COUNTERING RECIPROCAL FORCES IN STEAM LOCOMOTIVE DRIVE MECHANISMS

A balanced approach

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Introduction

Apologies for the change of subject: centrifugal forces left out …

But then these are not that interesting, as total cross-balancing them is unproblematical (though not always practiced till the very end of steam)

→

One main subject here: *sway & surge caused by 2 cylinder steam locomotive engines & what to do about it*, including practical recommendations for actual locomotives / projects

(Chapelon still in 1938: "A subject shrouded in obscurity since 1849": may not really change today but still …)

Introduction

https://www.google.com/search?client=firefox-b-d&q=9f+steam+locomotive+footplate+ride#fpstate=ive&vld=cid:3b160cc4,vid:ZRz1Un-zUlI,st:0

from 3:50

https://www.youtube.com/watch?v=GPCm3uNgHlY&t=602s

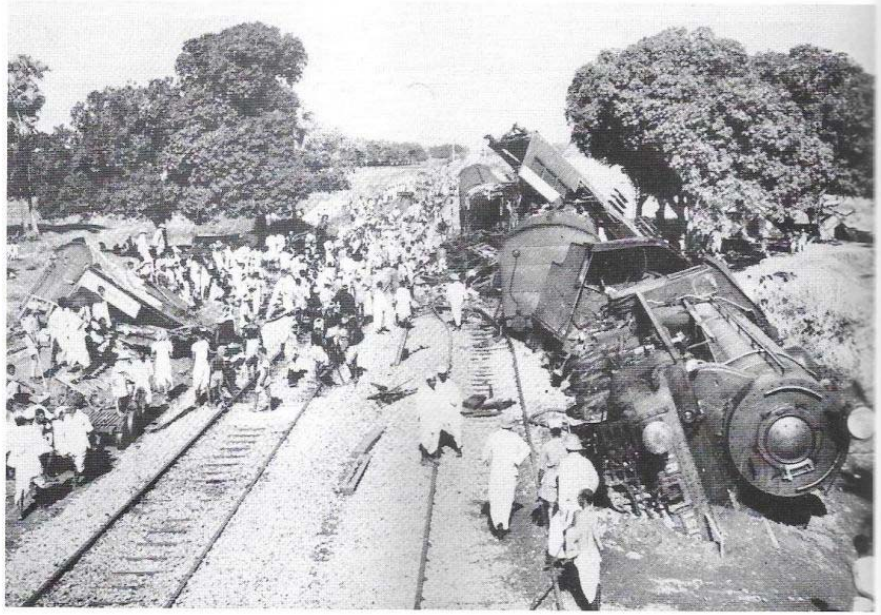
Introduction

Historical importance of the problem: great majority of ± 660,000 steam loco's built were / are 2 cyl engines → kept more than some people awake underway (& at drawing boards)

+ engine & track wear, incl. frame fatigue, reduction of mechanical efficiency (energy "used up" in parasitic movement + in extra friction within engine en between loco & rail)

+ worse:

Introduction



Scene of devastation. In the small hours of the 17th of July 1937 East Indian Railway XB No 1916 (later Northern Railway 22170) from Jhaja depot left the rails at Bihta on the EIR main-line from Mughal Sarai to Howrah; the train, 18 down *Punjab Express* was travelling at considerable speed. This train was normally a 4-6-0 working because it had already been established that the XBs were unstable at high speeds and they had been restricted to 45mph. This particular XB had already been reported for "hunting" but had to provided because a large number of Jhaja depot's 4-6-0s were under repair. The combination of the instability of the locomotive, recent repairs to the track and wooden-bodied coaches resulted in 107 deaths and 117 serious injuries. The picture was taken later during the morning of the crash, the train comprised ten bogie vehicles, the first five were telescoped and reduced to matchwood, the next two were derailed but without casualties and the last three remained on the rails. The locomotive does not appear to have been very badly damaged and the crew suffered no serious injuries. Following much research, including an official enquiry, modifications were made, inter alia, to the bogie pivots, trailing truck including removal of the Cartazzi inclined slides, substitution of existing drawgear and stiffening of main frames. As modified, engines of classes XA, XB and XC lasted until the early 1980s.

Introduction

Indian derailment probably caused by other & related factors as well: vibrations at critical speeds, related to spring / suspension issues, insufficient straight line stability (malfunctioning leading bogie &c.), wheelrim taper, track straightness, permanent way stability, …

(Part of this to be discussed later on)

Introduction

Sway & surge caused by: pistons, piston rods, crossheads &c. + parts of connecting rods not yet moving in circles but "to & fro", impairing unwanted longitutional & lateral movement to the engine unless

a. more or less compensated for (counterweights, more cylinders, …),

b. The whole of the engine is made "unmovable" some or other way (apart from moving in the right direction)

This presentation's objective: **integration of a** ("internal" approaches) **& b** ("external" approaches)

