醫工學會誌：第 13 卷 第 3 號, 1992
J. of KOSOMBE : Vol. 13, No. 3

研 究 論 文
92 - 13 - 3 - 08

Impact Behavior Analysis of Mechanical Monoleaflet Heart Valve Prostheses in the Opening Phase

Gill Jeong Cheon*, K. B. Chandran**

= Abstract =

In this paper, fluttering behavior of mechanical monoleaflet tilting disc heart valve prostheses during the opening phase was analyzed taking into consideration the impact between the occluder and the guiding strut at the fully open position. The motion of the valve occluder was modeled as a rotating system, and equations were derived by employing the moment equilibrium principle. Forces due to lift, drag, gravity and buoyancy were considered as external forces acting on the occluder. The 4th order Runge-Kutta method was used to solve the governing equations. The results demonstrated that the occluder reaches steady equilibrium position only after damped vibration. Fluttering frequency varies as a function of time after opening and is in the range of 8-84 Hz. Valve opening appears to be affected by the orientation of the valve relative to gravitational force. The opening velocities are in the range of 0.65-1.42m/sec and the dynamic loads by impact of the occluder and the strut are in the range of 90-190 N.

I. INTRODUCTION

The hemodynamic characteristics of flow past heart valve prostheses including back flow, velocity distribution near the occluder, energy loss, pressure drop, regions of flow seperation, and dynamic behavior of the occluder are closely related to thrombosis and fatigue failure(Schoen et al., 1982 ; Unsworth and Drury, 1986). The opening and closing characteristics of the valve occluders depend upon the dynamic interactions between the occluder and the fluid. Very few studies have been reported on the dynamic behavior of the occluders in heart valve prostheses. Sikarskie et al.(1984) as well as Mazumdar and Knight(1984) have reported on the heart valve sounds by vibration analysis. Hung and Schuessler(1977) and Peskin(1972) studied the time dependent motion of the tissue valve leaflets, and Reif et al.(1986) reported on the dynamics of a monoleaflet valve occluder. But the above studies did not consider fluttering which is observed during the initial systolic phase at the maximum opening angle.

Prabhu and Hwang(1988) considered the fluttering motion of the occluder by using the concept of lift force, and indicated that the fluttering of the occluder might be the result of vortex shedding at the back of the occluder. They pointed out that the natural bending frequency and the natural twisting frequency of the occluder are in the range of 10^3Hz which is different from the frequency of vibrations observed in in-vivo studies. Considering the occluder as a 2nd order rotating system, Reif et al.

〈접수 : 1992년 7월 3일〉
* Department of Mechanical Engineering
Won Kwang University
** Department of Biomedical Engineering
University of Iowa

(1990) reported that the natural rotating frequency of the occluder is the primary parameter for the fluttering motion. In that analysis, they assumed the flow past the valve as a step function and that the occluder can rotate by an infinite angle. But the actual valve occluders are limited to a maximum opening angle due to the presence of guiding struts. Hence, the results obtained by using the assumption that the occluder can rotate without any restricition may not be reasonable. Moreover the actual flow across a valve during systole is more similar to a sine wave rater than a step function.

In this paer, the occluder is considered as a 2nd order rotating system similar to Reif et al.(1990), and the lift and drag forces are computed as reported in their study. However the occluder was restricted by struts at the maximum opening angle, and the flow across the valve was considered to resemble a sine wave. The valve model used in this analysis was representative of a Bjork-Shiley 29mm monoleaflet valve.

II. ANALYSIS

A freebody diagram of the occluder is shown in Fig. 1 External forces considered to derive the dynamic governing equations are the reaction forces R_x and R_y at the hinge point, lift force L, drag force D and equivalent gravity m_eg. Friction torque at hinge point is neglected in this study. Dynamic equations of rotational motion are derived from the conditions of moment equilibrium

$$d^2\theta/dt^2 = (M_L + M_D + M_G)/I_o \quad (1)$$

Where θ is the opening angle of the occluder and M represents the moments induced by the external forces about the hinge point 'O'. The initial conditions are specified as

$$\theta(0) = \theta_o \quad (2)$$

$$d\theta/dt(0) = 0 \quad (3)$$

As a simplification in this initial attempt, the curvature of the occluder is neglected. Initial angle θ_o of Bjork-Shiley valve is specified to be 0° Mass moment of inertia I_o about the hinge point 'O' is expressed as

$$I_o = mr^2/4 + md^2 \quad (4)$$

where m is the mass of the occluder. The moments induced by lift force, drag force, and equivalent gravity are expressed as follows.

