometers are to some degree sensitive to acceleration in the perpendicular direction causing disturbances from the axial acceleration to superpose the transverse measurement.

The relations shown in Figure 6 are results from two preliminary friction experiments and the difference between dry and lubricated friction is obvious. The form of the curves indicates that friction conditions for a dry steel surface contact change during the loading and unloading sequence, so that the friction coefficient decreases. A possible physical explanation may be that generated heat lowers the strength of the asperities in contact. In the case of a lubricated contact no such change in friction conditions is noticed. These preliminary observations are however yet to be verified.

It should also be pointed out that in principle other quantities related to flexural deformation than acceleration (velocity, displacement or strain) could also be used for evaluation of transverse force. Acceleration is however best suited for FFT analysis since it is of transient character and falls to zero immediately after the event. The natural frequency of the accelerometers is a limiting parameter and should be as high as possible.

From the result of this preliminary investigation it is concluded that: (i) the suggested method is capable of simultaneous measurement of normal and transverse forces during an impact event; (ii) the achieved accuracy is encouraging; (iii) a more exact evaluation model in combination with optimally chosen parameters for the beam may improve the accuracy further; and (iv) friction phenomena can be studied with this method.

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