

# «Loco» - Simulation of Walschaerts Valve Gear

Jan Mathisen, March 17, 2021

## 1 Introduction

I am building a model of the NSB Type 23 steam locomotive in 1/8 scale and wanted to be able to analyse the valve motion of both the original and the model. I found Allan Wallace's simulation program (ref.1) a few years ago and used it, but eventually decided to code my own simulator in order to have full control, and because I enjoy programming in Fortran. Two other members of the Norwegian Model Engineer Association are building a model of the Dovregubben locomotive, with a slightly different valve gear and I have developed a separate version to cope with it. An explanation of the operation and principles of the Walschaerts valve gear is not included here, but may be found in ref.2 and ref.3. The "loco" program is documented here, together with the differences found in the "dovreg" version.

## 2 Method

### 2.1 Mechanism

Fig. 1 shows the valve gear of the Type 23 locomotive in the science museum in Oslo, seen from the right-hand side. There are a fair number of pin-jointed components and it is impractical to make a direct calculation of the motion of all these components. Some sort of indirect or approximate approach is called for.

I have applied a least squares approach, utilising the routine minpack/lmdif1 from Netlib (ref.4). The basic idea is to describe all the joints in the valvegear by coordinates; that are initially unknown, but have to satisfy a set of conditions such that:

- all the components have the correct length;
- joints in the middle of a continuous component do not allow the component to bend;
- some of the motion, arising from rotation of the driven wheel is given directly.

For example, suppose the two ends of a link have trial coordinates  $(x_1, y_1)$  and  $(x_2, y_2)$  and the length is  $l$ . Then an error term  $e^2$  may be defined by the difference between the actual length and the length computed from the trial coordinates:

$$e^2 = \left( \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} - l \right)^2$$

If the correct coordinates are found, then the error term reduces to zero. A single condition of this type is insufficient to determine 4 unknown coordinates, but a larger number of similar conditions can be set up to determine the unknown coordinates in the valve gear with sufficient accuracy.

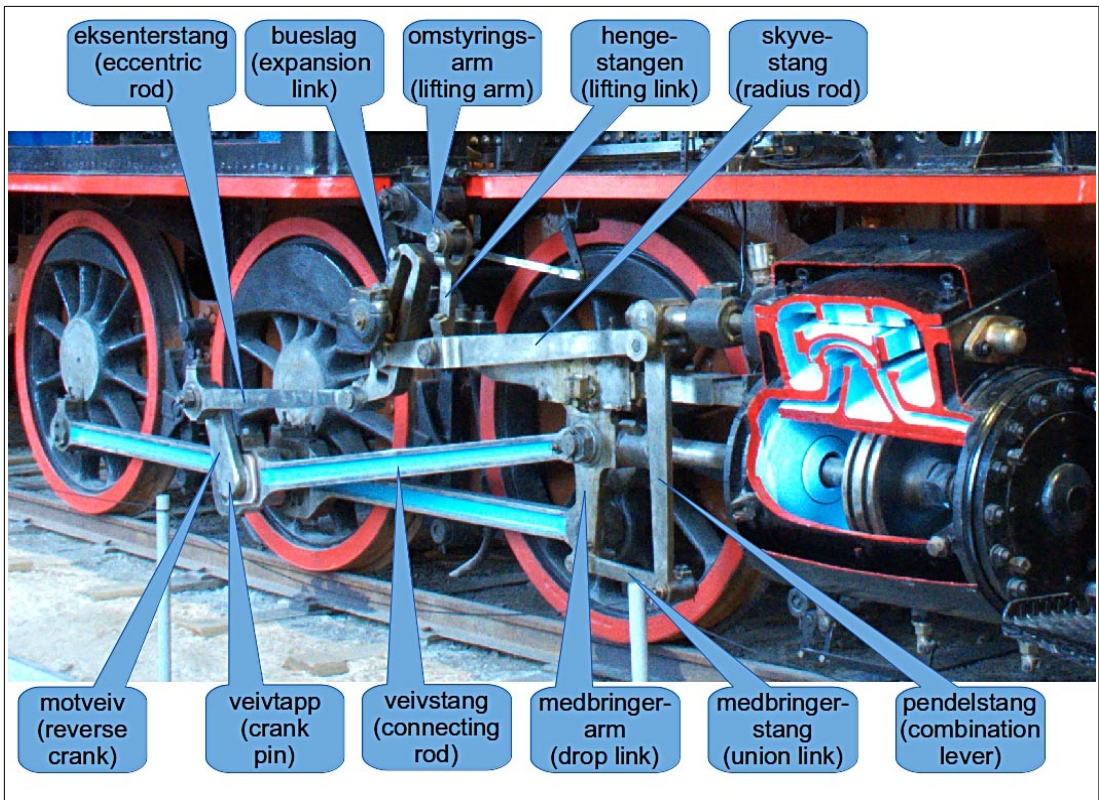


Fig. 1: Names of components of a Walschaerts valve gear in Norwegian and English.