$$M_L = L(r-a-b)\sin(\theta) \quad (5)$$

$$M_D = D(r-a)\cos(\theta) \quad (6)$$

$$M_G = m_eg(r-a)\cos(\theta-\phi) \quad (7)$$

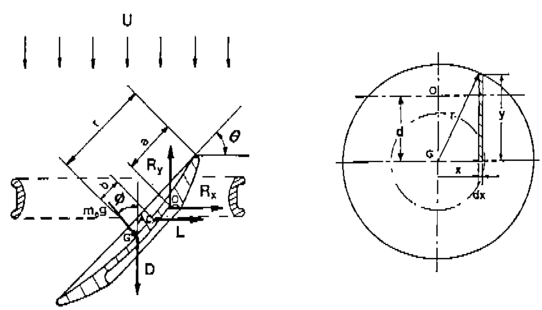
With fluid density ρ, free stream velocity U, and lift coefficient C_L, lift force L is derived as

$$L = \int_{-r}^{r} 2C_L(\rho U^2/2)ydx = \rho U^2\pi r^2 C_L/2 \quad (8)$$

The drag force D is given by(Blevins, 1990)

$$D = \rho U^2 A_D C_D/2 \quad (9)$$

where C_D is the drag coefficient and A_D is the projection area of the occluder. By using the condition



U : free stream velocity, θ : occluder opening angle, O : hinge point, A. C. : lift center, G : center of gravity, D : drag force, L : lift force, Rx, Ry : reactional force at hinge point, m_eg : equivalent gravitational force, ϕ : angle between gravity and flow, a : distance between leading edge and hinge point, b : distance between center of the occluder and lift center, d : distance between center of the occluder and hinge point, r : radius of occluder

Fig. 1 Freebody diagram of the valve occluder during the opening phase that the point of action of the lift force is at a distance equal to 1/4 of the length from the leading edge(Blevins, 1990), the distance 'b' from the center of the occluder to the center of lift force 'A. C.' is calculated by integrating discrete elements which are generated by dividing the occluder into a number of equal width strips in the direction perpendicular to the pivotal axis. Thus,

$$b=(1/2r)\int_{-r}^{r}\{[2(r^2-x^2)^{1/2}]/4\}dx=\pi r/8 \qquad (10)$$

Considering stall conditions, lift coefficient C_L and drag coefficient C_D are expressed as(Reif et al., 1990)

$$C_L=\begin{cases}0, & \theta<60\\ 2\pi\cos\theta & \theta\geq 60\end{cases} \qquad (11)$$

$$C_D=\begin{cases}C_{DS} & \theta<60\\ C_{LO}+C_L^2/A_{LO}, & \theta\geq 60\end{cases} \qquad (12)$$

Coefficients C_{DS}, C_{LO}, and A_{LO} are listed in Table 1 (Reif et al., 1986).

Assumming that the entrance velocity U is symmetric over the cross-section and the flow pattern can be represented by a sinewave, velocity U and flow Q are defined as

$$U=Q/A \qquad (13)$$

$$Q=Q_{max}\sin(\pi t/T_s) \qquad (14)$$

Where A is the orifice area, Q_{max} is the instantaneous maximum flow rate, and T_s is the systolic ejection period. Disregarding regurgitation, the relation between Q_{max} and flow rate per beat Q_b is expressed as

$$Q_b=\int_0^{T_s}Qdt=2T_sQ_{max}/\pi \qquad (15)$$

The equivalent mass with the effect of buoyancy is expressed as

$$m_e=A_vh(\rho_o-\rho) \qquad (16)$$

where A_v is the area, and h is the mean thickness of the occluder and ρ_o is the density of the occluder.

When the occluder is opened to the maximum angle, it impacts against the guiding struts. After impact, the occluder will bounce from the struts to decrease the opening angle. The relation between angular velocities before and after impact is expressed as

$$\omega_2=-e\omega_1 \qquad (17)$$

where e is the coefficient of resilience, ω_1 and ω_2 are angular velocities before and after impact, respectively.

To change the angular velocity by impact, external moment should act on the occluder during the impact. The relation between moment and angular velocity change is expressed as

$$T=I_o(\omega_2-\omega_1)/t_i \qquad (18)$$

where t_i is impact duration. The moment T is generated by the force exerted on the occluder by the struts, and can be expressed as

$$T=F_il \qquad (19)$$

where F_i is a impact force and l is the distance between the contact points of the inlet and outlet struts[Fig. 2]. Combining equations (18) and (19), the following expression is obtained.

$$F_i=(I_o/l)(\omega_2-\omega_1)/t_i \qquad (20)$$

Impact duration t_i is expressed as(zukas et al., 1982)

$$t_i=2/94[5/(4Mn'v^{1/2})]^{2/5} \qquad (21)$$

where,

$$v=\omega_1 l \qquad (22)$$

$$M=1/m_i+1/m_t \qquad (23)$$

$$n'=16(C_R/s^3)^{1/2}/[3\pi(k_i+k_t)] \qquad (24)$$

$$k_i=(1-v_i^2)/\pi E_i,\ k_t=(1-v_t^2)/\pi E_t \qquad (25)$$

Table 1 Various fluid properties and valve dimensions used in this study[10, 11]

