Highlights

Considerations regarding geometric judder in multiplate clutch systems

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- Research highlights item 1
- Research highlights item 2
- Research highlights item 3

Considerations regarding geometric judder in multiplate clutch systems

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ABSTRACT

judder in plate clutch in MBS simulation. characteristic of plate clutch and relevant dynamic phenomenon: many contacts, surface deviations after production.
\beginabstract ...\endabstract and \begin{keyword} ... \end{keyword} which contain the abstract and keywords respectively.
Each keyword shall be separated by a \sep command.

1. Introduction

Cost savings in automotive industry, consequences from production deficiencies, vibration phenomena elimination. Different vibration phenomena lead to increased costs. Criterion at end of line testing with clear thrash limits. Avoid driver complaints.
Acoustic problems due to follower loads of the sliding contact can originate e.g. from the wobbling Eigenmode [5, 18], clutch-gear-interaction [14], elasticity of the contact surface [8, 13]. Here: the low-frequency torsional vibration problem adressed, also called judder [16].
Three types of judder can be distinguished, namely, friction induced, pressure induced, geometrically induced [4]. All have in common: in sliding phase (launch, shift). It lead to torsional vibrations at low frequency which can be critical regarding drivetrain resonance and be felt by driver. Friction induced: sliding friction coefficient's speed dependency [9, 15], negative gradient, negative contribution to damping. This is an instability. Pressure induced: whenever actuation piston vibrates axially, it modifies the torque, thus, torsional vibrations. External excitation. Geometric excitation: geometrical deviations of the sliding surfaces modulate the local normal pressure, then local frictional torque is modified. In this paper adressed. Nature of the problem: external excitation, and it is impossible to extinct it. Only reduce.(surfaces never flat because of production). The less surface deviations and the better the material homogenity (i.e., high production quality), the less vibration excitation.
Frequency: integer slip multiples. At clutch close, any Eigenmode can be excited because the excitation is at slip multiples and base frequency decays toward zero. Therefore critical. Here: considerations about how to obtain low judder values. This is an optimization problem [1, 3, 7] which can only be tackled by arranging the production deficiancies in an appropriate manner.
Measurement difficulty with plate clutch: very bad reproducibility. Probable reason: many contacts, many uncertainties. Many measurements necessary for profound understanding of influence parameters. Therefore a non-trivial question for experimental investigations [10]
In this contribution, a simulation which reproduces measurement quality (reproducibility, parameter influences, some dependencies). Then Monte-Carlo simulation and evaluation. [2, 6, 11, 12].

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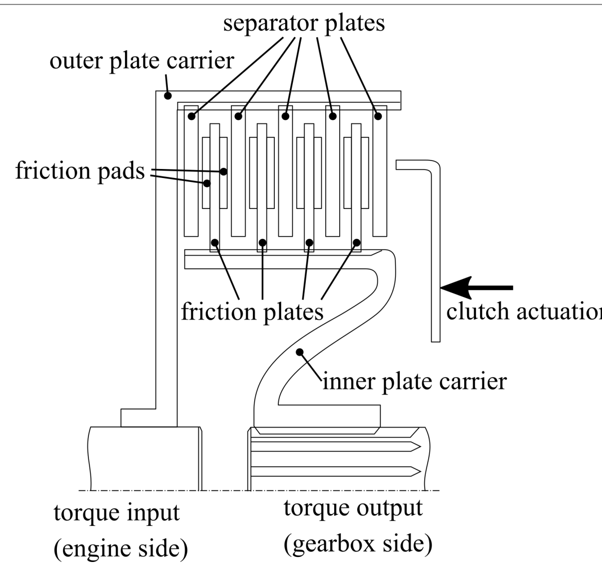

Figure 1: Design elements of plate clutch.

