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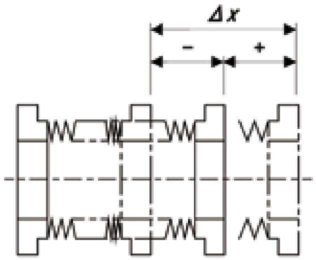
Design Guidelines and Troubles for DYNAMICBELLOWS™ and Countermeasures

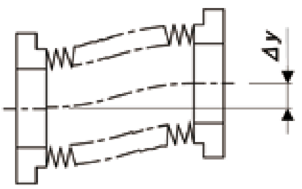
1. Introduction

The functions of welded metal DYNAMICBELLOWS™ (hereafter "Bellows") are to absorb displacement parallel with the axis, perpendicular to the axis, and in a bending direction as shown in Figure1. The Bellows absorb displacement while maintaining airtightness. When selecting Bellows that absorb displacement parallel with the axis, it is easy to select from the catalog, but for Bellows that absorb displacement perpendicular to the axis and in a bending direction, selection is often difficult.

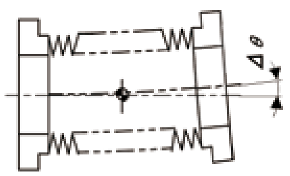
Also, when the Bellows' inner pressure is greater than the outside pressure to maintain airtightness, buckling sometimes develops as shown in Figure2, resulting in the risk of deformation and breakage. Therefore, care is required when designing.



Displacement parallel with axis (Δx)

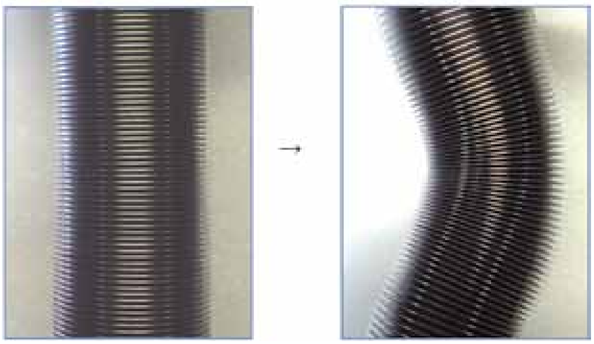


Displacement perpendicular to axis (Δ y)



Displacement in bending direction (Δθ)

Figure1 Types of displacement



Before buckling After buckling

Figure2 Bellows' buckling

In addition, when Bellows are attached in a horizontal direction, the Bellows' own weight causes horizontal deflection as shown in Figure3. Therefore, care is required like the case of buckling.

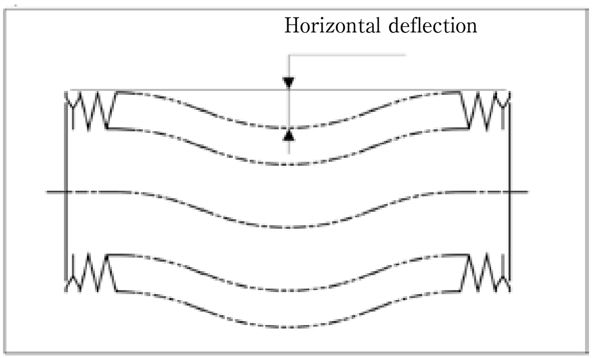


Figure3 Bellows' horizontal deflection

This article examines the case of our standard product V series (catalog No. PC08), and describes the selection method for Bellows that absorb displacement perpendicular to the axis, and design considerations for buckling and horizontal deflection.

