How to determine allowable steam turbine piping loads

The allowable forces and moments on steam turbine nozzles must be considered if a turbine is expected to operate reliably. Here is a graphical presentation of allowable reactions and an example of how to use this method

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MOST MANUFACTURERS of rotating equipment, such as steam turbines, follow NEMA Standards[1,2] for allowable loads on nozzles. Because of the time required to determine allowable loads by hand calculations, a graphic method of solutions for nominal diameter sizes between 3 inches and 20 inches is presented here.

For rotating machinery, excessive external forces and moments could upset alignment of the casing, thus reducing the minimum clearances needed between rotor and casing. The allowable deflection of the machinery shaft at the coupling which is influenced by external forces and moments is also important. Due to the broadness of this topic, the example is limited to the allowable forces and moments on the inlet and exhaust flanges of single stage steam turbines.

The piping stress analyst, while trying to use the NEMA Code equations, needs more information or explanation of different terms used. By means of this paper, the authors will try to throw some light on different terms used.

The piping systems are first analyzed by digital computers using piping flexibility programs. As a general practice, the stress analyst treats the inlet and exhaust nozzles as separate anchors. The forces and moments acting on these nozzles are obtained from the run condition required as weight, thermal or pressure loading or any combination of these. The NEMA Codes are then applied to see whether the actual forces and moments obtained from flexibility analysis are below allowable code values. Pertinent portions of NEMA Code are given here to aid the discussion.

LOCAL ALLOWABLE FORCES AND MOMENTS

The forces and moments acting on mechanical-drive steam turbines due to the steam inlet, extraction and exhaust connections are limited by the following rule:

1. The total resultant force and total resultant moment imposed on the turbine at any connection must not exceed the following:

$$F = \frac{500D - M}{3} \qquad (1)$$

F — Resultant force (pounds), including pressure forces where unrestrained expansion joints are used at the connection except on vertical exhausts.

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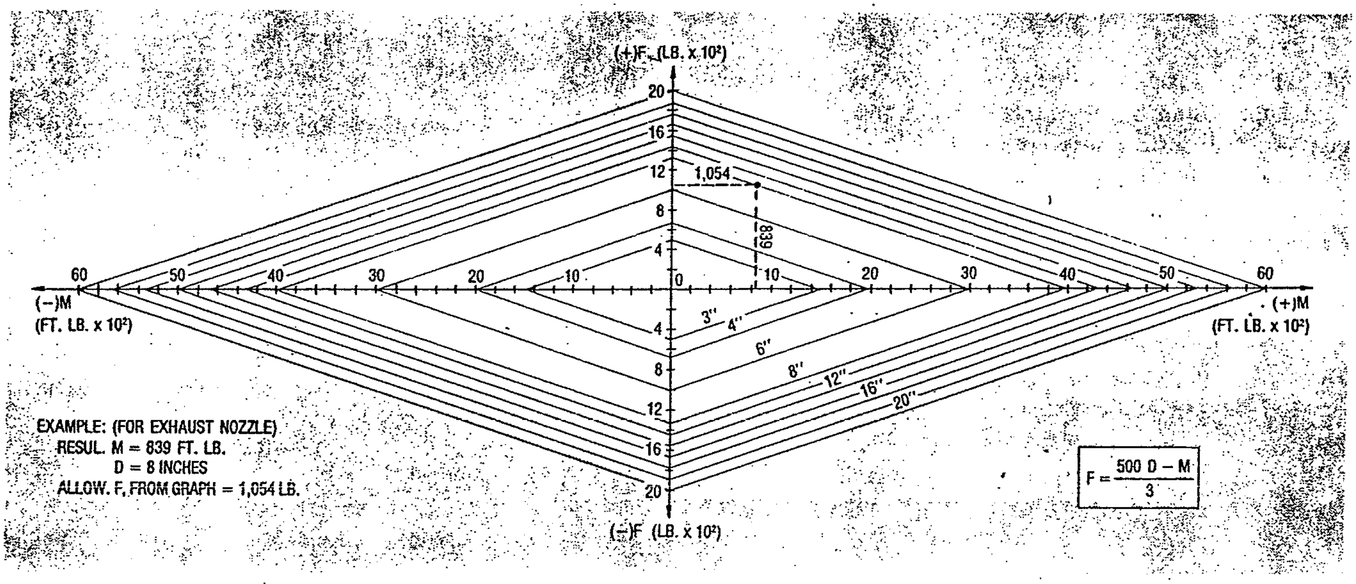

Fig. 1—NEMA allowable local resultant forces and moments on steam turbine flanges.