Parameter	Value
a	0.006m
A	0.0046m^2
A_{LO}	19.6
C_{DS}	1.03
C_{LO}	0.353
h	0.0015m
r	0.012m
T_s/T_c	0.4
θ_{max}	70°
ρ	1060kg/m^3
ρ	2480kg/m^3

$1/C_R = 1/R_{im} + 1/R_{tm} + 1/R_{iM} + 1/R_{tM}$ (26)

In these equations, m, E and v are mass, Young's modulus, and Poisson's ratio, respectively. The subscripts i and t refer to the impactor and the target. In this case, they refer to the occluder and the strut, respectively. R_{im}, R_{iM} are principal radii of curvature of the occluder and R_{tm}, R_{tM} are principal radill of the struts. 's' is a function of radius of curvature and is given in Table 2 as a function of η(Zukas et al., 1982), where

$$\eta = \arccos\{C_R[(1/R_{im} - 1/R_{iM})^2 + (1/R_{tm} - 1/R_{tM})^2 + 2(1/R_{im} - 1/R_{iM})(1/R_{tm} - 1/R_{tM})]^{1/2}\} \quad (27)$$

Bucause struts and valve ring are attached to the root of the annulus, it can be assumed that m_t is much larger than m_i and equation (23) can be simplified as

$$M = 1/m_i \quad (28)$$

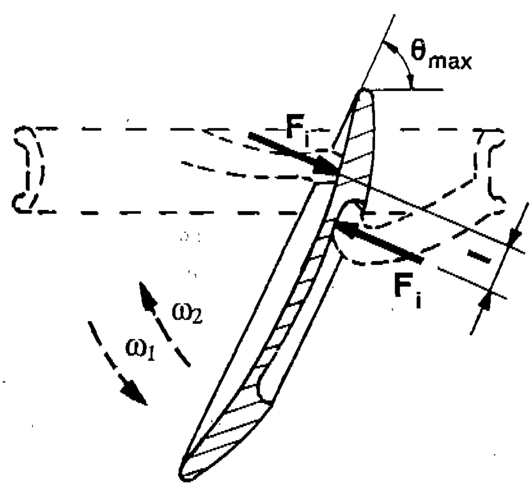


Fig. 2 Schematic diagram depecting the impact between the occluder and the guiding struts in the fully open position

Table 2 Value of η and s defined in equations (24) and (27) in the text[17]

η	0	10°	20°	30°	40°	50°	60°	70°	80°	90°
s	—	0.851	1.220	1.453	1.637	1.772	1.875	1.987	1.994	2.00

Ⅲ. RESULTS

Using values of various constants listed in table 1 (Reif et al., 1986, 1990), 4th order Runge-Kutta method is applied to solve the dynamic governing equations along with the specified initial conditions. Discrete time interval $\triangle t$ is selected as 1 mesc, and cardiac output(C. O.) is assumed to be in the range of $0.5 \times 10^{-4} - 1.67 \times 10^{-4} m^3/sec$(3−10 L/min). The ratio of systolic time to the time for a complete cardiac cycle is assumed as 0.4, and the heart rate is assumed as 70 beats per minute for these calculations.

Opening angle of the occluder as a function of time at various flow rates are plotted in Fig. 4 for the case when the direction of the flow is the same as that of gravity . This is equivalent to the opening of the mitral valve when a person is in the standing position[Fig. 3-a]. The occluder opens to the maximum angle after about 50 msec from the initiation of the opening and fluttering is observed. The valve behaves as an underdamped system, and comes to a steady state at the maximum angle after several oscillations. The periods of subsequent oscillations decrease during fluttering. This means that damping coefficient changes with respect to time, and frequency of fluttering is not a constant.

As flows increase, the opening velocity also increases and the time before the steady state is reached is correspondingly reduced. Increased flows tend to open the occluder by correspondingly larger moment, and the occluder reaches the steady state more rapidly. Damping ration ζ is expressed as (Thomson, 1988)

$$\zeta = \delta/(4\pi^2 + \delta^2)^{1/2} \quad (29)$$

$$\delta = \ln(x_o/x_n)/n$$

where x_n represents the amplitude after n cycles have elapsed. Damping ratios are in the range of 0.214-0.301 and frequencies are in the range of 11-84 Hz for this valve orientation.