2. Design guidelines for Bellows

2-1) Concept of displacement perpendicular to the axis

When investigating the Bellows' displacement perpendicular to the axis, first the displacement perpendicular to the axis is converted into the displacement parallel with the axis, using the equation:

$$\Delta x(y) = \frac{3 \times D \times \Delta y}{L} \qquad \cdots\cdots\cdots\cdots (1)$$

where, Δx (y) : value converted into displacement parallel with axis (mm)
D : Bellows' outside diameter (mm)
Δy : displacement perpendicular to axis (mm)
L : Bellows' length (mm)

When the converted allowable displacement parallel with the axis is known, the allowable displacement perpendicular to the axis can then be calculated by the equation:

$$\Delta y(\max) = \frac{\Delta x(y) \times L}{(3 \times D)} \qquad \cdots\cdots\cdots\cdots (2)$$

where, Δy (max) : allowable displacement perpendicular to axis (mm).

2-2) Combination of displacement parallel with axis and displacement perpendicular to axis

In Section 2-1), only displacement perpendicular to the axis was given. However, generally, Bellows are often used with both displacement perpendicular to the axis and displacement parallel with the axis. According to Equation (1), the smaller L is, the larger the converted displacement parallel with the axis Δx (y). Therefore, the calculation should be made to minimize L under the influence of displacement parallel with the axis.

In this case, Equation (1) becomes:

$$\Delta x(y) = \frac{3 \times D \times \Delta y}{(L - \Delta x)} \qquad \cdots\cdots\cdots\cdots (3)$$

Equation (2) becomes:

$$\Delta y(\max) = \frac{\Delta x(y) \times (L - \Delta x)}{(3 \times D)} \qquad \cdots\cdots\cdots\cdots (4)$$

However, Δx is displacement parallel with the axis on the contraction side (mm).

Regarding Sections 2-1) and 2-2), the shape of Bellows with displacement perpendicular to the axis is such that expanded parts and contracted parts are combined as shown in Figure4. Therefore, regarding the

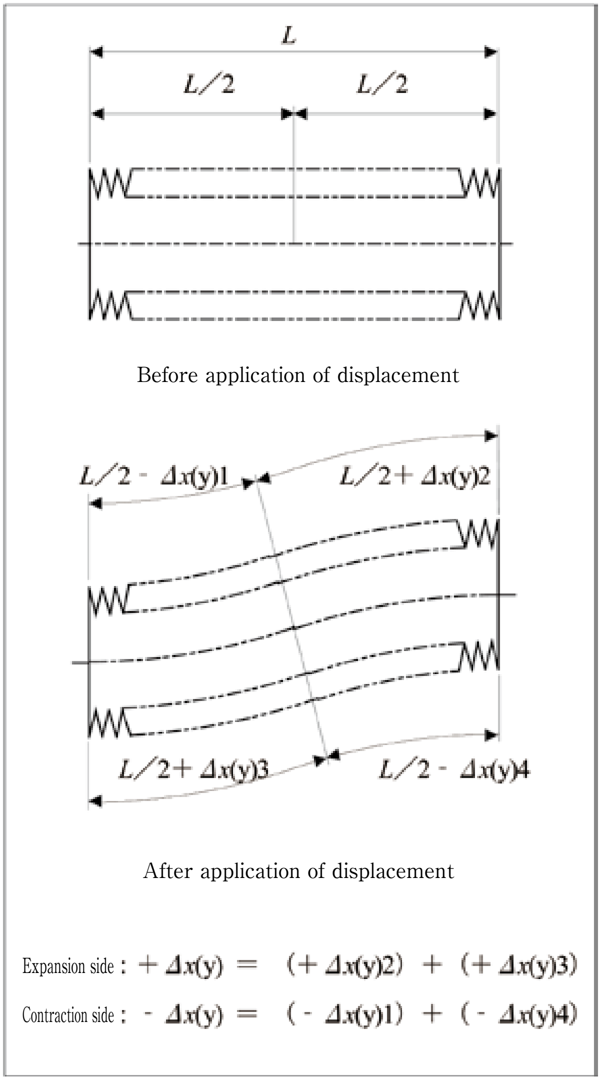


Figure4 Shape of displacement perpendicular to axis

converted displacement parallel with the axis Δx (y), allowance ranges should be prepared for both the expansion side and the contraction side.
Therefore, a Bellows with a length of L is given the value of "+Δx (y) and -Δx (y) ."