2. Multiplate clutch system description

2.1. Design

Multiplate clutch can be situated in a transmission, separator, ... The design regarding judder has a uniform description: components of a multiplate clutch are friction plates, separator plates, piston, outer plate carrier (OPC) and inner plate carrier (IPC). (Fig. 1). Plate carriers are connected with torque input (engine) and ouput (gearset, ...), rotate about an inertial-fixed axis. Plates mounted by spline on plate carriers, can move axially and have slight play due to clearance (Fig. 2). Contact pads on friction plates for defined contact area; pad geometry is the secret of the plate

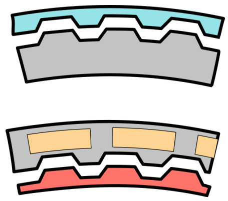

Figure 2: tooth contact geometry.

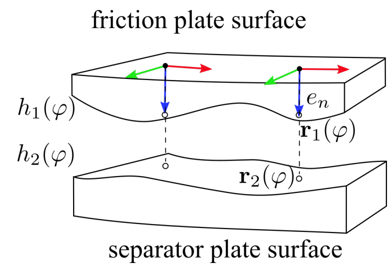

Figure 3: Rough surface contact kinematics (simplified).

manufacturer. Piston pushes plates in axial direction, which leads to torque transmission.

2.2. Flank contact description

There are n_o and n_i tooth contacts. Contact kinematics as in textbooks [19], applied for the rigid tooth geometry. Equal distribution. Implementation: point-plane contact. starting from body-fixed center, the coordinate is

$$\boldsymbol{r}_f^{\mathcal{I}} = r_{pitch}\boldsymbol{e}_r^{\mathcal{B}}\left(\varphi_{left}\right) \tag{1}$$
$$\boldsymbol{e}_{n,f}^{\mathcal{B}} = \boldsymbol{R}\boldsymbol{r} \tag{2}$$
$$\boldsymbol{v}_f^{\mathcal{B}} = \boldsymbol{v}_s^{\mathcal{I}} + \boldsymbol{\omega}^{\mathcal{B}} \times \boldsymbol{r}_f \tag{3}$$
$$\boldsymbol{v}_{T,f}^{\mathcal{B}} = \boldsymbol{v}_f^{\mathcal{I}} - \left(\boldsymbol{v}_f^{\mathcal{I}} \cdot \boldsymbol{e}_{n,f}^{\mathcal{B}}\right)\boldsymbol{e}_{n,f}^{\mathcal{B}} \tag{4}$$

gap function [19]

$$g = \left(\boldsymbol{r}_f^{\mathcal{I}} - \boldsymbol{r}_f^{\mathcal{I}}\right) \cdot \boldsymbol{e}_{n,f}^{\mathcal{B}} \tag{5}$$
$$\dot{g} = \left(\boldsymbol{v}_f^{\mathcal{I}} - \boldsymbol{v}_f^{\mathcal{I}}\right) \cdot \boldsymbol{e}_{n,f}^{\mathcal{B}} \tag{6}$$

local normal force and friction force (regularized [17])

$$\boldsymbol{f}_n = \begin{cases} (cg + d\dot{g})\boldsymbol{e}_n & cg + d\dot{g} \leq 0 \\ 0 & \text{else} \end{cases} \tag{7}$$
$$\boldsymbol{f}_t = \mu|f_n| reg(v_t)\boldsymbol{e}_t \tag{8}$$

with $reg(\cdot)$ the regularization of $sign(\cdot)$. The piecewise definition of the normal force represents the gap. These force act on the plate COM:

$$f = \sum f_n + f_t \tag{9}$$
$$t = \sum r_{f,i} \times \left(f_n + f_t\right) \tag{10}$$

2.3. Pad contact description

surface parametrization: contact ring with circular thickness distribution. Assumption: no "waviness", i.e., height profile symmetric on both contact sides

$$\boldsymbol{r}_i = r\boldsymbol{e}_r + h\boldsymbol{e}_z \tag{11}$$
$$h = h_0 + \sum_{k=11}^{n} h_k \cos\left(k\varphi - \beta_k\right) \tag{12}$$