State of the art

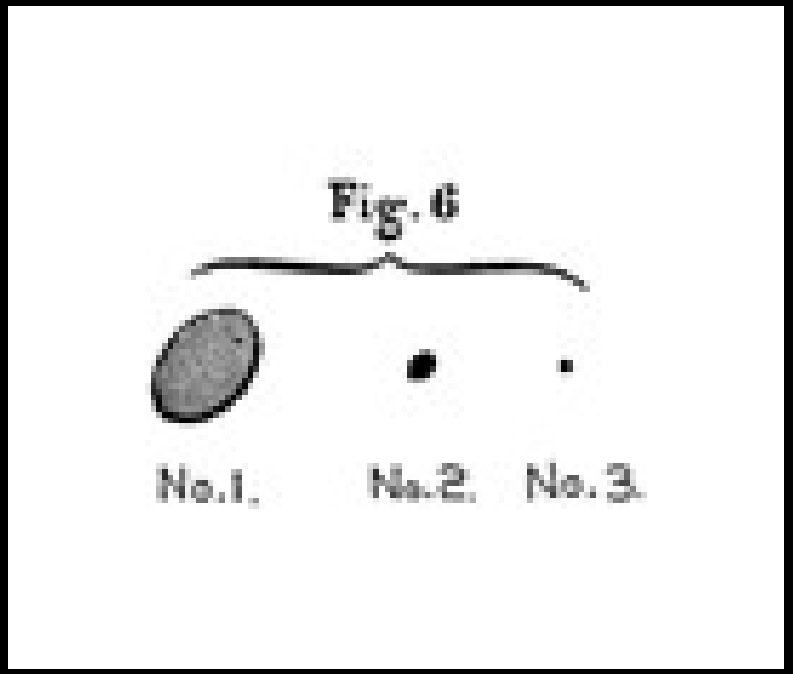
L. Lechatelier, *Etudes sur la Stabilité des Machines Locomotives en Mouvement* (1849): the first & final complete analysis of the "internal" reciprocal force issue, popularised in the English speaking world by D.K. Clark in *Railway Machinery* (1855) (+ Nollau in Germany)

L.H. Fry, "Locomotive Counterbalancing" + discussion (1933) (on cross balancing & back again)

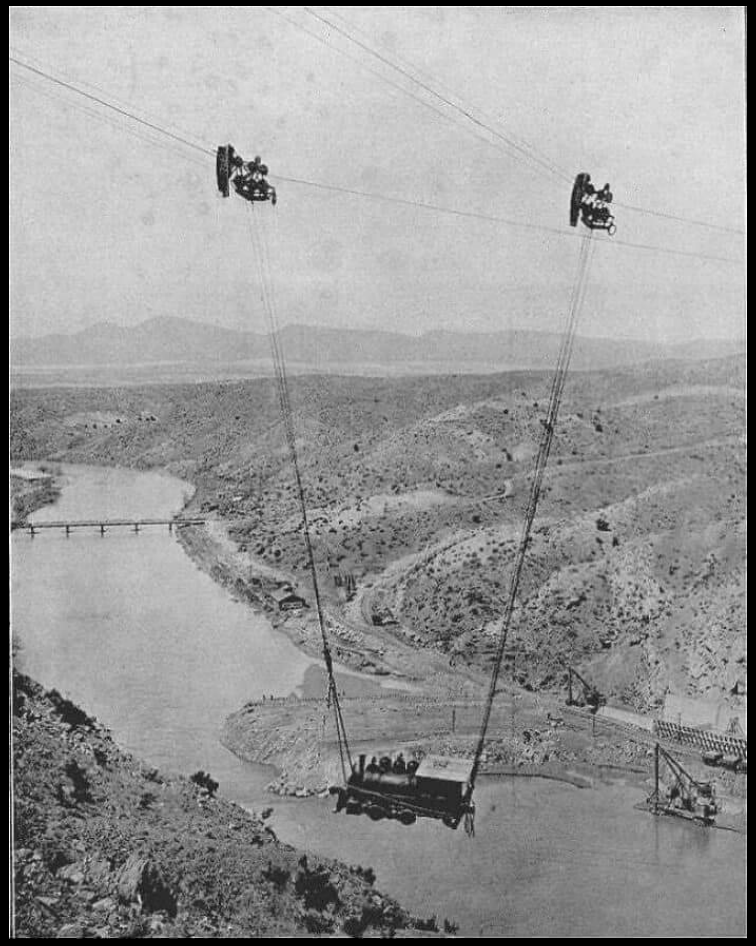
J.M. Jarvis on balancing of BR Class 9 2-10-0 locomotives (1951 f.): "surge only"

No relationship to speed

Results of no, partial & complete Balancing as measured by Lechatelier on a freely suspended locomotive: no relationship to speed



Lechatelier's suspended locomotive



Overview

1. Radical solutions: no steam cylinders at all / more than 2 cylinders &c.: marginal / unworkable / no longer relevant, so:
2. Analysis of the 2 outside cyl issue (mass v. gas v. other forces &c.)
3. (a.) "Internal" remedies: counterweights, weight ratios &c.
4. (b.) "External" remedies: "fixing the engine to the track"
5. Practical recommendations (for Clan rebuild, SR Pacific, possibly Revolution, …)