Opening angles of the occluder are plotted as a function of time in Fig. 5 for the case when the direction of the flow is perpendicular to gravity[Fig. 3-b]. In this orientation, the effect of gravity will aid in the opening of the occluder. The general tendency of opening is the same as in the previous case [Fig. 4]. However, the occluder opens after some time delay especially at lower flow rates, and reaches the steady state later than that seen in Fig. 4 Damping ratios are in the range of 0.216–0.291 and frequencies are in the range of 10–84 Hz in this orientation.

Opening angles of the occluder are plotted as a function of time in Fig. 6 for the case when the direction of the flow is opposed to gravity[Fig. 3-c]. This is equivalent to the aortic valve opening when a person is in the standing position. The occluder opens after a longer time delay, and reaches the steady state later than those seen in Fig. 4 and Fig. 5 In the case of very low flow rate, the occluder begins to close after a short steady state. Damping ratios are in the range of 0.219–0.280 and frequencies are in the range of 10–63 Hz.

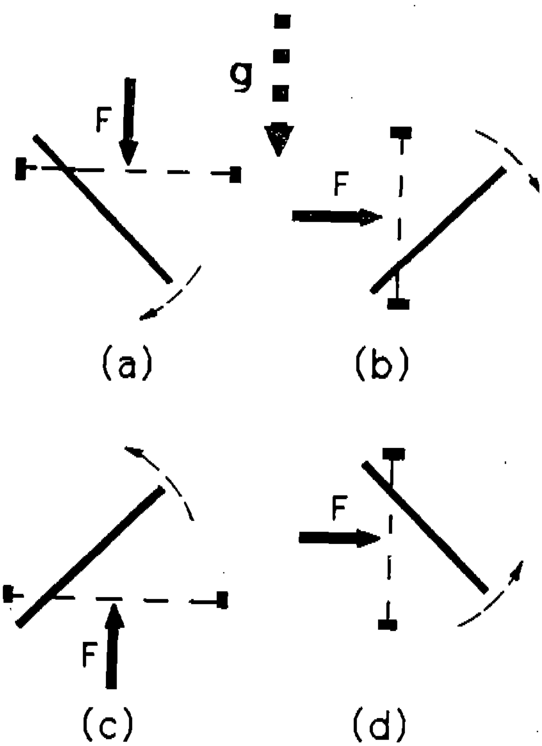


Fig. 3 Schematic diagram showing various orientation of the occluder with respect to gravity and flow

Opening angles of the occluder are plotted as a function of time in Fig. 7 for the case when the direction of the flow is perpendicular to gravity[Fig. 3-d]. In this orientation, the effect of gravity will aid in closing the occluder. If the flow rate is very low, the occluder begins to close after a short steady state. Damping ratios are in the range of 0.202–0.284 and frequencies are in the range of 8–84 Hz.

Moments by lift force, drag force, and equivalent gravity are plotted against time in fig. 8 for a flow rate of $1.67\times10^{-4}m^3/sec$(10L/min) and the relative angle between flow and gravity is 0°. Lift moment is zero during the stall condition, but increases rapidly after the stall condition and are much larger than other moments. It has the dominant influence on valve opening. The shape of lift moment is very similar to the input flow sine wave. The moment by equivalent gravity is almost constant and is very small. The contribution to valve opening by equivalent gravity appears to be much smaller than that by other moments.

Fig. 9 show the moments for a flow rate of $0.5\times10^{-4}m^3/sec$(3L/min)and the relative angle between flow and gravity is 180°. In this case, lift moment exists during only a short period and the magnitude is of the same order as that of drag moment. The equivalent gravity moment is always negative and is relatively larger than that with the larger flow rate[Fig. 8].

The vortex shedding frequency behind the occluder is calculated as(Blevins, 1990)

$$f=S_tU/d \tag{30}$$

where S_t is the Strouhal number, and d is the valve diameter. If S^t is assumed to be about 0.25, vortex