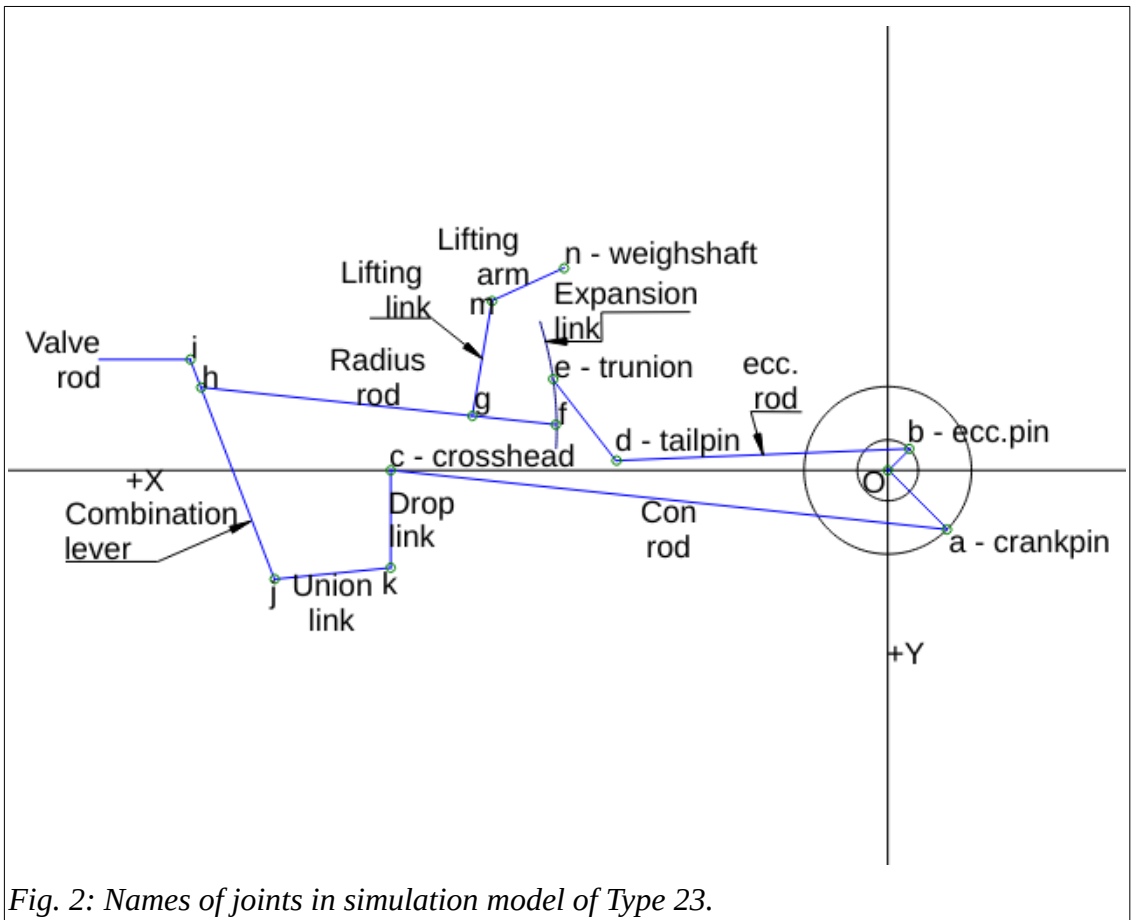


Fig. 2: Names of joints in simulation model of Type 23.

Fig. 2 shows the valvegear components in the simulation model of Type 23, seen from the left-hand side of the locomotive. The origin (O) of the coordinate system lies on the axis of the driven wheel, with the x-axis positive forwards and the y-axis positive downwards. Positive rotation of the wheel corresponds to forward motion and negative rotation to reverse. At zero crank angle the piston is at front dead centre; at 180° crank angle the piston is at back dead centre. The crank angle is increased in a series of steps (of 1 degree) and the coordinates of the joints are calculated at each step. The following joints are fixed in the locomotive and their x & y coordinates are provided as input:

- e – the trunion of the expansion link;
- n – the weighshaft.

The following constraints are applied:

- the crosshead (c) is constrained to move along the x-axis – the oscillatory motion of the piston is necessarily in line with the crosshead, and the projection of this line normally passes through the axis of the driven wheel, when the axle is in its mean position relative to the suspension springs;
- the drop link is fixed to the crosshead, such that the joint (k) moves parallel to the x-axis;
- the valve rod joint (i) also moves parallel to the x-axis - the valve rod is normally parallel to the piston rod;
- the tailpin (d) is fixed to the expansion link which rotates about the trunion (e);
- the end of the radius rod (f), the dieblock, oscillates with the expansion link, but can be adjusted up and down by means of the reverser, acting through the weighshaft, lifting arm and lifting link.

The locations of the crankpin (a), eccentric pin (b), crosshead (c), joint (k), and tailpin (d) are calculated directly for each crank angle; the locations of the other joints (f, g, h, i, j) are found by the least squares approach. A quadratic equation arises in determination of the location of the tailpin (d), with two possible solutions – the solution closest to the x-axis is adopted. The neutral angular orientation of the lifting arm (mn) is found with the dieblock (f) located at the expansion link trunion (e); the location of joint (m) is computed both for the piston at front dead centre and at back dead centre and the mean of these two locations is taken; then the angular orientation of the lifting arm is found from the relative positions of joints (m) and (n). Subsequent calculations are carried out for a series of gear angles; i.e. angles relative to the neutral angular orientation of the lifting arm; forward motion of the locomotive corresponds to positive gear angles, when joint (m) is below its neutral location; motion in reverse corresponds to negative gear angles, when joint (m) is above its neutral location. (This convention does not necessarily apply to all Walschaerts valve gears). Thus, the gear angle implies the location of joint (m).

The radius of curvature of the expansion link is assumed equal to the length of the radius rod – this is the standard procedure for Walschaerts valve gears, but deviations from this standard are not inconceivable. In neutral gear, as defined above, the centre (p) of the circle through the expansion link is assumed to coincide with the joint (h) at the end of the radius rod, when the piston is at front

dead centre. As the expansion link oscillates about the trunion, under the action of the eccentric rod, this centre (p) will move; the coordinates of the centre (p) are determined for each crank angle that is considered; note that the location of the centre (p) is not affected by the gear angle.

Knowledge of the instantaneous location of the centre (p) is used to provide a numerical constraint for the dieblock (f), to demand that it follows the oscillations of the expansion link.

When the motion of the valve rod relative to the crank angle (and the piston location) has been determined, the valve events can be defined; i.e. when the transfer ports to the cylinder start to open (for steam admission and exhaust release) and when they finish closing (for steam cut-off and exhaust compression). The basic width of both valves is assumed equal to the width of the transfer port; the valve width is usually increased on one side by steam lap, which delays valve opening to incoming steam and brings cut-off forward; the width may also be increased on the other side by exhaust lap, but this is less usual and is not allowed for in the program at present.

## 2.2 Simplified indicator diagram

Once the valve events have been determined a simplified indicator diagram can be developed from thermodynamics. Quite sweeping assumptions are required:

- flow restrictions in the transfer ports and due to partially open valves are ignored, incoming steam is at the temperature and pressure delivered by the boiler; exhaust steam is at the back pressure in the smoke box;
- heat transfer to or from the cylinder is ignored; i.e. the process is assumed adiabatic;
- friction between the piston and the cylinder is ignored;
- a constant mass of fluid (steam and water) during the expansion process and a constant mass during the compression process;
- on this basis it is reasonable to assume the expansion and compression processes are reversible and isentropic;
- flow energy lost during the exhaust process is taken into account by applying constant specific enthalpy;
- the effect of a small volume of steam from the compression process on the input process is ignored.

With these assumptions, the varying states through the expansion and compression processes can easily be computed using steam tables, or rather steam algorithms in place of steam tables: a small step decrease (or increase in pressure) is considered and other steam and water properties after the step are obtained from constant entropy; these properties include temperature, steam quality (or steam fraction) and specific volumes. Given the mass, the quality and specific volumes are used to obtain the actual volume, which leads to the position of the piston. The small steps in pressure are continued until the next valve event is reached.

Steam algorithms have been coded from ref.6. A sufficient range of water and steam states are included to cover the states found in ordinary steam locomotives, although the full range of states available in the reference is not covered.

Bill Hall (ref.7) has shown that saturated steam tends to partially condense on entry into the cylinder and re-evaporate later during the expansion phase. This behaviour is important for the detailed understanding of the working of a steam engine; it is not covered by the present simplified indicator diagram.

### 3 Input data

Input to the program is given in a file named, loco\_input.txt, as shown below. An exclamation mark '!' in column 1 indicates a comment record, which is ignored. Note that tabulator characters are not allowed in the input file; this is a feature of Fortran. Each data record starts with an identifier, up to 5 characters in length. The identifier tells the program which input data is provided on the data record. The identifier is separated from the data by one or more blank spaces. Subsequent data on the same record is also separated by blanks. Further explanatory text can follow the data values, as in the example file below, but is ignored by the program.