3. Selection procedure for V series

3-1) When only displacement perpendicular to the axis is present

Based on the design guidelines described above, we consider the selection of V series (Catalog No. PC08). Refer to the catalog and follow the steps.
Figure5 shows the selection flow. Each step is described below.

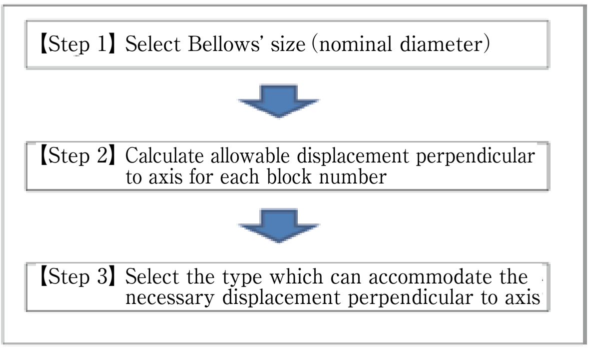


Figure5 Selection procedure for V Series

【Step 1】Select the Bellows size (nominal diameter)

Based on the space in which the Bellows is attached, the Bellows size (nominal diameter) is selected. Here, we selected V20.

Catalog value of V20 (1-block specification)

Internal diameter = 20mm,
Outside diameter = 40mm
Expansion and contraction length = 10mm,
Expansion length = 15mm,
Contraction length = 5mm

【Step 2】Calculate the allowable displacement perpendicular to the axis for each block number

For the selected size (nominal diameter), the allowable displacement perpendicular to the axis is calculated for each block number.

In the case of 1 block:

Expansion and contraction length = 10mm, Expansion length = 15mm, Contraction length = 5mm
In this case, the Bellows length L = 10mm, Δx = ±5mm.
According to Equation (2) ,

$$\Delta y\,(\max) = \frac{5 \times 10}{(3 \times 40)} \fallingdotseq 0.4\text{mm}$$

In the case of 2 blocks:

Expansion and contraction length = 20mm, Expansion length = 30mm, Contraction length = 10mm
In this case, the Bellows length L = 20mm, Δx = ±10 mm.
According to Equation (2) ,

$$\Delta y(\max) = \frac{10 \times 20}{(3 \times 40)} = 1.6\text{mm}$$

In the same manner, increase the block number and calculate for each block number. Table1 shows the results.

Table1 V20's block number and displacement amount

Block number	1	2	3	4	5
L (mm)	10	20	30	40	50
Δx (mm) ±	5	10	15	20	25
Δy (max) (mm)	0.4	1.6	3.7	6.6	10.4

【Step 3】 Determine the type which can accommodate the necessary displacement perpendicular to the axis

Select the block number which can accommodate the necessary displacement perpendicular to the axis and select the Bellows type.
For example, if the necessary displacement perpendicular to the axis is 5mm, the block number is 4 according to Table 1. So, the required type is V20-111-4.
Regarding the Bellows length L, note that the length excludes the length of fittings on both ends. In the case of V20-111-4, this length on both ends is 3mm, so the overall length is 46mm.

3-2) Displacement perpendicular to the axis and displacement parallel with the axis

In the case where there is both displacement perpendicular to and parallel with the axis, as shown in Section 2-2) , the calculation should be made with the length which becomes minimum under the effects of displacement parallel with the axis. The selection flow is the same as in Figure5.

【Step 1】Select the Bellows size (nominal diameter)

Based on the space in which the Bellows is attached, the Bellows size (nominal diameter) is selected. Here, we selected V30.

Catalog value of V30 (1-block specification)

Internal diameter =30mm, Outside diameter =50mm

Expansion and contraction length = 10mm, Expansion length = 15mm, Contraction length = 5mm

【Step 2】Calculate the allowable displacement perpendicular to the axis for each block number

For the selected size (nominal diameter), the allowable displacement perpendicular to the axis against displacement parallel with the axis is calculated for each block number. When the necessary displacement parallel with the axis is 10mm and the block number is 1, the converted displacement parallel with the axis Δx (y) is 0. Therefore, at least 2 blocks are needed.