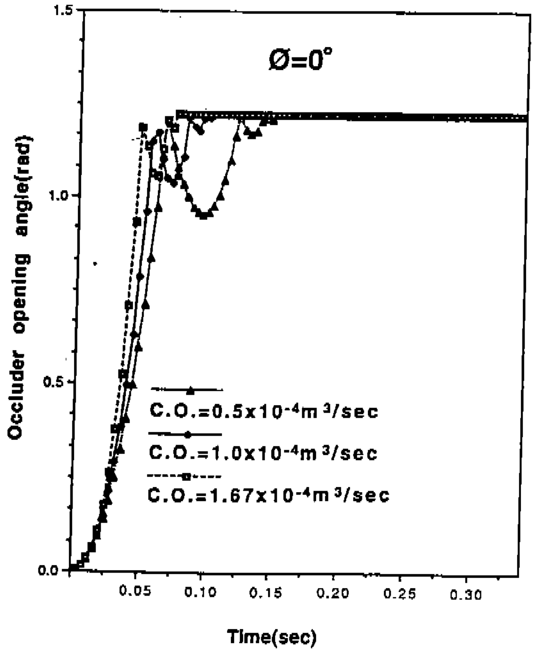


Fig. 4 Occluder opening angle as a function of time for $\phi=0°$

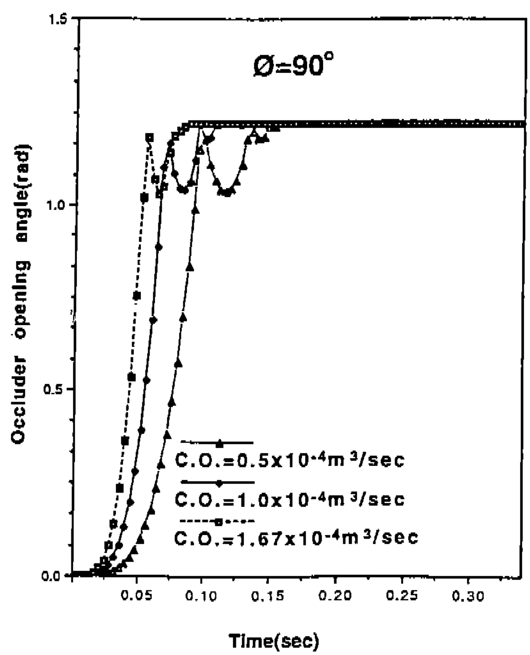


Fig. 5 Occluder opening angle as a function of time for $\phi=90°$

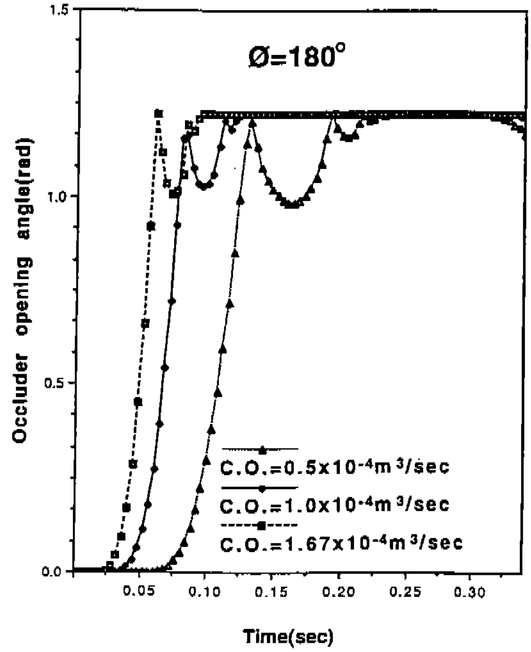


Fig. 6 Occluder opening angle as a function of time for $\phi=180°$

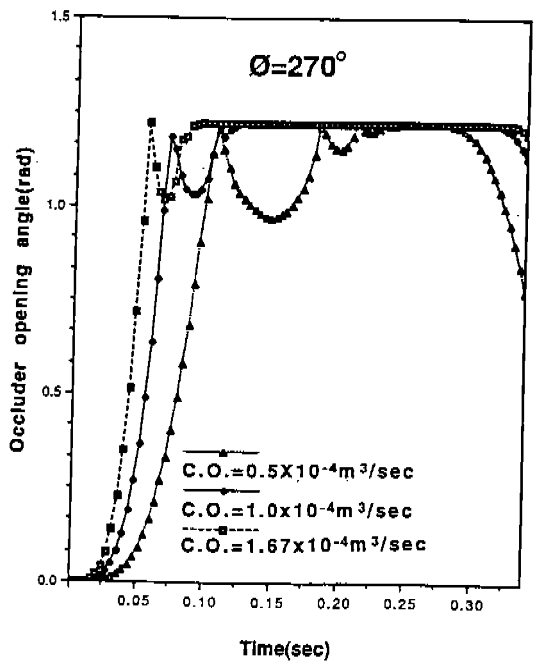


Fig. 7 Occluder opening angle as a function of time for $\phi=270°$

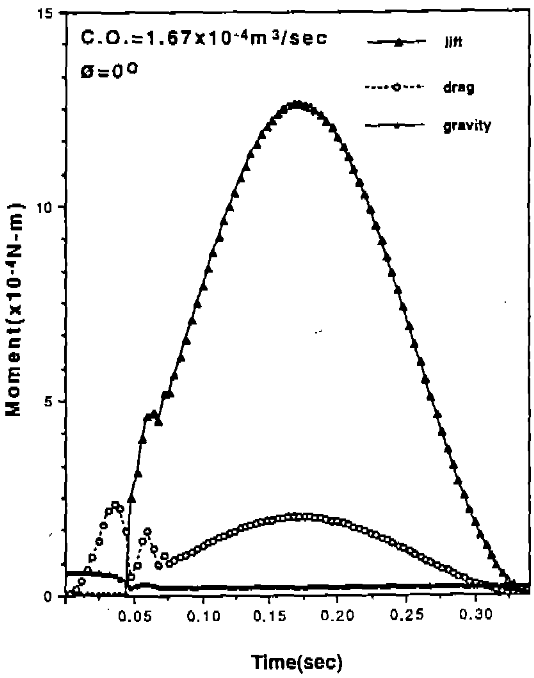


Fig. 8 Moments due to external forces as a function of time for C.O.$=1.67\times10^{-4}$m^3/sec(10L/min), $\phi=0°$

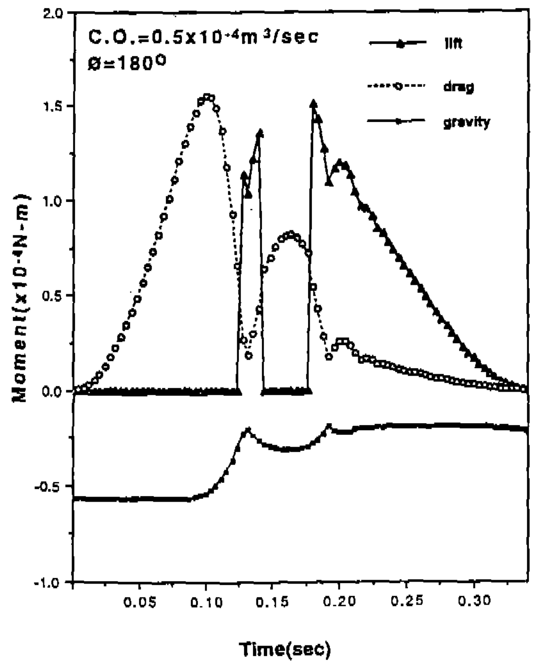


Fig. 9 Moments due to external forces as a function of time for C.O.$=1.67\times10^{-4}$m^3/sec(10L/min), $\phi=0°$

shedding frequency is in the range of 1-16 Hz, and these values are much different from the values observed in vivo(Reif et al., 1990). Hence, the fluttering of the occluder during the valve opening might be in duced by impact of the occluder and the strut rather than by vortex shedding as suggested by Prabhu and Hwang(1988).

Fig. 10 and Fig. 11 show the opening angle and the velocity of the occluder tip for the case when flow rate and relative angle between flow and gravity are 0.5×10^{-4}m^3/sec(3L/min), 0° and 1.67×10^{-4}m^3/sec(10L/min), 180°, respectively. The maximum velocity of the occluder tip is in the range of 0.65-1/42m/sec. Amann et al.