The geometry of the mechanism is described in millimetre units here, but any consistent units of length could be applied. However, steam pressures (p\_cut and p\_rel) must be in MegaPascals (= MegaNewtons per square metre), superheat (sup\_ht) in degrees Celsius and the cylinder diameter in metres for consistency with the steam tables that are applied.

#### 3.1 'loco\_input.text'

! An exclamation mark in column 1 indicates a comment and is ignored.

! Tabulator characters are not allowed.

!

ident	NSB T23	Name of system, max. 8 characters
l_ac	1840.0	Length con.rod
l_bd	963.2	Length ecc.rod
l_oa	275.0	Radius to crankpin
l_ob	100.0	Radius to eccentric pin
a_aob	90.0	Lead angle of eccentric pin wrt. crank pin in degrees
l_de	316.5	Radius to tailpin
l_fg	254.0	Length of radius rod from expansion link to lifting link
l_gh	918.0	Length of radius rod from comb. lever to lifting link
l_ck	320.0	Length of drop link
l_jk	382.0	Length of union link
l_hj	645.0	Length of comb.lever from union link to radius rod
l_hi	66.5	Length of comb.lever from valve rod to radius rod
l_mn	264.0	Length of lifting arm
l_gm	324.0	Length of lifting link
xy_e	1040.0 -312.0	Coordinates of axis of expansion link

xy_n	1064.0 -664.0	Coordinates of axis of lifting arm
xy_i	-364.0	Y-coordinate of valve rod
w_p	10.0	Length of an inlet port in steam chest
w_s	23.0	Length of steam lap on a valve
adm	outside	Steam admission, either 'inside ' or 'outside'
del_nm	8.0	Step between gear angles that are analysed
i_gear	3	Sequence number of gear angle to be simulated (1:7)
diam	0.41	Cylinder diameter (m)
clr	3.0	Clearance volume in cylinder and ports (%)
su_ht	0.0	Degrees of superheat $\geq 0$ (C)
p_cut	0.6	Pressure inside cylinder at cut-off (MPa)
p_rel	0.12	Back-pressure, inside cylinder after release (MPa)

## 4 Output

The program is run from a terminal window, which only provides very limited output, but may give error messages if the program detects any errors; e.g. numerical inaccuracy in the least squares analysis. The results from the analysis are provided in a number of files, as listed below. Several of these files are intended for plotting with the ‘gnuplot’ program (ref.5).

### 4.1 ‘loco\_result.txt’

The main results of the analysis are listed in this file in a comma-separated format for easy insertion into a spreadsheet; which is recommended for convenience when studying the results. This file is very detailed, to enable the calculated coordinates to be checked or used to estimate inertia forces. The more important results are right at the end of the file. The contents are as follows:

- list of input data;
- a table of xy-coordinates for the joints that are defined by the crank angle ( $a_{oa}$ ), alone, the crankpin (a), the eccentric pin (b), the crosshead (c), the tailpin (d), the angle of the eccentric rod ( $a_{bd}$ ) and the angle of the line from the expansion link trunion to the tailpin ( $a_{ed}$ ) – two alternatives are obtained for the tailpin location, as mentioned in section 2.1 and plotted in Fig. 3;
- a table of xy-coordinates for joints (g, h, i, m) for the system in mid-gear, with the piston at front dead centre and back dead centre – and the neutral angle defined for the lifting arm ( $a_{nm0}$ );
- tables of xy-coordinates for the other joints, as functions of crank angle ( $a_{oa}$ ), for each gear angle ( $d_{nm}$ ) that is considered;
- a table of valve rod motion ( $x_i$ ) and valve events (admission, cut-off, release, compression) as a function of gear angle. These events are calculated by linear interpolation between the coordinates originally calculated for each step in crank angle. Results are

included for both the front part of the cylinder and the back part. The middle x-coordinate of the valve rod is denoted by  $x_{i0}$  and used to define the valve events; i.e. starting to open a port or finishing closing a port. The middle position of the valve can be defined relative to  $x_{i0}$  by the chosen length of the valve rod and the steam ports can be located symmetrically about the middle position of the valve, with any suitable spacing, sufficient to avoid over-running the exhaust and the steam supply.

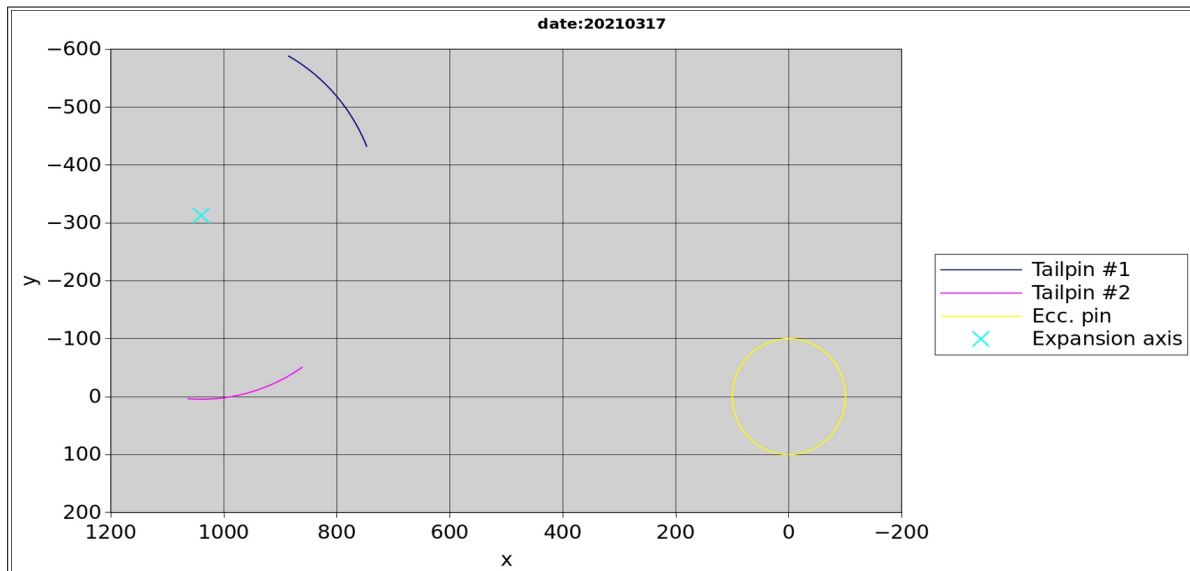


Fig. 3: The two possible solutions for the path of the tailpin as the crank rotates, shown as  $x$  and  $y$  coordinates. The yellow circle is the path of the eccentric pin while the diagonal cross is the location of the expansion link trunion.