Radical solutions

3 & 4 cyl loco's:

3 cyl with relatively stronger sway compared to 2 cyl with equal reciprocating weight & outside cylinder distance but then (subjectively) much better riding, with no surge at all

4 cyl still much better on paper

But then extra complication → not very popular … (But then e.g. Düring: rather lower driving mechanism maintenance costs of *Länderbahn* 4 cyl compounds compared to 2 cyl *Einheitslokomotiven*)

Radical solutions

Fishy approach: get a fake 4 cyl out of a 2 cyl engine by adding *saumon* (salmon), to *Nord* 141TC: (like 19th century bob weights)

Radical solutions

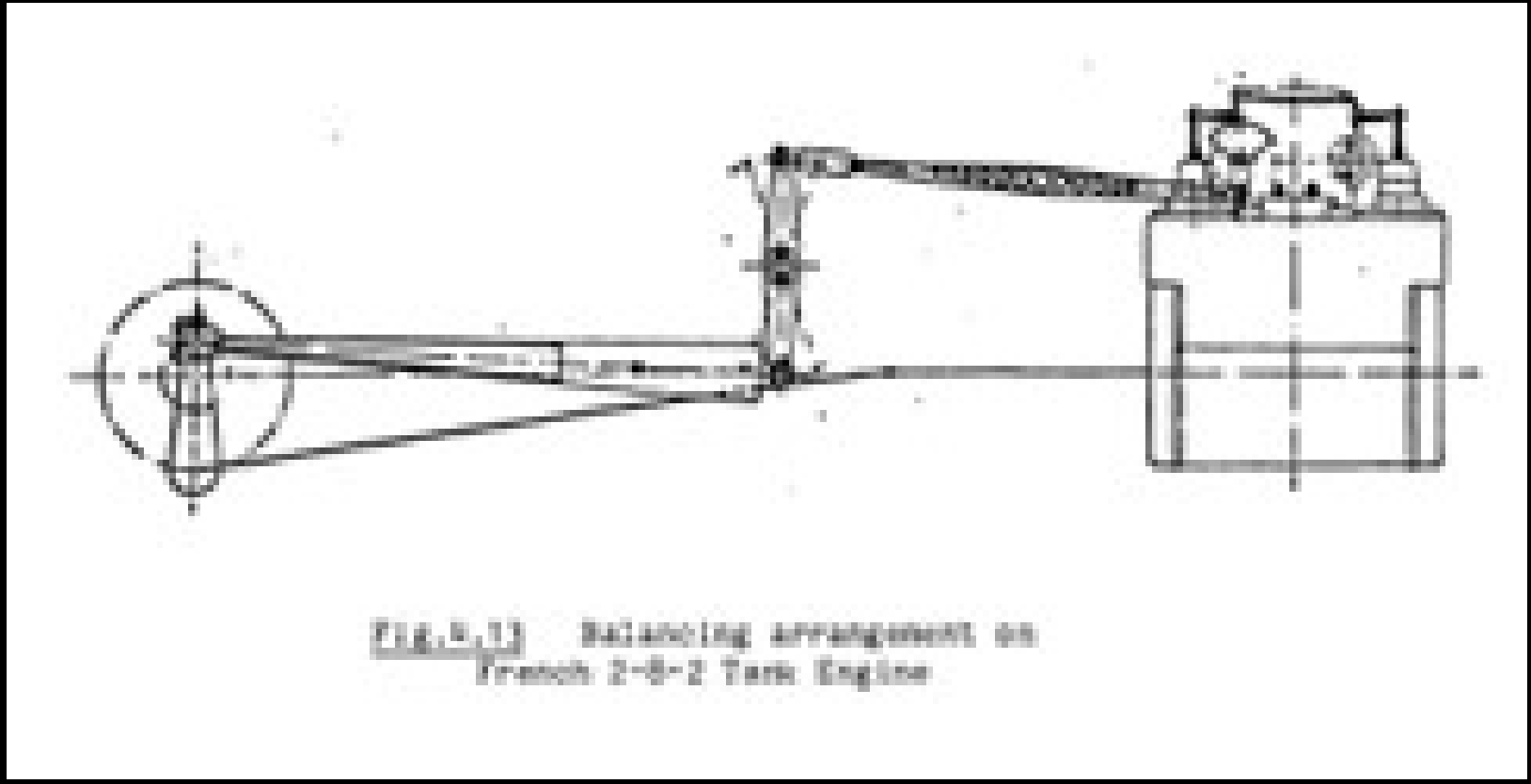


Fig. 5.13 Balancing arrangement on French 2-8-2 Twin Engine

Radical solutions

Worked well (compensating up to ± 50% of reciprocating driving mechanism masses, with no valve gear to be dealt with), but then unduly loaded driving wheel / axle bearings & axleboxes against reciprocating forces loading cylinder covers by compression (desirable apart from this issue)