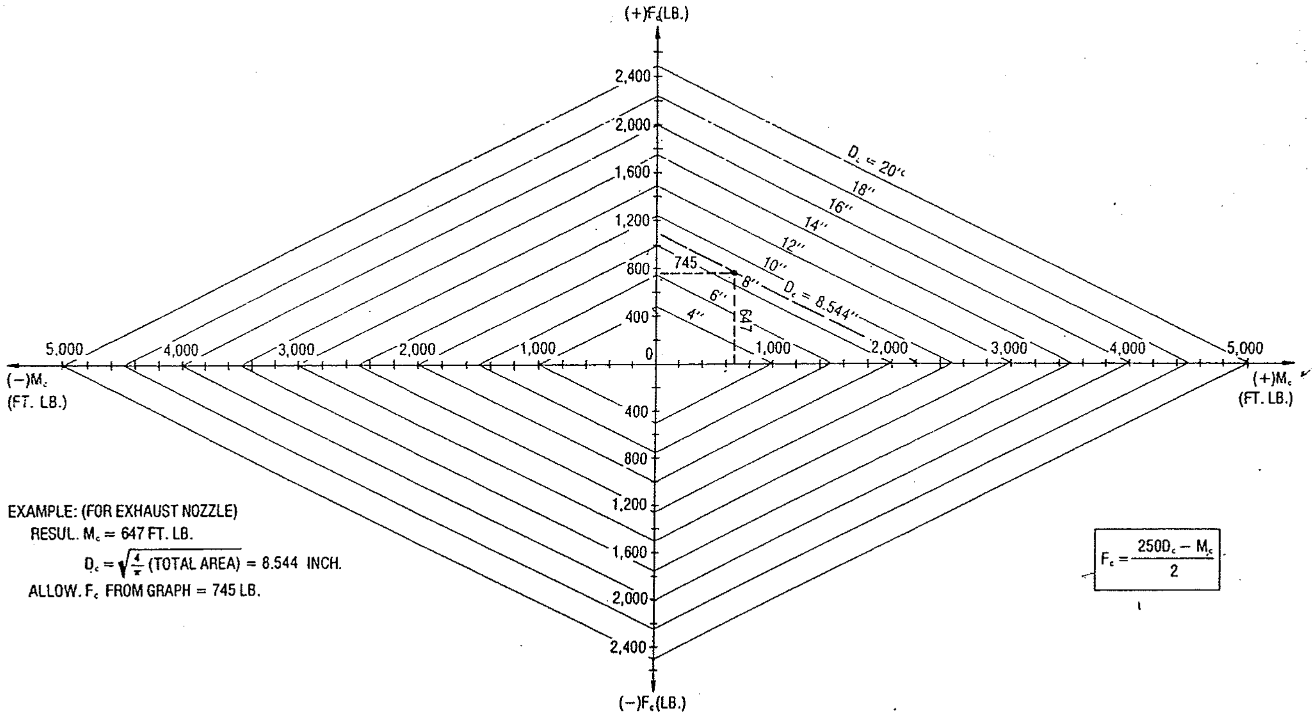

Fig. 2—NEMA allowable combined resultant forces and moments on steam turbine flanges.

M — Resultant moment (pound-feet).
D — Pipe size of the connection (I.P.S.) in inches up to 8 inches in diameter. For sizes greater than this, use a value of D equal to $\frac{(16 + \text{I.P.S.})}{3}$ inches.