## 4.2 'plt\_i.txt'

This file is intended to be plotted using the gnuplot program, with a sequence of commands:

```
gnuplot
gnuplot> load 'plt_i.txt'
gnuplot> quit
```

Note that the single quotes around the file name are essential. The contents of the file can be read with a text editor and provide the required data and commands for the gnuplot program. The graph appears in a window on the display and can be exported in various formats using a menu at the top-left of the window.

A sample is shown in Fig. 4. The various curves correspond to the gear angles listed in the legend; positive gear angles for forward motion of the locomotive and negative gear angles in reverse. The amplitude of the valve motion increases with the magnitude of the gear angle. The distances of the curves from the lap-lines at crank angles of  $0^\circ$  and  $180^\circ$  are equal to the lead of the valve mechanism; i.e. the width of the port opening at front dead centre and back dead centre. Valve events occur when the curves cross the lap lines. It is instructive to compare the valve events in this

figure with the table at the end of 'loco\_result.txt' file. The actual data may also be found in this file.

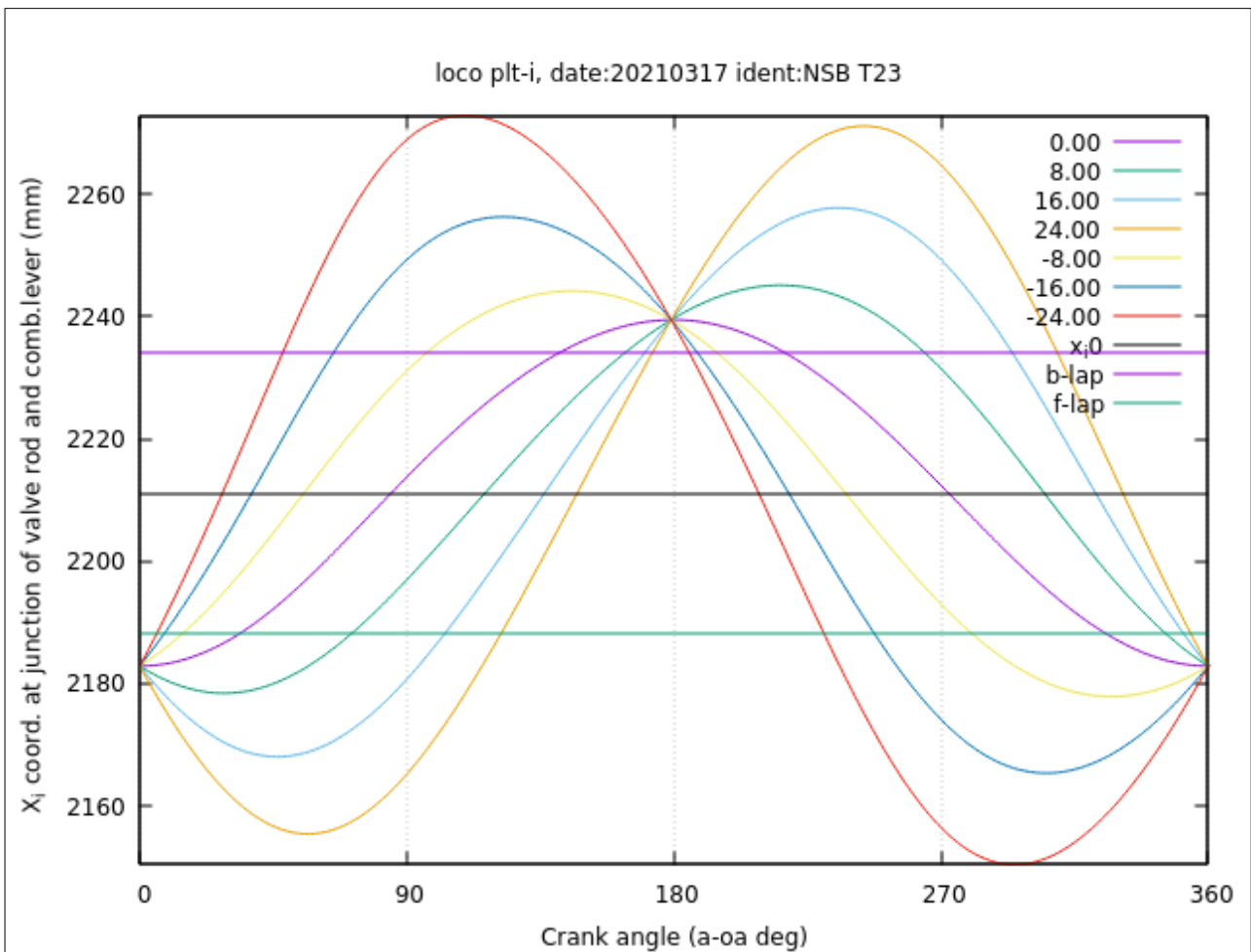


Fig. 4: X-coordinate of valve rod ( $x_i$ ) as a function of crank angle for various gear angles ( $d_{nm}$ ). The central position of the valve rod ( $x_{i0}$ ) and steam lap lines are also shown for the front cylinder (f-lap) and the back cylinder (b-lap).

### 4.3 'plt\_oval.txt'

This file is also intended to be plotted using the gnuplot program, with a sequence of commands corresponding to those in section 4.2. A sample is shown in Fig. 5. This graph is simply a different way of plotting the results in Fig. 4; the abscissa is now the crosshead coordinate, instead of the crank angle, but the ordinate values are identical. Differences between valve behaviour in forward and in reverse are more easily apparent in Fig. 5.