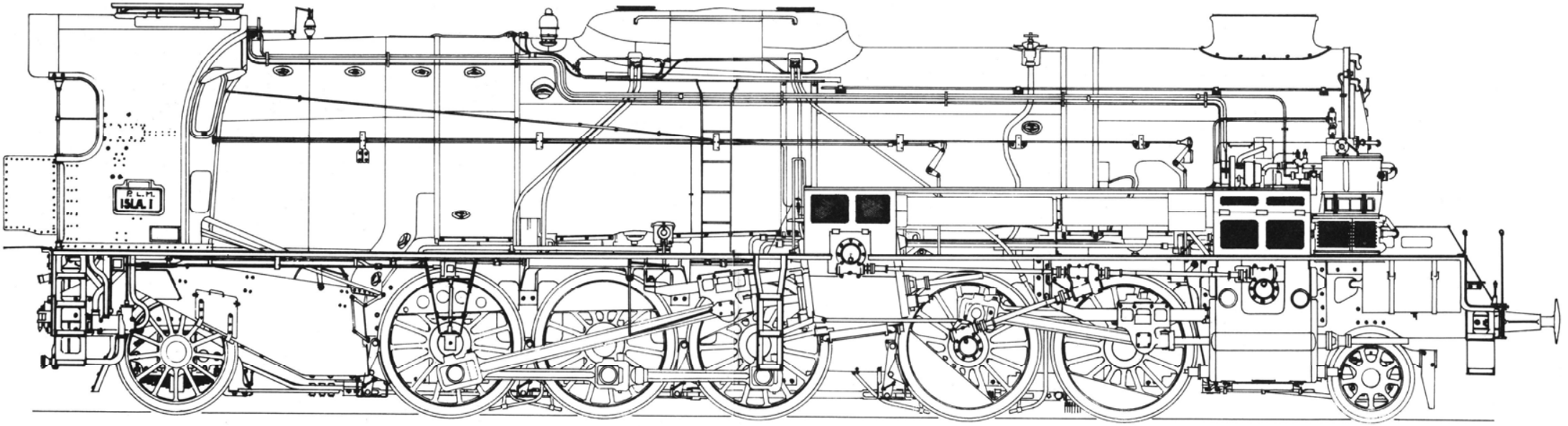
→

Need for partly stronger & thus heavier mechanisms …

(Rotating counterweights against reciprocal forces normally divided over all driving & coupled axles)

Radical solutions

The perfect 4 cyl engine (successful PLM 151A, 1932, // ACE 3000):



Radical solutions

+ varieties of duplex drives: Mallet, articulated, Garratt + like, divided drive à la PRR S1 & Co., …

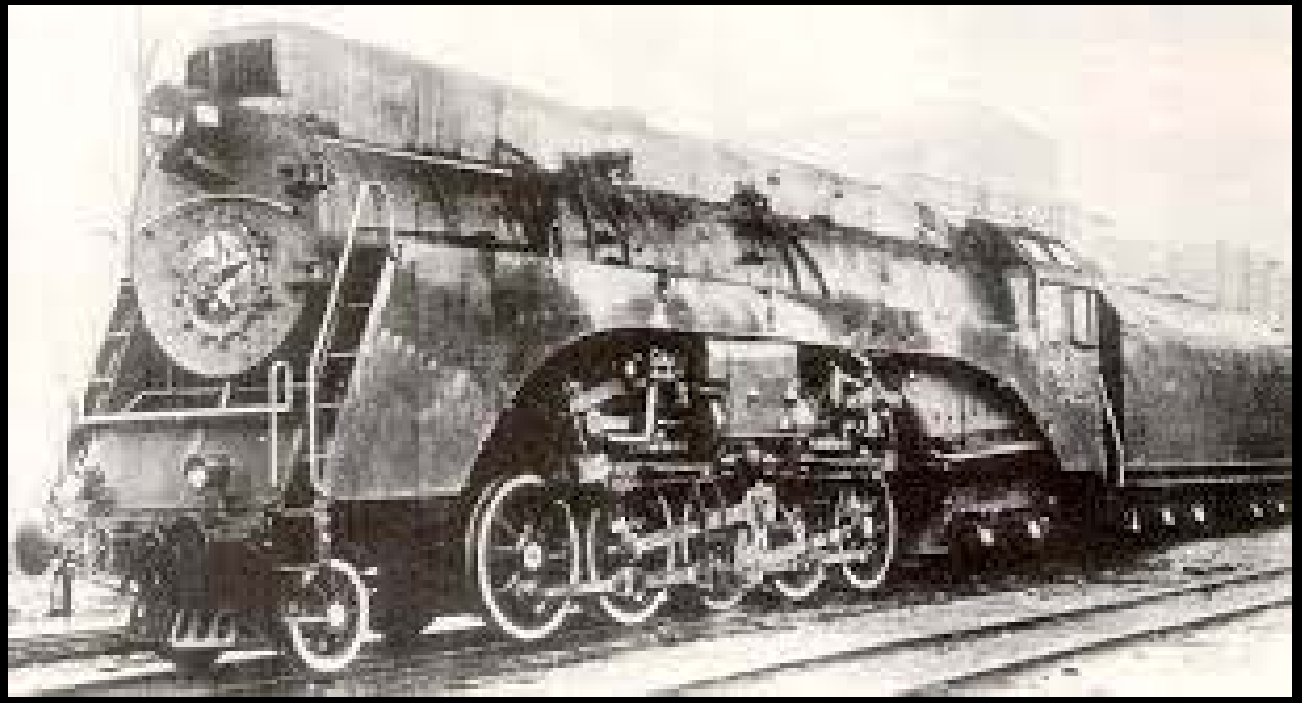
Synchronisation possibly undoing positive effects + no improvement in track load