In the case of 2 blocks:

Expansion and contraction length = 20mm, Expansion length = 30 mm, Contraction length = 10mm

Bellows length L = 20mm; when there is only displacement parallel with the axis, then Δx of up to ±10mm is acceptable.

When the necessary displacement parallel with the axis of 10 mm is Δx = ±5mm, Δx (y), the converted value of allowable displacement parallel with the axis when displacement perpendicular to the axis is applied, is 5mm (10mm – 5mm = 5mm).

According to Equation (4),

$$\Delta y(\max) = \frac{5 \times (20-5)}{(3 \times 50)} = 0.5\ \text{mm}$$

In the case of 3 blocks:

Expansion and contraction length = 30mm, Expansion length = 45mm, Contraction length = 15mm

Bellows length L = 30mm; when there is only displacement parallel with the axis, Δx of up to ±15mm is acceptable.

When the necessary displacement parallel with the axis of 10mm is Δx = ±5mm, Δx (y), the converted value of allowable displacement parallel with the axis when displacement perpendicular to the axis is applied, is 10 mm (15mm – 5mm = 10mm).

According to Equation (4),

$$\Delta y(\max) = \frac{10 \times (30-5)}{(3 \times 50)} = 1.6\ \text{mm}$$

In the same manner, increase the block number and calculate for each block number. Table2 shows the results.

Table2 V30's block number, displacement parallel with the axis, displacement perpendicular to the axis

Block number	2	3	4	5	6
L (mm)	20	30	40	50	60
Δx (mm) ±	5	5	5	5	5
Δx (y) (mm) ±	5	10	15	20	25
Δy (max) (mm)	0.5	1.6	3.5	6.0	9.1

【Step3】Determine the type which can accommodate the necessary displacement perpendicular to the axis

Select the block number which can accommodate the necessary displacement perpendicular to the axis and select the Bellows type.

For example, if the necessary displacement perpendicular to the axis is 5mm, the block number is 5 according to Table2. So, the required type is V30-111-5. The Bellows length including the fitting length on both ends is 56mm.

4. Design troubles and countermeasures

4-1) Investigation of Bellows' buckling

One of the design problems of Bellows is buckling. Bellows, like columns and springs, suffer buckling due to compressive forces and lose straightness. Refer to Figure2.

This buckling threshold value can be approximated by using the widely-used Euler's formula:

$$Fcr = \frac{4 \times \pi^2 \times EI}{L^2} \quad \cdots\cdots\cdots\cdots \ (5)$$

where, Fcr : buckling load limit (N)

EI: Bellows' bending stiffness (N・mm^2)

L : Bellows' length (mm)

Note : Regarding EI, refer to *Valqua Review* Vol. 40, 1st issue.[1)]

4-2) Bellows' buckling pressure

When Bellows are subjected to internal pressure, the limit pressure which triggers buckling, or buckling pressure, can be calculated assuming that thrust develops in response to the pressure applied to the effective area of the Bellows, and that the buckling load is equivalent to the thrust.

$$Pcr = \frac{4 \times \pi^2 \times EI}{(A \times L^2)} \quad \cdots\cdots\cdots\cdots (6)$$

$$A = \left(\frac{(d+D)}{2}\right)^2 \cdot \frac{\pi}{4} \quad \cdots\cdots\cdots\cdots (7)$$

where, Pcr : Bellows' buckling pressure (MPa)
A : Bellows' effective area (mm^2)
d : Bellows' inner diameter (mm)
D : Bellows' outside diameter (mm)

In this case, the longer the Bellows length L becomes, the smaller the buckling pressure becomes, reducing the strength against buckling. Therefore, when calculating, the maximum service length (expansion length) should be used.

When the pressure significantly exceeds this limit pressure, the Bellows will buckle and not expand or contract, which may result in deformation, a shorter lifespan or early breakage.