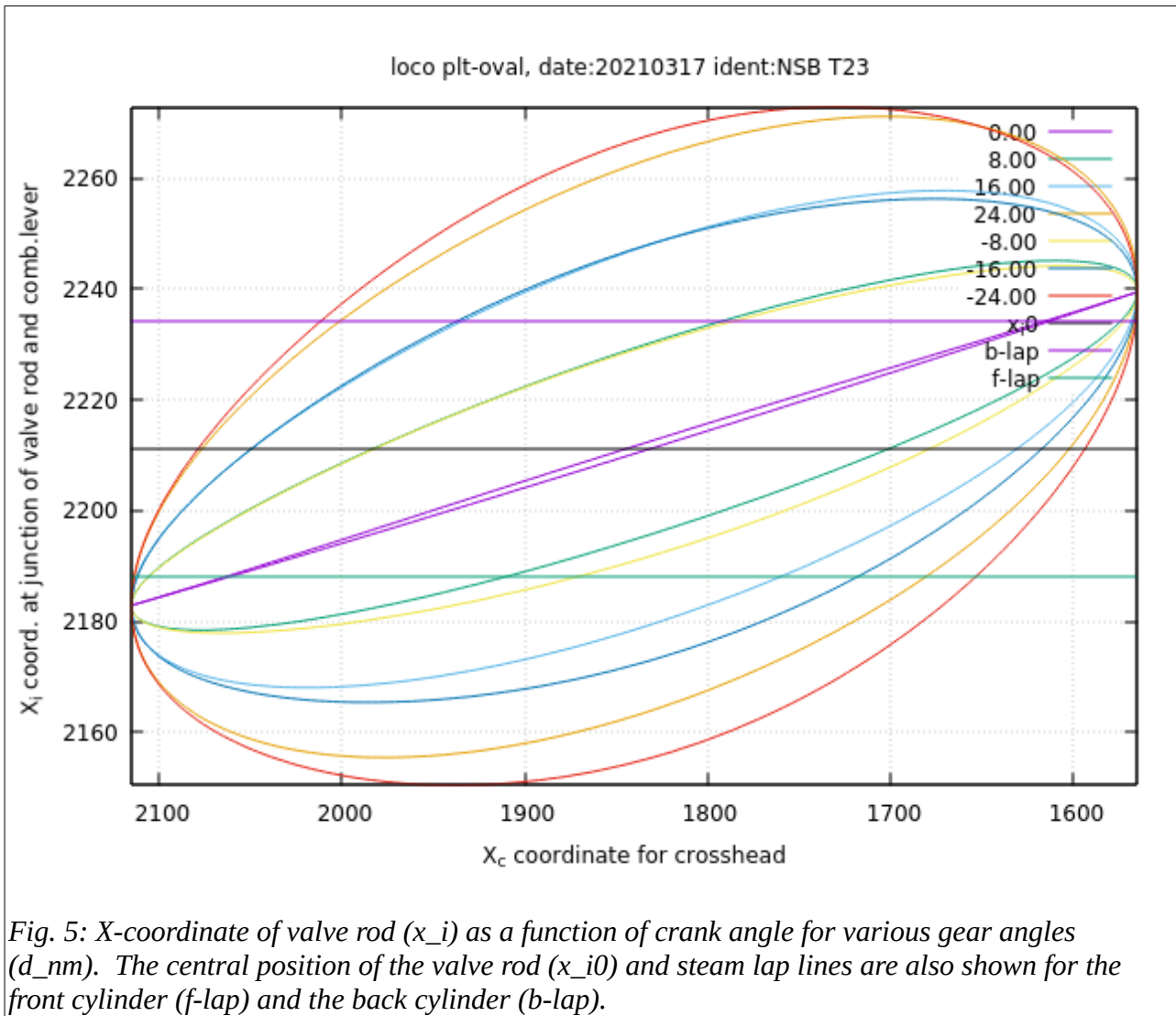


Fig. 5: X-coordinate of valve rod ( $x_i$ ) as a function of crank angle for various gear angles ( $d_{nm}$ ). The central position of the valve rod ( $x_{i0}$ ) and steam lap lines are also shown for the front cylinder (f-lap) and the back cylinder (b-lap).

#### 4.4 'plt\_config.txt'

This file is also intended to be plotted using the gnuplot program, with a sequence of commands corresponding to those in section 4.2. It provides a simulation of the valve gear by simply plotting the mechanism for each crank angle that has been analysed. The simulation can be repeated by repeating the command: load 'plt\_config.txt'.

An image of the final crank angle from the simulation is shown in Fig. 6. The components of the mechanism can be identified with reference to Fig. 2; the sector of an ellipse superimposed on the mechanism is a circle through the expansion link with centre at point (p); the circle appears elliptical due to the difference in vertical and horizontal scales. A representation of the piston, cylinder and slide valve is included below the mechanism; it illustrates the opening and closing of the ports during the simulation.

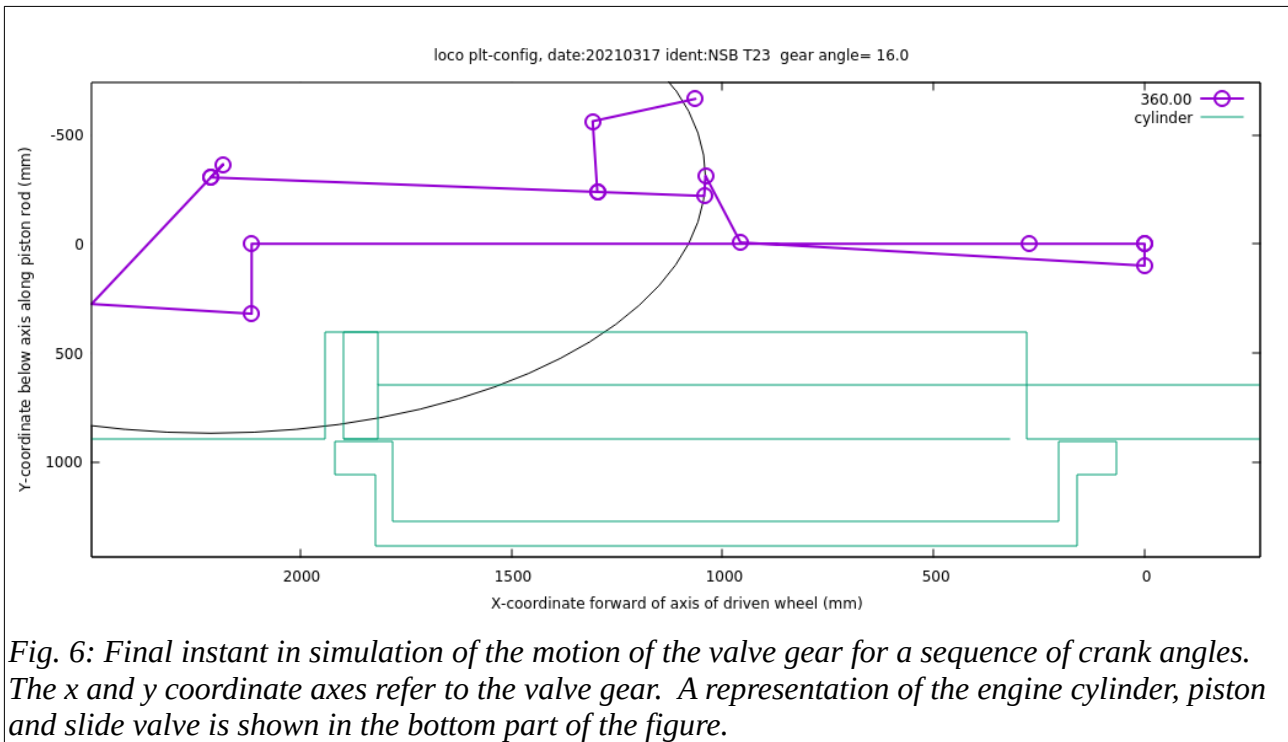


Fig. 6: Final instant in simulation of the motion of the valve gear for a sequence of crank angles. The x and y coordinate axes refer to the valve gear. A representation of the engine cylinder, piston and slide valve is shown in the bottom part of the figure.

## 4.5 'indicator.txt'

This files contains results calculated for the simplified indicator diagrams in a comma-separated format, for easy insertion into a spread-sheet. A sequence of tables is provided for:

- a) front cylinder, forward motion;
- b) front cylinder, reverse motion;
- c) back cylinder, forward motion;
- d) back cylinder, reverse motion.