Radical solutions

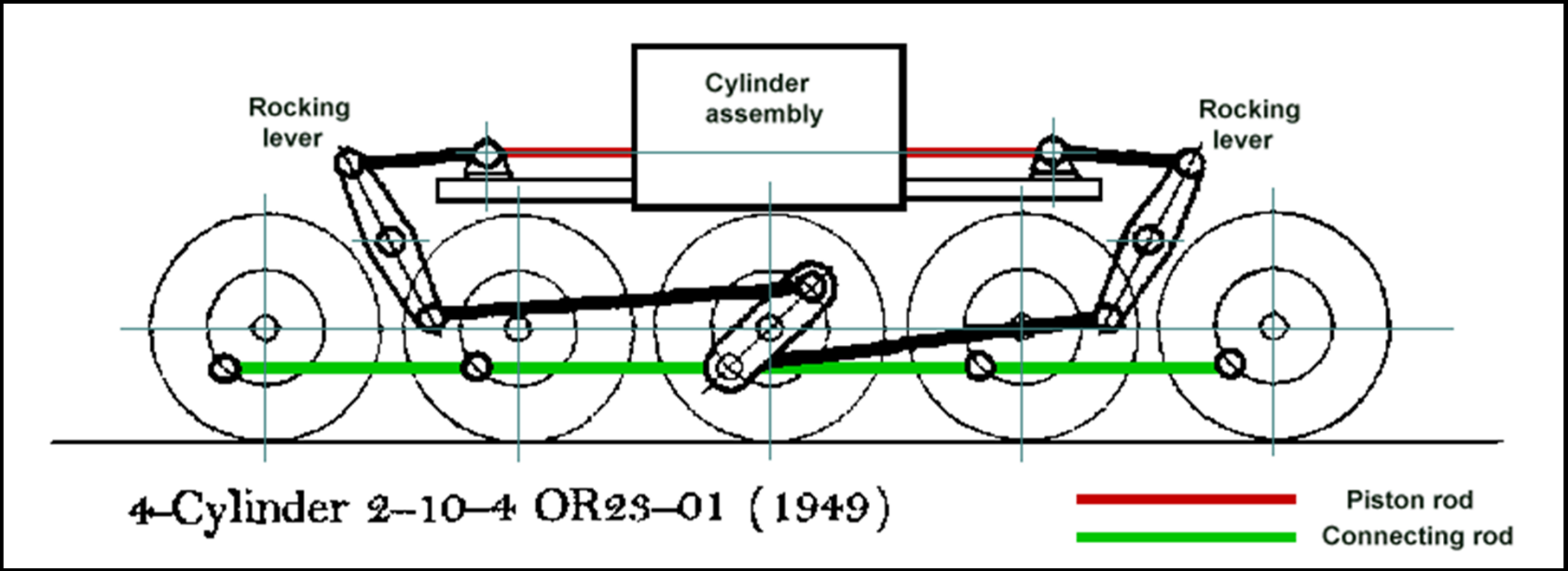
Rarities like (1881-1996!):

Radical solutions

Rather less successful:



Radical solutions



Radical solutions

Steam motor loco's (DR 19[1001]), turbine loco's,or even no drive mechanism at all (jet propulsion, J.A.E. de Grand, 1838):