(1981) reported that opening velocities of the St. Jude valve are in the range of 0.43-1.6m/sec. Felman et al.(1982) reported that opening velocities of the St. Jude valve are in the range of 0.27-0.54m/sec. The maximum velocity magnitudes calculated in this study for a monoleaflet valve are of the same order of magnitudes as those reported for the bileaflet valve in the above studies.

Fig. 12 and Fig. 13 depict the impact forces between the occluder and the strut during fluttering for a flow rate of 0.5×10^{-4}m^3/sec(3L/min)and 1. 67×10^{-14}m^3/sec(10 L/min), respectively. It was assumed that e=0.5, E_i=200GN/m^2, E_t=210GN/m^2, v_i=0.29, v_t=0.3, $R_{im}=R_{iM}$=0.1m, R_{tm}=0.001m, and R_{tM}=0.01m for these computation. Impact durations are in the range of 39-57μsec. The maximum impact forces occur at the first impact, and are in the range of 90-190 N depending upon the flow rate and relative angle between flow direction and gravity. These values are much higher than those previously reported under static loading conditions. The previous results on the maximum load were reported to be 15.7 N and 9.1 N for the inlet and outlet struts, respecitively. Using these values, Ritchie and Lubock(1986) estimated the maximum surface stresses at the base of the strut and concluded that

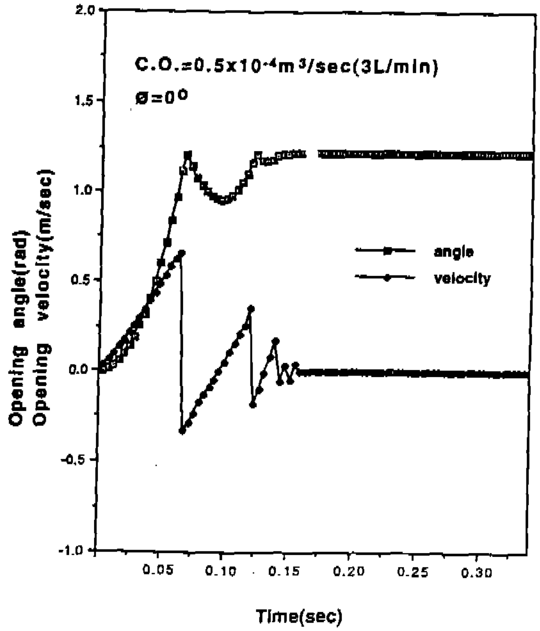


Fig. 10 Occluder opening angle and velocity as a function of time for case C.O.$=0.5\times10^{-4}m^3$/sec(3L/min), $\phi=0°$