The diameter, *D*, used here is the nominal diameter. The usage of nominal diameter here was clarified with NEMA. The term I.P.S. in the code stands for iron pipe size and denotes here nominal pipe diameter. As an example, for 8-inch, Sch. 20 pipe, the nominal diameter, or iron pipe size, is 8 inch, whereas O.D. is 8.625 inch and I.D. is 8.125 inch.

When the resultant moment is equal to 500*D*, the allowable resultant force is zero. This is the limit of this equation. Any further increase in *M*, will give a negative value for *F* which is meaningless even though some interpret the negative sign for *F* as force in the opposite direction.

It can be easily seen that Equation 1 is of straight line form and can be represented graphically for various values of the nominal diameter, *D*. The authors developed the graphical form for equation 1 and it is presented here as Fig. 1. Example problem given at the end of this article explains the use of this graph.

COMBINED RESULTANTS AND THEIR COMPONENTS

NEMA Code equations 2a and 2b define the allowable values for combined resultants and their components. The two equations are given below.

The combined resultants of the forces and moments of the inlet, extraction and exhaust connections, resolved at the centerlines of the exhaust connection must not exceed the following two conditions:

2a. These resultants must not exceed:

$$F_C = \frac{250\ D_C - M_C}{2} \qquad \text{(2a)}$$

F_C — Combined resultant of inlet, extraction and exhaust forces, pounds.
M_C — Combined resultant of inlet, extraction and exhaust moments and moments resulting from forces, pound-feet.
D_C — Diameter (in inches) of circular opening equal to the total areas of the inlet, extraction and exhaust openings up to a value of 9 inches in diameter. For values beyond this, use a value of D_C equal to $\left(\frac{18 + \text{Equivalent diameter}}{3}\right)$ inches

Equation 2 (a) is represented in graphical form and is given as Fig. 2.

2b. The components of these resultants shall not exceed:

$F_y = 125D_c$ $\quad M_y = 125D_c$
$F_z = 100D_c$ $\quad M_z = 125D_c$
$F_x = 50D_c$ $\quad M_x = 250D_c$
F_y — vertical component of F_c.
F_z — horizontal component of F_c at right angles to turbine shaft.

Continued

F_x — horizontal component of F_c parallel to turbine shaft.
M_x — component of M_c in a vertical plane at right angles to turbine shaft.
M_y — component of M_c in a horizontal plane.
M_z — component of M_c in a vertical plane parallel to the turbine shaft.

The coordinate system used in the NEMA Code is shown in Figure 3. The diameter D_c is calculated as follows:

D_c = equivalent diameter up to 9″ diameter

$$= \left(\frac{18 + \text{equivalent diameter}}{3} \right) \text{for diameter greater than } 9''.$$

$$\text{where equivalent diameter} = \sqrt{\frac{4}{\pi}(\text{total area})}$$

Equivalent diameter for circular openings =

$$\sqrt{D^2_{\text{Inlet Nominal}} + D^2_{\text{Exhaust Nominal}}}$$

Total area is the total of inlet, exhaust and extraction areas using the nominal diameters. The usage of inside diameter, because of the presence of the word "openings" in the code, may not be correct since the flow characteristics are not considered here.

COMPONENTS OF ACTUAL RESULTANTS

As required by Equation 2 (a) the forces and moments at the inlet nozzle, are to be transferred to the exhaust nozzle.

The following equations are used to obtain the components of the actual resultant forces and moments along the specified axis at the exhaust nozzle.