There is a table for each gear angle within each of these categories. Each table lists the sequence of pressures considered for an indicator diagram. Additional fluid properties are included in the table, beyond what is shown in the indicator diagram:

- pp pressure (Mpa);
- tt Celsius temperature ;
- vf specific volume of water (m<sup>3</sup>/kg);
- vg specific volume of steam (m<sup>3</sup>/kg);
- xx steam quality or steam fraction;
- hf specific enthalpy of water (kJ/kg);
- hg specific enthalpy of steam (kJ/kg);
- yp% piston position (%)

- uf     specific internal energy of water (kJ/kg);
- ug     specific internal energy of steam (kJ/kg);
- sf     specific entropy of water (kJ/kg/K);
- sg     specific entropy of steam (kJ/kg/K).

A default value of -99 is shown for water properties when the pressure and temperature correspond to super-heated steam.

It may be worthwhile to consult these tables to check how much condensation is predicted by this simplified analysis: (1-xx) is the water fraction.

## 4.6 'plt.indicator.txt'

This file is also intended to be plotted using the gnuplot program, with a sequence of commands corresponding to those in section 4.2. A sample is shown in Fig. 7. Rather high pressures are shown from the compression phase for the smallest gear angles; perhaps this gear angle would be avoided, or the high pressures could be reduced by decreasing the lap, which increases the lead; i.e. opens the port for admission earlier.

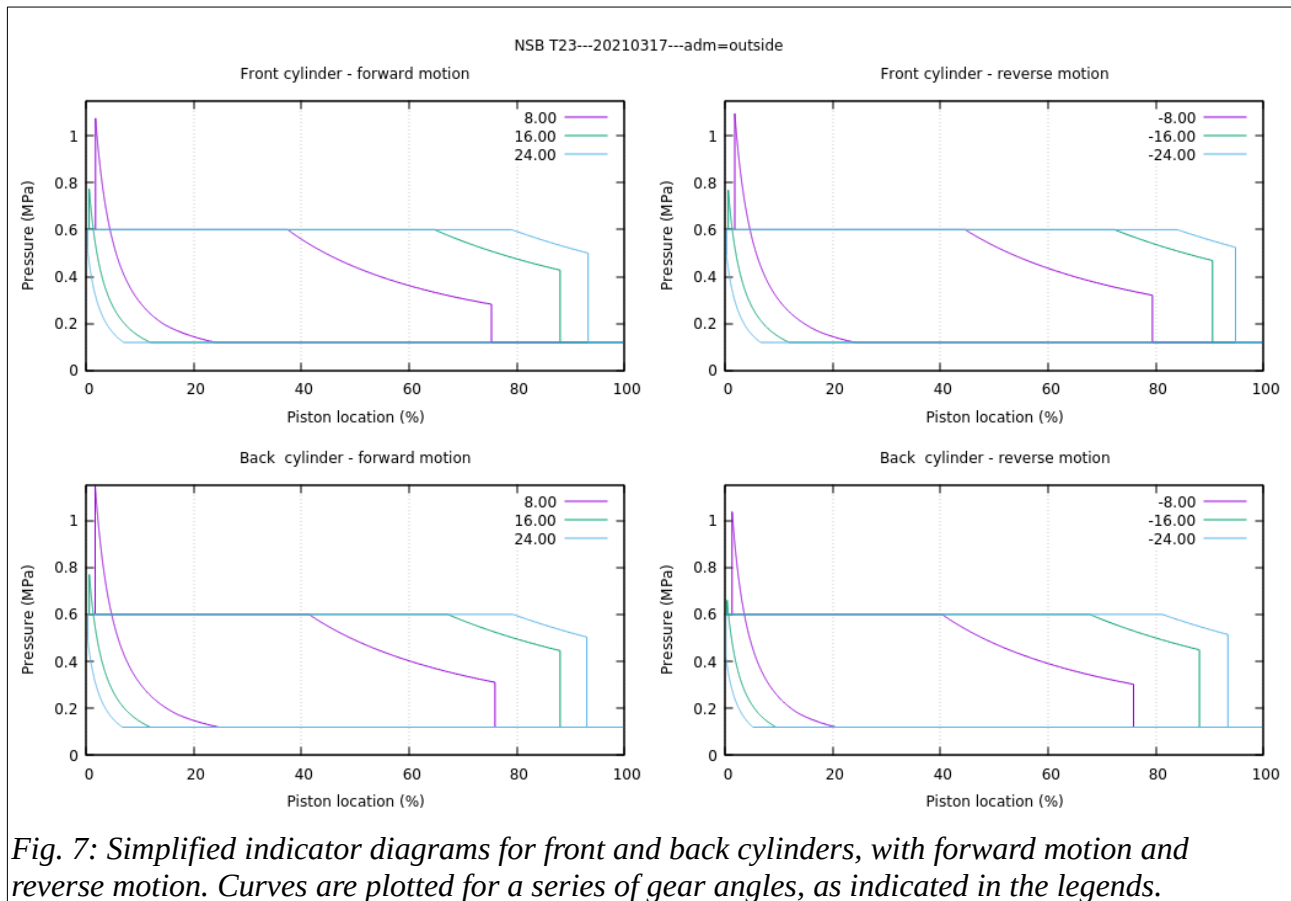


Fig. 7: Simplified indicator diagrams for front and back cylinders, with forward motion and reverse motion. Curves are plotted for a series of gear angles, as indicated in the legends.

## 5 Program structure

The program has been coded in Fortran using the gfortran compiler, ref. 8, on an Ubuntu/Linux operating system. There is a Makefile to automate compilation and linking. The structure of the program is indicated in Fig. 8, showing input and output files and subroutines.