Figure6 shows a case of breakage due to buckling.

Figure6 Breakage due to buckling of Bellows

4-3) Investigation of V Series' buckling

Next, we examine the buckling of our standard product V Series (Catalog No. PC08). Refer to the catalog and follow the steps.

In the catalog, one column shows the block number limitation. This shows the case in which the V Series' allowable pressure of 0.1 MPa is outside pressure and the case in which the allowable pressure is the internal pressure. Among these block numbers, when the allowable pressure is internal pressure, the block number limitation is determined based on the buckling pressure explained in Section 4-2).

An example of calculating the buckling pressure is shown below.

Example 1. According to Equation (6) when the block number is 4 which is V20's block number limit,

$$Pcr = \frac{4 \times \pi^2 \times 15477}{(706.86 \times 60^2)} = 0.24 \quad \text{MPa}$$

In this case, the Bellows length L is calculated using the expansion length.

The details of EI are omitted here.

When the block number is 4, L is 60mm (expansion length 15mm × 4 blocks = 60mm) .

Regarding the Bellows' effective area A, according to Equation (7),

$$A = \left(\frac{(20+40)}{2}\right)^2 \times \frac{\pi}{4} = 706.86 \quad mm^2$$

Example 2. According to Equation (6), when the block number is 6 which is V100's block number limit,

$$Pcr = \frac{4 \times \pi^2 \times 485068}{(10386.89 \times 90^2)} = 0.22 \quad \text{MPa}$$

In this case, when the block number is 6, the Bellows length L is 90mm (15mm × 6 blocks = 90mm) .

Regarding the Bellows' effective area A, according to Equation (7),

$$A = \left(\frac{(100+130)}{2}\right)^2 \times \frac{\pi}{4} = 10386.89 \quad mm^2$$

Based on the results of the above calculation, the inner pressure of 0.1 MPa is not greater than the buckling pressure, so buckling does not develop.

When the block number which can be used for the necessary displacement parallel with the axis is selected and the selected block number is greater than the block number limitation, the guide shown in the catalog should be attached. This guide is shown in Section 4-4) below.

4-4) Countermeasures to prevent buckling

When the block number exceeds the block number limitation, a guide should be attached. An example of the structure is as follows.

【Example 1】When a shaft is present on the inside of the Bellows

Figure7 is a frequently used structure.

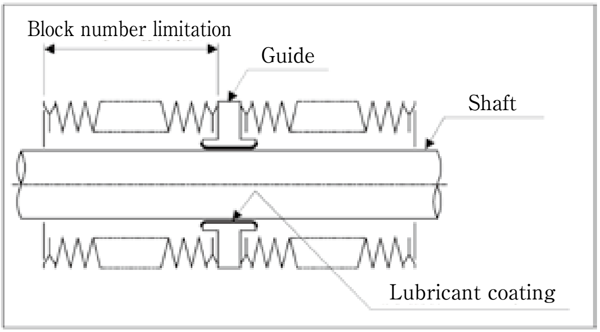


Figure7　A guide inner surface is coated with lubricant

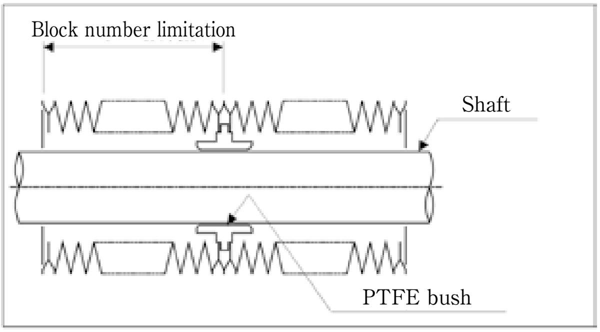


Figure8　A PTFE bush is attached to the guide inner surface

【Example 2】When a shaft is absent on the inside of the Bellows

The structure becomes more complex and accurate positioning of the guide rod is needed.