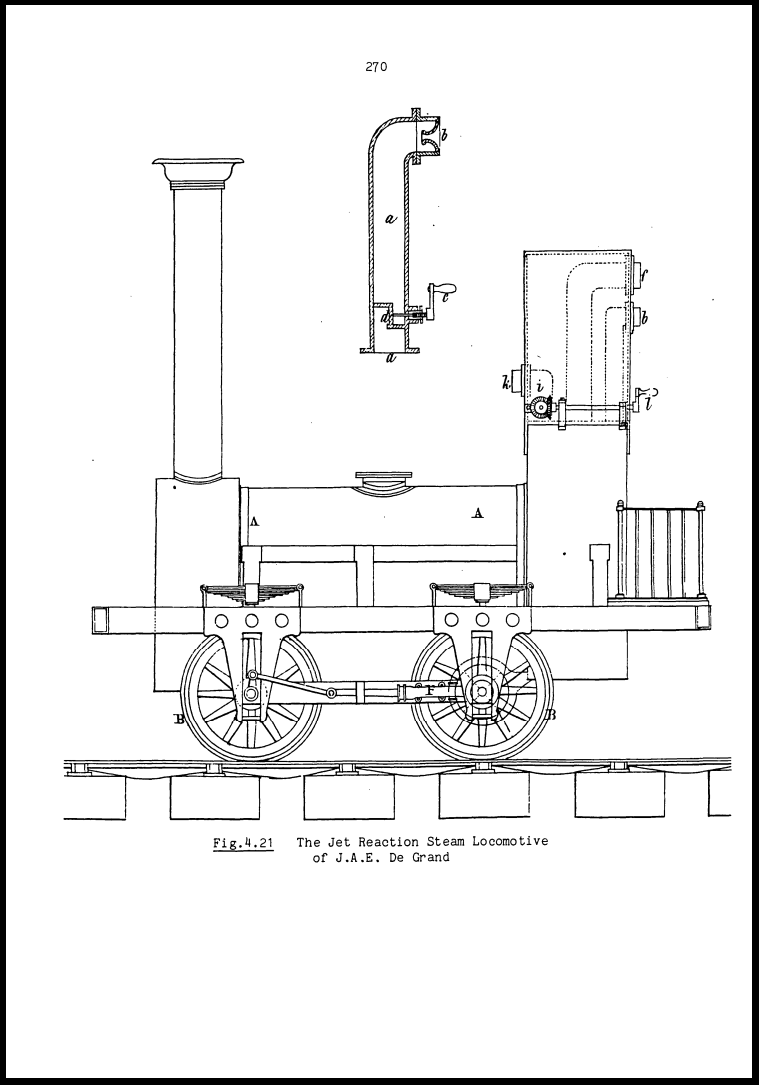


Fig.4.21 The Jet Reaction Steam Locomotive of J.A.E. De Grand

The issue

A. Reciprocating forces caused by piston, piston rod, crosshead, part of connecting rod & valve gear mechanism: $F_m max = (W \times rpm^2 \times S) / 1800$ (with connecting rod angle = 0)
B. Free gas (compression & drive) forces "leaving the engine" through slidebars, piston covers & axleboxes (in stationary engines on slidebars / cylinder walls only)