$$\begin{aligned}
\Sigma F_x &= F_x\ (\text{inlet}) + F_x\ (\text{exhaust}) \\
\Sigma F_y &= F_y\ (\text{inlet}) + F_y\ (\text{exhaust}) \\
\Sigma F_z &= F_z\ (\text{inlet}) + F_z\ (\text{exhaust}) \\
\Sigma M_x &= M_x\ (\text{inlet}) + M_x\ (\text{exhaust}) \\
&\quad - F_y\ (\text{inlet})\ (Z_1) + F_z\ (\text{inlet})\ (Y_1) \\
\Sigma M_y &= M_y\ (\text{inlet}) + M_y\ (\text{exhaust}) \\
&\quad + F_x\ (\text{inlet})\ (Z_1) - F_z\ (\text{inlet})\ (X_1) \\
\Sigma M_z &= M_z\ (\text{inlet}) + M_z\ (\text{exhaust}) \\
&\quad - F_x\ (\text{inlet})\ (Y_1) + F_y\ (\text{inlet})\ (X_1)
\end{aligned} \qquad (3)$$

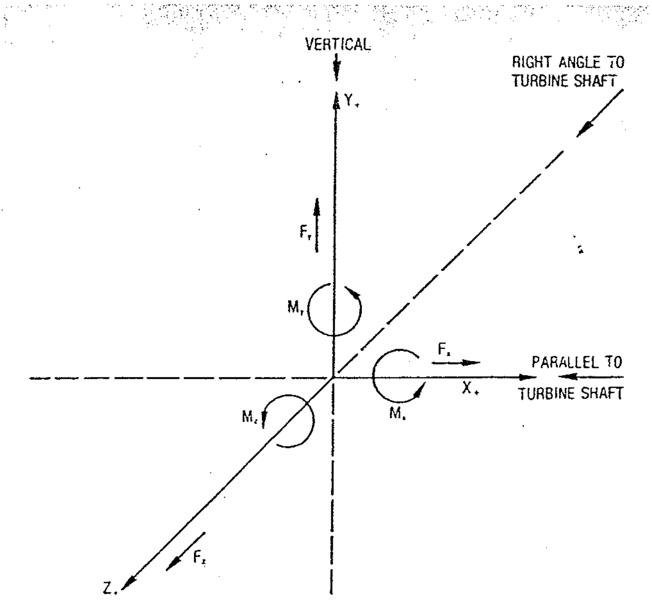

Fig. 3—Coordinate system used in NEMA code.