Because of the periodicity, the surface can be approximated by a Fourier series, which is generated out of geometric measurements, has the advantage of an analytic formula for the surface parametrization.

gap function [19] at angle φ and normal velocity

$$g(\varphi) = \left(\boldsymbol{r}_2 - \boldsymbol{r}_1\right) \cdot \boldsymbol{e}_n \tag{13}$$
$$\dot{g}(\varphi) = \left(\boldsymbol{v}_2 - \boldsymbol{v}_1\right) \cdot \boldsymbol{e}_n \tag{14}$$

projection on analytical formula ensures that there is no rattling effect due to mesh change. distributed friction forces: regularized, no tensile forces

$$\boldsymbol{f}_N = f_n(g)\boldsymbol{e}_n \approx c_n g\boldsymbol{e}_n \tag{15}$$
$$\boldsymbol{f}_T = \mu|\boldsymbol{f}_N|\boldsymbol{e}_t \tag{16}$$

There is no need for transition modeling between slide and stick, as only sliding states are considered in the simulation. Result is the integral (sum) of all contact forces on the distributed contact.

$$f = \sum f_n + f_t \tag{17}$$
$$t = \sum r_{f,i} \times \left(f_n + f_t\right) \tag{18}$$

2.4. MBS

Finally, dynamic system equations are obtained in a MBS implementation. The model structure is as follows: 4 friction plates (pad friction, tooth friction), 5 steel plates (pad friction, tooth friction), piston, opc Piston has tilting DoF and given axial displacement Set of equations has the following structure

$$M\ddot{q} + f_{ij}(q) = 0 \tag{19}$$
$$M\ddot{q} + f_{ij}(q) = 0 \tag{20}$$

2.5. Boundary conditions

particular role: piston boundary condition

3. Simulation settings

stochastic influences from surface distributions are obvious. Main randomness contributors: plate mount orientation, initial conditions, friction coefficient. In addition, material inhomogeneity, ...

according, simulation setup: randomness in friction coefficient, normal stiffness, plate orientation, initial coefficients.

Stochastic

4. Linear regression analysis

5. Further regression analysis methods

6. Conclusion

Boundary conditions importance: softness of actuation is important regarding intensity.
Friction coefficient between plates and plate carriers: stochasticity and intensity. Mainly in force model.
Initial conditions: stochasticity, but not as influent as friction coefficient.

7. Introduction

The Elsevier cas-dc class is based on the standard article class and supports almost all of the functionality of that class. In addition, it features commands and options to format the

- document style
- baselineskip
- front matter
- keywords and MSC codes
- theorems, definitions and proofs
- lables of enumerations
- citation style and labeling.

This class depends on the following packages for its proper functioning:

1. natbib.sty for citation processing;
2. geometry.sty for margin settings;
3. fleqn.clo for left aligned equations;
4. graphicx.sty for graphics inclusion;
5. hyperref.sty optional packages if hyperlinking is required in the document;

All the above packages are part of any standard LaTeX installation. Therefore, the users need not be bothered about downloading any extra packages.

8. Front matter

The author names and affiliations could be formatted in two ways:

(1) Group the authors per affiliation.
(2) Use footnotes to indicate the affiliations.

See the front matter of this document for examples. You are recommended to conform your choice to the journal you are submitting to.

Figure 4: The evanescent light - $1S$ quadrupole coupling ($g_{1,l}$) scaled to the bulk exciton-photon coupling ($g_{1,2}$). The size parameter kr_0 is denoted as x and the PMS is placed directly on the cuprous oxide sample ($\delta r = 0$, See also Table 1).

9. Floats

Figures may be included using the command, `\includegraphics` in combination with or without its several options to further control graphic. `\includegraphics` is provided by graphic[s,x].sty which is part of any standard LaTeX distribution. graphicx.sty is loaded by default. LaTeX accepts figures in the postscript format while pdfLaTeX accepts *.pdf, *.mps (metapost), *.jpg and *.png formats. pdfLaTeX does not accept graphic files in the postscript format.