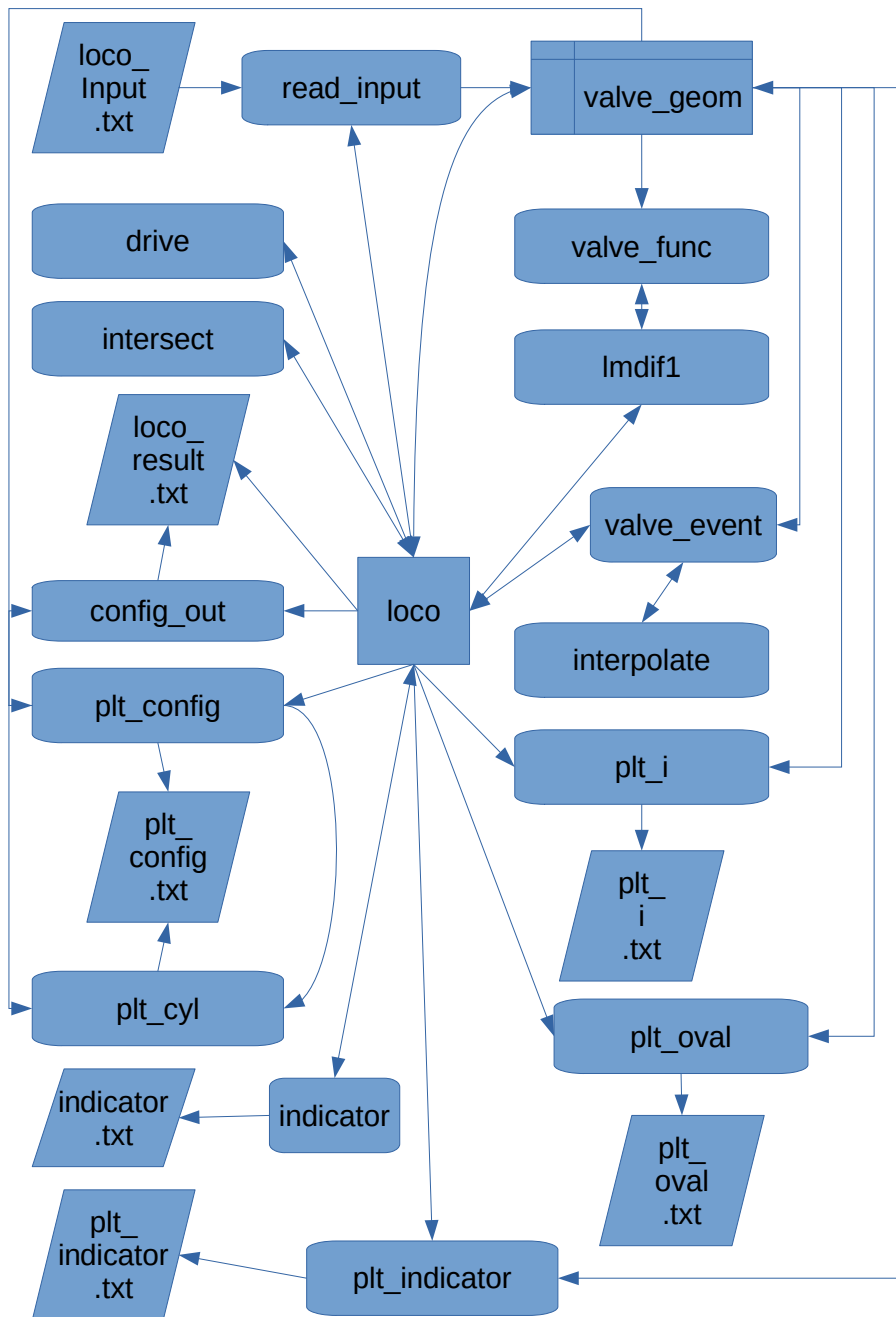


Fig. 8: Structure of program "loco."

The 'valve\_geom' module is used to transfer data between the various parts of the program. In particular, it provides the data needed by the least-squares minimisation, supplied to the entry subroutine, 'lmdif1,' via the 'valve\_func' subroutine. 'Lmdif1' makes use of a series of other Fortran subroutines from the netlib-minpack library:

d1mach.f, dpmpar.f, enorm.f, fdjac2.f, lmdif.f, lmpar.f, qrfac.f, qrsolv.f.

The algorithms for steam and water properties are grouped together in a library archive, 'steamlib,' which contains the following subroutines:

- gibbs1.f90 - water properties in region 1;
- gibbs2.f90 - steam properties in region 2;
- indicator.f90 - calculation of indicator diagram;
- isenthalic.f90 - process with constant specific enthalpy;
- isentropic.f90 - process with constant entropy;
- p1\_of\_h\_s.f90- pressure from enthalpy and entropy in region 1;
- saturation.f90 - saturation line for water and steam;
- t1\_of\_p\_h.f90 - temperature from pressure and enthalpy in region 1;
- t1\_of\_p\_s.f90 - temperature from pressure and entropy in region 1;
- t2a\_of\_p\_h.f90 – temperature from pressure and enthalpy in region 2a;
- t2a\_of\_p\_s.f90 – temperature form pressure and entropy in region 2a;
- (testg1.f90 - a program used in initial verification of the routines;)
- (wiredraw.f90 - a program for a throttling process).

The regions referred to above are properly defined in ref.6: region 1 is on the water side of the saturation line; region 2 is on the steam side; inverse relationships in region 2a are relevant to conditions in normal steam locomotives.

## 6 “dovreg” version

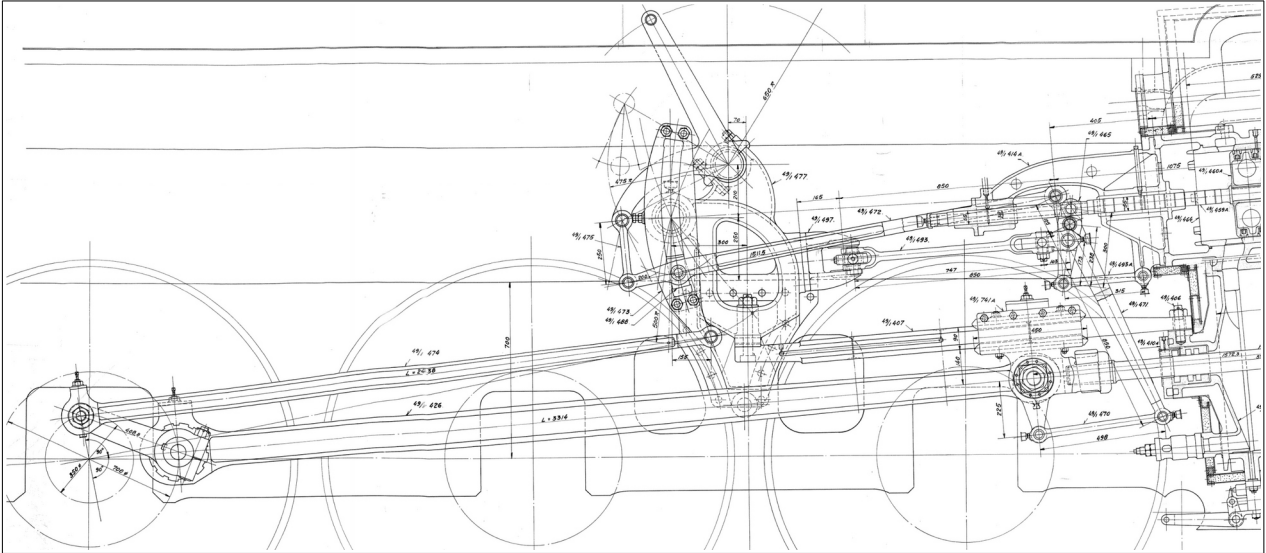
### 6.1 “dovreg” mechanism

The valve gear is shown in an extract from an original drawing of Dovregubben below – from the right-hand side of the locomotive. Fig. 9 shows the notation applied to the joints of this mechanism in the 'Dovreg' version of the program – from the left-hand side of the locomotive. There are several changes compared to the original mechanism in the 'loco' program:

- the eccentric pin follows the crank by close to 90° rather than leading it by exactly 90°;
- the lifting arm is reversed;
- the joint between lifting arm and radius rod is behind the expansion link, not in front;
- the other end of the radius rod is attached to the top of the combination lever;

- there is an additional hanger link, attached to the locomotive at joint (q), and to a lever at joint (r), with the other end of the 2<sup>nd</sup> lever attached to the valve rod at joint (i) and pin-jointed to the combination lever at (s).