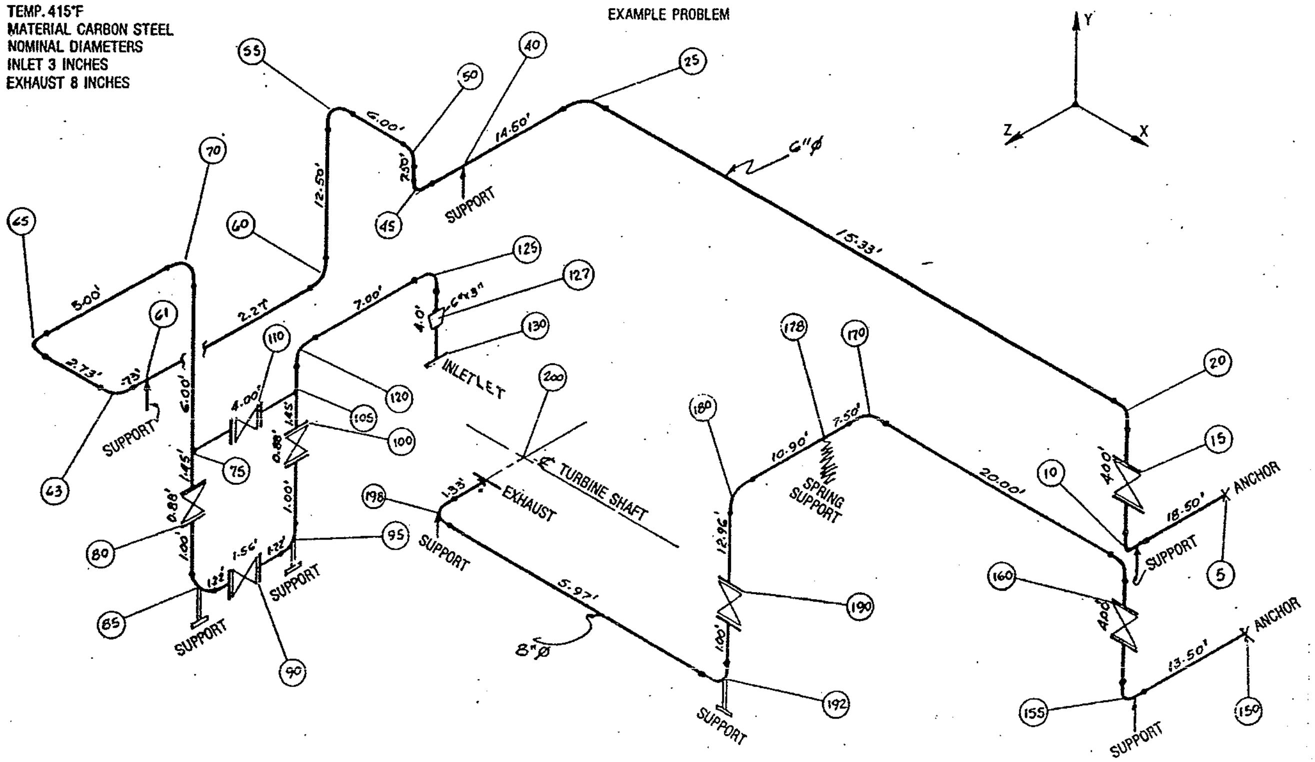

Fig. 4—Typical steam turbine piping system.

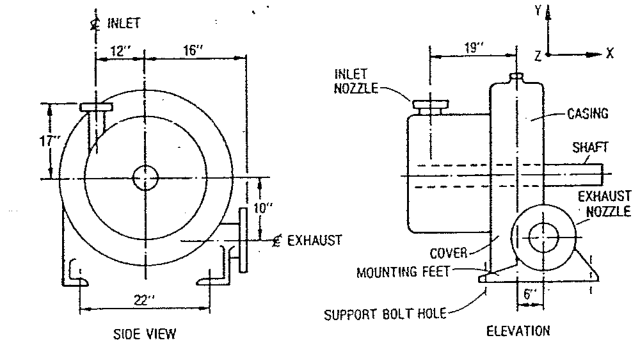

Fig. 5—Typical single stage vertically split steam turbine.

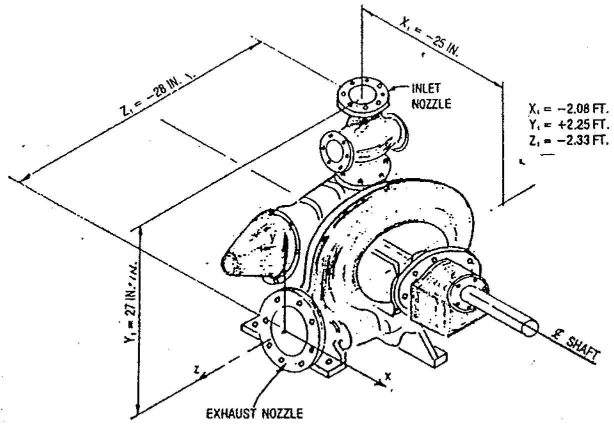

Fig. 6—X, Y, Z distances used in the example problem for Equations 3.

The summation sign is used in Equation 3 to denote that these are the components of the resultants after being transferred to the exhaust nozzle. The distances X_1, Y_1, Z_1, are linear distances from the exhaust nozzle to the inlet nozzle. The orientation of the X, Y, Z axes of piping isometrics should be the same as the coordinate system used in NEMA Code.

EXAMPLE PROBLEM

General layout of the piping system in consideration here is given as Fig. 4. The numbers inside circles are the reference data points for the computer program used. The steam turbine used in this example is a vertically split single stage turbine, the outline dimensions of which are given in Fig. 5.

The orientation of X, Y and Z axes and the distances X_1, Y_1, and Z_1 for the example problem are shown in Fig. 6. The distances are from the exhaust nozzle to the inlet nozzle. The minus sign shown with X_1 and Z_1 distances correspond with moment summations from Equations 3. The sign for these distances depend upon location of inlet nozzle with respect to exhaust nozzle in the NEMA coordinate system.