The `table` environment is handy for marking up tabular material. If users want to use multirow.sty, array.sty, etc., to fine control/enhance the tables, they are welcome to load any package of their choice and cas-dc.cls will work in combination with all loaded packages.

Table 1
This is a test caption. This is a test caption. This is a test caption. This is a test caption.

Col 1	Col 2	Col 3	Col4
12345	12345	123	12345
12345	12345	123	12345
12345	12345	123	12345
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12345	12345	123	12345

10. Theorem and theorem like environments

cas-dc.cls provides a few shortcuts to format theorems and theorem-like environments with ease. In all commands the options that are used with the `\newtheorem` command will work exactly in the same manner. cas-dc.cls provides three commands to format theorem or theorem-like environments:

```
\newtheorem{theorem}{Theorem}
\newtheorem{lemma}[theorem]{Lemma}
```

```
\newdefinition{rmk}{Remark}
\newproof{pf}{Proof}
\newproof{pot}{Proof of Theorem \ref{thm2}}
```

The `\newtheorem` command formats a theorem in LaTeX's default style with italicized font, bold font for theorem heading and theorem number at the right hand side of the theorem heading. It also optionally accepts an argument which will be printed as an extra heading in parentheses.

```
\begin{theorem}
 For system (8), consensus can be achieved with
 $\|T_{\omega z}$ ...
   \begin{eqnarray}\label{10}
   ....
   \end{eqnarray}
\end{theorem}
```

Theorem 1. *For system (8), consensus can be achieved with* $\|T_{\omega z}$ ...

$$....\tag{21}$$

The `\newdefinition` command is the same in all respects as its `\newtheorem` counterpart except that the font shape is roman instead of italic. Both `\newdefinition` and `\newtheorem` commands automatically define counters for the environments defined.

The `\newproof` command defines proof environments with upright font shape. No counters are defined.

11. Bibliography

Two bibliographic style files (`*.bst`) are provided — model1-num-names.bst and model2-names.bst — the first one can be used for the numbered scheme. This can also be used for the numbered with new options of natbib.sty. The second one is for the author year scheme. When you use model2-names.bst, the citation commands will be like `\citep`, `\citet`, `\citealt` etc. However when you use model1-num-names.bst, you may use only `\cite` command.

`thebibliography` environment. Each reference is a `\bibitem` and each `\bibitem` is identified by a label, by which it can be cited in the text:

In connection with cross-referencing and possible future hyperlinking it is not a good idea to collect more that one literature item in one `\bibitem`. The so-called Harvard or author-year style of referencing is enabled by the LaTeX package natbib. With this package the literature can be cited as follows:

- Parenthetical: `\citep{WB96}` produces (Wettig & Brown, 1996).
- Textual: `\citet{ESG96}` produces Elson et al. (1996).
- An affix and part of a reference: `\citep[e.g.][Ch. 2]{Gea97}` produces (e.g. Governato et al., 1997, Ch. 2).

In the numbered scheme of citation, `\cite{<label>}` is used, since `\citep` or `\citet` has no relevance in the numbered scheme. natbib package is loaded by cas-dc with `numbers` as default option. You can change this to author-year or harvard scheme by adding option `authoryear` in the class loading command. If you want to use more options of the natbib package, you can do so with the `\biboptions` command. For details of various options of the natbib package, please take a look at the natbib documentation, which is part of any standard LaTeX installation.

A. My Appendix

Appendix sections are coded under `\appendix`.

`\printcredits` command is used after appendix sections to list author credit taxonomy contribution roles tagged using `\credit` in frontmatter.

CRediT authorship contribution statement

Georg Jehle: Conceptualization of this study, Methodology, Software. **Mingan Jiang:** Data curation, Writing - Original draft preparation.

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