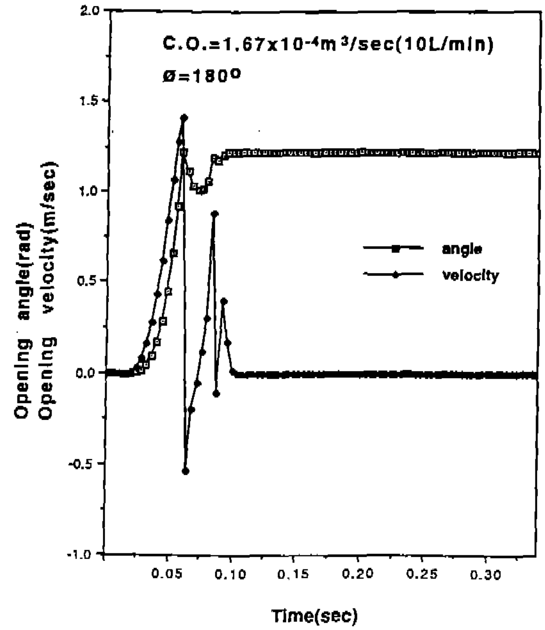


Fig. 11 Occluder opening angle and velocity as a function of time for case C.O.$=1.67\times10^{-4}$ m^3/sec(10L/min), $\phi=180°$

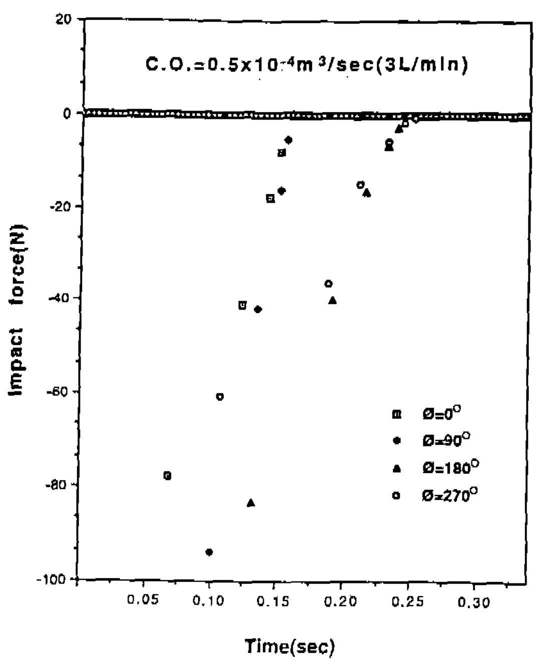


Fig. 12 Impact forces between the occluder and the strut during fluttering

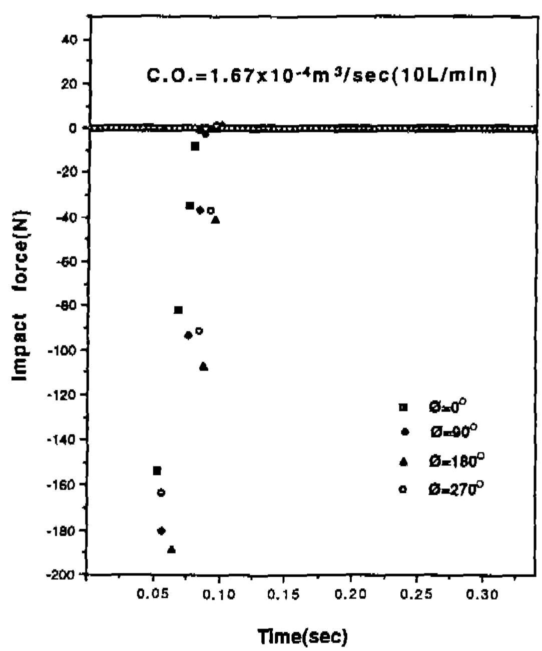


Fig. 13 Impact forces between the occluder and the strut during fluttering

the struts are safe enough to endure the load for more than approximately 90 years of valve function. However, they estimated the load on the strut under static loading conditions, and did not take into account the impact of the occluder and strut. The dynamic loads and stresses should be considered to estimate the expected fatigue life of heart valve. Hence, the expected fatigue life might be much less than that of those indicated in the earlier study.