The original Dovregubben has high pressure steam cylinders inside the frame and the valve gear for the HP cylinders is linked to the low pressure valve gear on the outside of the frame – which adds some complexity to the drawing above, and is not taken into account in the program. It also has piston valves with inside admission, rather than slide valves with outside admission.



Extract from drawing of Dovregubben.

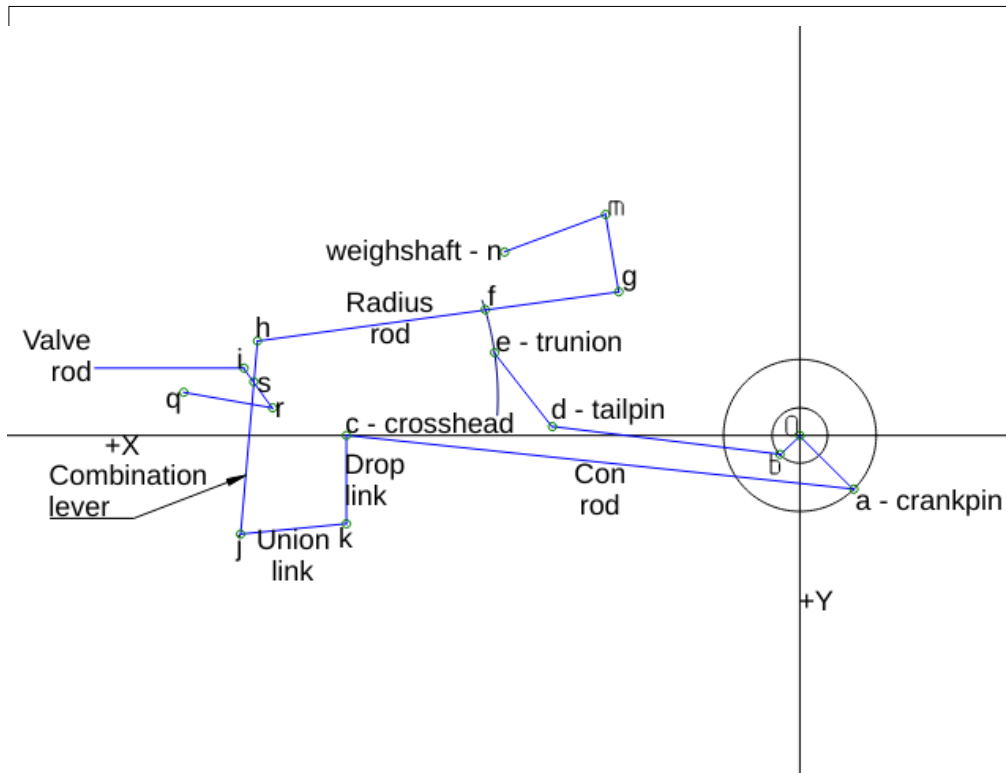


Fig. 9: Notation applied to the mechanism for 'Dovreg.'

## 6.2 “dovreg” input

The input file for ‘dovreg\_input.txt’ is listed below:

```

! An exclamation mark in column 1 indicates a comment and is ignored.
! Tabulator characters are not allowed.
!
ident      DOVREG      Name of system, max. 8 characters (ident)
l_ac       3314.0       Length con.rod
l_bd       2438.0       Length ecc.rod
l_oa       350.0        Radius to crank pin
l_ob       175.0        Radius to eccentric pin
a_aob      -96.559      Lead angle of eccentric pin wrt. crank pin in degrees
l_de       500.0        Radius from expansion link trunion to tail pin
l_fg       200.0        Length of radius rod from die block to lifting link
l_fh       1511.5      Length of radius rod from comb. lever to die block
l_ck       225.0        Length of drop link
l_jk       498.0        Length og union link
l_js       850.0        Length of comb.lever from union link to 2nd lever
l_hs       125.0        Length of comb.lever from radius rod to 2nd lever
l_mn       475.0        Length of lifting arm
l_gm       250.0        Length of lifting link
l_qr       315.0        Length of front hanger link
l_rs       238.0        Length of 2nd lever from hanger link to comb.lever
l_is       62.0         Length of 2nd lever from comb.lever to valve rod
xy_e       2375.0 -750.0   Coordinates of axis of expansion link
xy_n       2625.0 -959.0   Coordinates of axis of lifting arm
xy_q       4215.0 -378.0   Coordinates of front hanger
xy_i       -660.0        Y-coordinate of valve rod
w_p        60.0         Length of an inlet port in steam chest
w_s        40.0         Length of steam lap on a valve
adm        inside      Steam admission, either 'inside ' or 'outside'
del_nm     9.0          Step between gear angles that are analysed (deg)
i_gear     6            Sequence number of gear angle to be simulated (1:7)
diam       0.7         Cylinder diameter (m)
clr        3.0         Clearance volume in cylinder and ports (%)
su_ht      0.0         Degrees of superheat >=0 (C)

```

p_cut	0.6	Pressure inside cylinder at cut-off (MPa)
p_rel	0.12	Back-pressure, inside cylinder after release (MPa)

Perhaps it is worthwhile to mention that clearance volume, the super-heat, and the pressures in the input files are not actual data for the original locomotives, but ad-hoc values that might be appropriate for the models of these locomotives.

### 6.3 “dovreg” code

All the subroutines from the ‘loco’ program, itself, (not the steamlib) have been duplicated and modified as necessary for the “dovreg” version. In particular, additional constraints are included in subroutine ‘valve\_func’ to take account of the additional components in the mechanism.

## 7 References

- 1 Allan Wallace, «Walschaerts and Stephenson Valvegear Programmes,» <http://www.avocetconsulting.com.au/modeleng/>.
- 2 C.S. Lake & A. Reidinger, “Valves and Valve Gears for Steam Locomotives,” (2008), Tee Publishing Ltd., Leamington Spa.
- 3 J. Mathisen, “Walschaerts ventilstyring,” Lurendreieren Nr. 2, 2016, Medlemsblad for Norsk Modell og Damp Forening.
- 4 <http://www.netlib.no/>, A repository of mathematical software.
- 5 gnuplot homepage, <http://www.gnuplot.info/>
- 6 The International Association for the Properties of Water and Steam, “Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam, (2007), <http://iapws.org/>.
- 7 W.B. Hall, “Measuring Steam Engine Performance.”
- 8 <https://gcc.gnu.org/fortran/>