Applied to a finite mass (locomotive) and thus

1. Creating unwanted movement (induced by other factors as well)
2. Reducing mechanical efficiency

With A (far) outweighing B at higher speeds

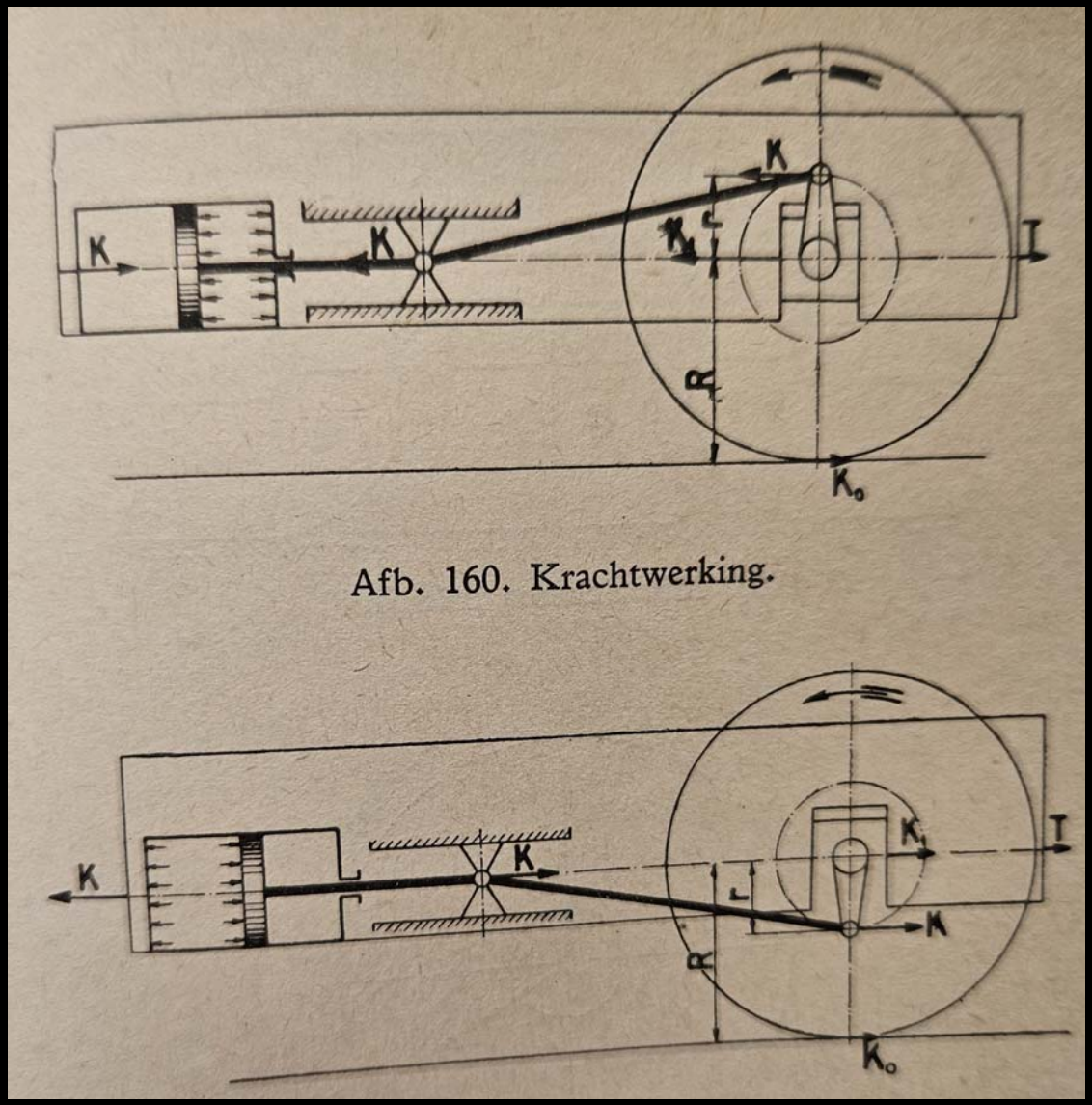
The issue

General assumption: reciprocating mass forces predominant, gas forces(on cylinder covers and on slidebars) marginal (“at slow speeds only”)

But Chapelon (“eerie quietness setting in as soon as regulator is closed”): bad 2 cyl riding caused mainly by gas forces (and play in drive mechanism):

The issue

"Free" one-sided
gas forces much higher
than driving forces
(Chapelon, Meineke & al.:
Much underestimated in its
negative effects on
"parasitic" movement):



Afb. 160. Krachtwerking.

The issue

(At least) two kinds of movement imparted by 2 cylinder engine forces:

A. **Sway** (lateral "turning" movement)
B. **Surge** (longitudional movement)

Outside cylinders → sway and surge

(Inside cylinders → less sway, more surge: same forces divided differently)

Internal remedies

Radical solution: fix the engine to (±) infinite mass

Practised in stationary engines even without any rotary balance

The same in Swiss paddle steamers with "21st century" steam engines (moving experience indeed)

→

Heavier locomotives the solution? Too high a price:

Instead go for lowest possible reciprocating masses (but within limits of course, US loco's doing better in this respect than the rest of the world)

Internal remedies

Sometimes nothing was done on this at all: Prussian loco's (with mixed results), WD 2-8-0's & 2-10-0's (so as to not further destroy poor wartime track):

→ No hammer blow indeed (like in 5AT design proposal)

Given sufficiently long fixed wheelbase + without (± unavoidable) driving mechanism play still ± acceptable riding qualities

Internal remedies

Standard counterbalancing, without or with cross balancing:

"moving the problem elsewhere"

Never 100% → unacceptable hammerblow … (remember quadratic relationship with speed as well)

DB 66 2-6-4 tank loco 15 t axleload with 15% hammerblow related to 20 t at top speed (100 km/h) (*lighter* loco the solution …) (reputedly riding like a good 3 cyl)

More or less effective against reciprocating masses but not against gas forces

(Chapelon even suggested heavier driving mechanisms against gas forces, without further explanation)

Internal remedies

Interaction of inertial forces & gas forces as well:

Compression also to "cushion" reciprocal forces to a degree (+ moving these forces forward from driving crankpins to cylinder covers creates less sway but more surge)

→

Effects of reciprocal counterweights to be transmitted through (play in) axleboxes + frames

(+ coasting without compression → reciprocal load transfer from cylinder covers to big ends)

Internal remedies

Standard: *no distinction between sway & surge* → relatively simple formulae for degrees of reciprocal force counterbalancing:

Back to Lechatelier's 19th century mathematics

Reprinted in standard textbooks

(But not always followed up to & including Chinese QJ's)

Internal remedies

Rotary compensation for reciprocal forces still limited in the end (hammerblow) → *why not go for one factor only?*

Again: 3 cyl sway no real problem

Even so without any counterweights against reciprocal forces

(Before WW II Holcroft had them removed from a SR Schools class 4-4-0 with no appreciable differences in riding)

Internal remedies

→ Why not leave 2 cyl sway (less than "equivalent" 3 cyl sway anyway) alone & go for surge compensation only?

Internal remedies

Radical simplification:

No more reciprocal cross balancing: counterweights in the same position on both sides (combined left / right)

Better relationship between degree of balancing & hammerblow ("more my be done within the same hammerblow limits")

Rarely practiced, still worthwhile for rebuilts / new loco's (see later on)

(+ Surge not sway suffered by passengers)

Internal remedies

+ No play (cf. Chapelon …)

Use of Compression to "cushion" reciprocal forces: where do you want these reciprocal couples to be? (though compression may create its own problems like in the GWR Kings)

Adequate coasting techniques (with "whiff of steam in mid-gear", no snifting, bypass &c. valves, good against bearing fatigue / failure as well)

(O14 9 driving style: close the throttle to 5 at steam chest pressure + long cut-off …)

Internal remedies

Abb. 63

Lokomotive mit stoßdämpfenden ovalen Radsätzen versehen.
(„Der Grubenhund" Wien, Pfingsten 1914)

6088

External remedies

So what about sway (given internal remedies against surge only)?