Ⅳ. DISCUSSIONS AND CONCLUSIONS

Dynamic behavior of Bjork-Shiley 29mm monoleaflet valve was analyzed in this study during the opening phase. Dynamic governing equations derived from moment equilibrium were solved with the boundary condition that the occluder bounces form the strut after impact at the maximum opening angle.

The fluttering frequencies were found to vary with the flow rate and the relative orientation of the occluder with respect to gravity. Occluder behaves as an underdamped vibration system in the frequency range of about 8-84 Hz. The damping ratios are in the range of 0.202-0.301. The relative angle of flow and gravity affect the behavior of the occluder, especially when the floww rate is small. The fluttering is observed to be induced by the impact of the occluder and the strut rather than by vortex shedding.

The maximum velocities of the occluder are in the range of 0.65-1.42m/sec and are of the same order of magnitudes as those reported for impact of the occluder and the strut are in the range of 90-190 N and are much higher than those computed under static loading conditions.

The above analysis considering the impact between the occluder and the strut may be applied to compute the fatigue stress acting on the struts and the suture ring.

ACKNOWLEDGEMENTS

Support provided by funds from KOSEF(Korea Science and Engineering Foundation) for Dr. Gill-Jeong Cheon's research at the University of lowa is gratefully acknowledged.

REFERENCES

1) Amann F. W, Burckhardt D., Hasse J., Gradel E., 1981, "Echocardiographic features of the correctly functioning St. Jude medical valve prosthesis", Ame. Heart J., Vol. 101, pp. 45-51.
2) Beer F. P., Johnston E. R., 1990, "Vector Mechanics for Engineering : Dynamics", 2nd ed., McGraw-Hill, pp. 614-617.
3) Blevins R. D., 1990, "Flow-Induced Vibration", 2nd ed., Van Nostrand Reinhold, pp. 104-108.
4) Carnahn B., Luther H. A., Wilkes J. O., 1969, "Applied Numerical Methods", John-Wiley & Sons, pp. 367-374.
5) Feldman H. J., Gray R. J., Chaux A., Halpern S. W., Kraus R., Allen H. N., Matloff J. M., 1982, "Noninvasive in Vivo and in Vitro Study of the St. Jude Mitral Valve Prosthesis", Amer. J. Cardiology, Vol. 49, pp. 1101-1109.
6) Hung T. K., Schuessler G. B., 1977, "An Analysis of the Hemodynamics of the Opening of Aortic Valves", J. of Biomechanics, Vol. 10, pp. 597-606.
7) Maxumdar J., Knight D. W., 1984, "A Mathematical Study of Semilunar Valve Vibration", J. of Biomechanics, Vol. 17, pp. 639-641.
8) Peskin C. S., 1972, "Flow Pattern Around Heart Valves : A numerical Method", J. of Computational Physics, Vol. 10, pp. 252-271.
9) Prabhu A. A., Hwang N. H. C., 1988, "Dynamic Analysis of Flutter in Disk Type Mechanical Heart Valve Prostheses", J. of Biomechanics, vol. 21, pp. 585-590.

10) Reif T. H., Silver M. D., Koppenhoefer H., Huffstutler M. C., 1986, "Estimation of the Abrasive Wear Coefficient in Lillehei-Kaster Cardiac Valve Prostheses", J. of Biomechanics, Vol. 19, pp. 93-101.

11) Reif T. H.Schulte T. J., Hwang N. C. H., 1990, "Estimation of the Rotational Undamped Natural Frequency of Bileaflet Cardiac Valve Prostheses", ASME J. of Biomechanical Engineering, Vol. 112, pp. 327-332.

12) Ritchie R. O., Lubock P., 1986, "Faatigue Life Estimation Procedures for the Endurance of a Caardiac Valve Prosthesis : Stress/Life and Damage-Tolerant Analyses'", ASME J. of Biomechanical Engineering, Vol. 108, pp. 153-160.

13) Schoen F. J., Titus J. L., Lawrie G. M., 1982, "Bioengineering Aspects of Heart Valve Replacement", Annals of Biomedical Engineering, Vol. 10, pp. 97-128.

14) Sikarskie D. L., Stein P. D., Vable M., 1984, "A Mathematical Model of Aortic Valve Vibration", J. of Biomechanics, Vol. 17, pp. 831-837.

15) Thomson W. T., 1988, "Theory of Vibration with Applications", 3rd ed., Prentice-Hall, pp. 33-35.

16) Unsworth A., Drury P. J., 1986, "Heart Valve Engineerig", Mep Press.

17) Zukas J., et al., 1982, "Impact Dynamics", John Wiley & Sons, pp. 57-70.