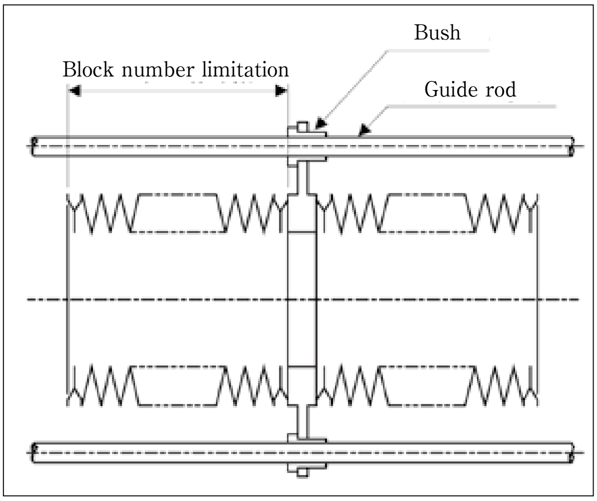


Figure9　Guide rods are placed on the surroundings

As shown above, guides should be placed at every location where the block number is equal to or less than the block number limitation.

When displacement perpendicular to the axis is present, guides cannot be placed. Therefore, displacement perpendicular to the axis which is greater than the block number limitation is not acceptable.

4-5) Block number limitation using outside pressure

The V Series' block number limitation is shown when the outside pressure is 0.1 MPa. In this case, we do not calculate the buckling pressure; we calculate the Bellows' horizontal deflection (refer to Figure3) to prevent the horizontal deflection from exceeding 1mm, using the equation:

$$y(\max) = \frac{9.8 \times W \times L^3}{(384 \times EI)} \quad \cdots (8)$$

where, y (max) : Bellows' horizontal deflection (mm)
W : Bellows' weight (kg)
L : Bellows' length (mm)
EI : Bellows' bending stiffness ($N \cdot mm^2$)

In this equation, the effects of outside pressure are ignored. When outside pressure is applied, the

Bellows' deflection is considered to decrease. Therefore, in this equation, we calculate values when the Bellows inside/outside pressure is atmospheric pressure.

Example 1) According to Equation (8), when the block number is 9 which is V20's block number limit,

$$y(\max) = \frac{9.8 \times 0.13 \times 135^3}{(384 \times 15477)} = 0.53 \quad \text{mm}$$

In this case, the Bellows length L is calculated using the expansion length.
The details of EI are omitted here.
When the block number is 9, L is 135mm (15mm × 9 blocks = 135mm). Also, the Bellows' weight W is 0.13kg.

Example 2) According to Equation (8), when the block number is 20 which is V210's block number limit,

$$y(\max) = \frac{9.8 \times 5.32 \times 300^3}{(384 \times 5653926)} = 0.65 \quad \text{mm}$$

In this case, when the block number is 20, L is 300 mm (expansion length 15mm × 20 blocks = 300mm) and the Bellows' weight W is 5.32kg.

4-6) Countermeasures to prevent horizontal deflection

When the block number exceeds the block number limitation, a guide should be attached. An example of the structure is similar to the example shown in Section 4-4).

5. Conclusion

This article described the case of our standard DYNAMICBELLOWS™ V series (catalog No. PC08) and examined the selection method when Bellows absorb displacement perpendicular to the axis, and design considerations regarding the block number limitation.
As noted already, when Bellows with a length longer than the block number limitation are used, there are risks of deformation, a shorter lifespan, and breakage, so care is required.
We hope that this article will help prevent design problems when selecting the V Series.

6. References

1) *Valqua Review* Vol.39, 4th issue, Lecture on seals (23)
Vol.39, 5th issue, Lecture on seals (24)
Vol.39, 6th issue, Lecture on seals (25)
Vol.39, 7th issue, Lecture on seals (26)
Vol.40, 1st issue, Lecture on seals (27)
Vol.40, 9th issue, Lecture on seals (28)

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