Back to completely unbalanced stationary / marine engines: no problem even without centrifugal balance …(apart from slightly reduced efficiency due to spurious movement)

→ "Best balanced" locomotive would be completely stationary as well … Not that practicable so:

Locomotive as a whole to be optimally stabilised by "outside factors"

External remedies

Anti-surge: "fix the loco to the load": more or less effective but then laterally & longitudionally totally stiff train coupling not practicable

Tenders may still be put to good use: Franklin style tender couplings or even totally stiff tender coupling ("articulated style")

+ long fixed wheelbase tenders (no bogies but *Flying Scotsman* style)

External remedies

Last remaining remedy: "fix the whole thing to the rails"

Given the need for traction this works against sway only (surge of course being a longitudional force coincident with the desired direction of travel)

→

Optimising wheel arrangements not just for adequate straight track & curve riding but for stabilisation against sway as well

External remedies

20th century development to generally both

Longer locomotives but also

Relatively shorter fixed wheelbases (or no fixed wheelbase at all: 4cyl 240.700 / 240P)

Standard “compromise” between lateral stability and good curve riding, generally by spring loaded lateral play of outer axles / wheelsets (pony trucks, bogies, Krauss-Helmholtz / Zara setups & the like)

(See among others Düring & Giesl for complex “curve theories”)

External remedies

Compromise comes at a price: “spring / rocker / roller loaded” lateral stiffness → static (& thus increase of dynamic) lateral forces in (tight) curves

N&W J class 4-8-4 a good example: adequate lateral control against sway as well (!) but prone to derailment (“compromise” at best between main line & tight curve riding …)

DR 01 2 cyl Pacific: no lateral loco control on straight track, scary riding of Peppercorn Pacifics, …

(+ issues like: lateral control of trailing axles further increases outside lateral front wheel forces in curves)

External remedies

Karl Gölsdorf: 2-12-0 kkStB 100 (1911):

External remedies

"Forgotten wisdom" in a different approach: *no lateral* (nr, 1, 5 & 6) *(spring &c.) restoring forces* at all, some lateral damping on leading (simple Adams) axle only

→

No static (+ thus less dynamic) lateral forces in curves

+ excellent riding qualities & minimal flange / track wear (see Giesl, *Lokomotiv-Athleten*)

// 9F apart from leading bissel truck lateral spring control instead of (probably still some) damping (Essery: by far the best riding of all major main line UK loco's including 3 & 4 cyl express engines)

External remedies

Apart from (continental) curve track widening this is limited only by:

- Maximum wheelrim / track angle deviation from 0°
- Maximum lateral wheelset play (no real problem apart from rod / wheel coupling, see e.g. cardanic joints in Gölsdorf's 2-12-0)
- Maximum thinning / absence of wheelrims / tyre width on driving wheels (as in 9F)

External remedies

But how to do away with static curve forces in a bogie / Krauss-Helmholtz like engine? No lateral bogie play, e.g. Prussian 4-4-0 2 cyl S3 (late 19th century 2 cyl express engines without any reciprocal balance to speak of but still running quite well, 1,000+ built until replaced by “more advanced” engines with lateral bogie play & [thus] running much worse)

External remedies

Or Gölsdorf again:
kkStB 2-6-4 210/310:
no lateral play in K.-H.
bogie pivot, thinned
driving wheelrims, no
lateral play in trailing
coupled axle, trailing
bogie lateral play

Remedies summarised

So go for optimal surge counterbalance only + longest possible fixed wheelbase: "9F style"

\+ (again)

Lightest weight driving gear

No play wherever in the whole of the driving mechanism (*Revolution*)

Optimum force / couple distribution ("cushioning" by compression)

Remedies summarised

So also no more conflict between stability at speed & tight curve negotatiation

+ go for strongest possible track / permanent way of course: good against running resistance as well

Agenda

Hopefully not just historical or even hypothetical: something may still be done with it, for example:

Clan suggestions:

- Counterbalance against surge only

- No leading bogie lateral play + thinner flanges on first coupled axle & driving axle (or thinner flanges / lateral play on leading & trailing coupled axle) + lateral damping only on trailing truck (no more restoring force) → (much) longer "fixed" wheelbase + no more static forces in (even minimum radius) curves (Gölsdorf style again)

Agenda

SR Pacific restreamlined &c.: rotary counterbalance only (as *per* original) + *Clan*-like lateral control?

P2: "maybe too late already" (given diesel engineer's input &c.) but still: again rotary counterbalance only, Gölsdorf style (leading &) trailing trucks

O149 &c.: ? / better general maintenance …

(Generally less wheelrim / track wear with such arrangements)

Agenda

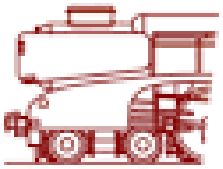
Revolution:

- Counterbalance against surge only?

- Laterally stiffer / more heavily damped leading truck (with reduced restoring force) combined with thinner flanges &c. on leading coupled axle & driving axle? (240P style w/o fixed wheelbase?)

(- *Saumon* fitted? ;o)

But then *Revolution* perfect already in a number of other respects including ± total elimination of unwanted driving / running gear play → less need for still more "reform"



Advanced Steam
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