Local forces and moments at the inlet and exhaust nozzles obtained from flexibility analysis are listed in Table 1. These forces and moments will be used in further calculations.

TABLE 1—Computer results of forces and moments at each turbine nozzle

LOCAL FORCES AND MOMENTS	AT INLET NOZZLE, 130	AT EXHAUST NOZZLE, 200
F_x, Lb	– 30.	– 155.
F_y	– 55.	1095.
F_z	204.	170.
$F = \sqrt{F_x^2 + F_y^2 + F_z^2}$	213.	1119.
M_x, Ft. Lb.	120.	44.
M_y	– 67.	– 425.
M_z	124.	– 722.
$M = \sqrt{M_x^2 + M_y^2 + M_z^2}$	185.	839.

Actual forces and moments:

Resultant force at exhaust nozzle,

$$\begin{aligned} F &= \sqrt{F_x^2 + F_y^2 + F_z^2} \\ &= \sqrt{(-155)^2 + (1095)^2 + (170)^2} \\ &= 1119 \text{ Lb.} \end{aligned}$$

Resultant force at inlet nozzle,

$$\begin{aligned} F &= \sqrt{(-30)^2 + (-55)^2 + (204)^2} \\ &= 213 \text{ Lb.} \end{aligned}$$

Resultant moment at exhaust nozzle,

$$\begin{aligned} M &= \sqrt{(44)^2 + (-425)^2 + (-722)^2} \\ &= 839 \text{ Ft. Lb.} \end{aligned}$$

Resultant moment at inlet nozzle,

$$\begin{aligned} M &= \sqrt{(120)^2 + (-67)^2 + (124)^2} \\ &= 185 \text{ Ft. Lb.} \end{aligned}$$

Components of resultant forces and moments after being transferred to exhaust:

using equation (3),

$$\begin{aligned} \Sigma F_x &= F_x \text{ (inlet)} + F_x \text{ (exhaust)} \\ &= (-30.) + (-155.) \\ &= -185 \text{ Lb.} \\ \Sigma F_y &= -55 + 1095 = 1040. \\ \Sigma F_z &= 204 + 170 = 374 \\ \Sigma M_x &= M_x \text{ (inlet)} + M_x \text{ (exhaust)} - F_y \text{ (inlet) } Z_1 \\ &\quad + F_z \text{ (inlet) } Y_1 \\ &= 120 + 44 - (-55)\ (-2.33) + (204)\ (+2.25) \\ &= 494.85 \text{ Ft. Lb.} \\ \Sigma M_y &= M_y \text{ (inlet)} + M_y \text{ (exhaust)} + F_x \text{ (inlet) } Z_1 \\ &\quad - F_z \text{ (inlet) } X_1 \\ &= -67 - 425 + (-30)\ (-2.33) \\ &\quad - (204)\ (-2.08) \\ &= 2.22 \text{ Ft. Lb.} \\ \Sigma M_z &= M_z \text{ (inlet)} + M_z \text{ (exhaust)} - F_x \text{ (inlet) } Y_1 \\ &\quad + F_y \text{ (inlet) } X_1 \\ &= 124. - 722. - (-30)\ (+2.25) \\ &\quad + (-55)\ (-2.08) \\ &= -416 \text{ Ft. Lb.} \end{aligned}$$

Continued

Combined resultant force and moment after being transferred to exhaust:

Combined resultant force at exhaust

$$= \sqrt{(-185)^2 + 1040^2 + 374^2}$$
$$= 1121 \text{ Lb.}$$

Combined resultant moment at exhaust

$$= \sqrt{494.85)^2 + (2.22)^2 + (-416)^2}$$
$$= 647. \text{ Ft. Lb.}$$

Allowable local forces and moments

NEMA Rule 1 is applied to calculate allowable forces and moments at each nozzle.

Exhaust nozzle:

$$\text{Allowable resultant force, } F = \frac{500D - M}{3}$$
$$= \frac{500\ (8) - 839}{3} = 1053.66 \text{ Lb.}$$

Using Figure 1, the graphical form of Equation 1, allowable resultant force F at the exhaust nozzle is obtained as 1054 lb. This particular calculation is marked with a dotted line as an example on Fig. 1.

Inlet nozzle:

$$\text{Allowable resultant force, } F = \frac{500\ (3) - 185}{3}$$
$$= 438.33 \text{ Lb.}$$

Allowable components of resultant forces and moments after being transferred to exhaust:

Using Equation 2b;

$$\text{Equivalent diameter} = \sqrt{D_{(inlet)}^2 + D_{(exhaust)}^2}$$
$$= \sqrt{3^2 + 8^2} = 8.344 \text{ inch.}$$

This is below 9 inch limit for diameter given in NEMA Code. Therefore, D_C = Equivalent diameter = 8.544 inch.

$$F_y = 125\ D_C = 125\ (8.544)$$
$$= 1068. \text{ Lb.}$$
$$F_z = 100\ (8.544) = 854.4$$
$$F_x = 50\ (8.544) = 427.$$
$$M_y = 125\ (8.544) = 1068 \text{ Ft. Lb.}$$
$$M_z = 125\ (8.544) = 1068.$$
$$M_x = 250\ (8.544) = 2136$$

About the authors

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Allowable combined resultant force and moment at exhaust:

Using Equation 2a,

$$\text{Allowable combined resultant force, } F_C = \frac{250D_C - M_C}{2}$$
$$= \frac{250\ (8.544) - 647}{2}$$
$$= 744.5 \text{ Lb.}$$

Fig. 2 can be used to obtain the allowable combined resultant force, F_C as 745 lb. This calculation is marked with a dotted line as an example in Fig. 2.

TABLE 2—Actual and allowable forces and moments

NOZZLE	ACTUAL VALUES	ALLOWABLE VALUES BY NEMA	REMARKS
Inlet	Result. F = 213 Lb.	Result. F = 438.	O.K.
Exhaust	Result. F = 1119 Lb.	Result. F = 1054.	Exceeds
Combined Components	$\Sigma F_x = -185.$	$F_x = 427$	O.K.
	$\Sigma F_y = 1040.$	$F_y = 1068$	O.K.
	$\Sigma F_z = 374.$	$F_z = 854$	O.K.
	$\Sigma M_x = 495.$	$M_x = 2136.$	O.K.
	$\Sigma M_y = 2.$	$M_y = 1068.$	O.K.
	$\Sigma M_z = -416.$	$M_z = 1068.$	O.K.
Combined Resultant	$F_C = 1121.$	$F_C = 745.$	Exceeds
	$M_C = 647.$		

The actual and allowable forces and moments are tabulated in Table 2. As can be seen, the local allowable resultant force at the exhaust (1119 Lb) exceeds the NEMA allowable force (1054. lb). Also the combined resultant force (1121 lb) exceeds the allowable force (745. lb). The situation may be corrected by altering the piping system slightly. The manufacturers of the turbine may also be contacted. They may allow higher values for allowables based on the strength of the particular turbine in question. When large turbines are analyzed, it would be advisable to use another method of summing forces and moments.[3]

It is the experience of the authors that the allowable values obtained by using NEMA Code are conservative. It would be extremely helpful if NEMA, in its next revision to the Code, publishes the basis and criteria of the equations. The authors hope that this paper and the example problem will help the people in the industry to understand the terms used in NEMA equations and that the graphical form will reduce calculation time.

ACKNOWLEDGMENT:

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LITERATURE CITED

[1] National Electrical Manufacturer's Association, Pub. No. SM-21-1970, "Multi-Stage Steam Turbines for Mechanical Drive Service."
[2] NEMA Pub. No. SM22-1970, "Single Stage Steam Turbines for Mechanical Drive Service."
[3] General Electric Co. Publication, "Steam Piping Systems Connected to Turbines."