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Effect of the impeller imbalance on the bending moment acting on a shaft in a stirred vessel

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ABSTRACT

The bending moment acting on an overhung shaft equipped with an unbalanced impeller, as one of the results of the lateral Fluid-Structure Interactions (FSI) in stirred vessels, was measured using a moment sensor, equipped with digital telemetry. The results show that the imbalance of impeller has a considerable influence on the characteristics of bending moment, such as the mean amplitude and the intensity of amplitude fluctuation. Analysis of the amplitude distribution shows that the distribution is well fitted by a Weibull distribution, which tends to flatten and become more symmetrical about the mean as the imbalance increases. Further analysis of the bending moment power spectral density shows that the speed frequency of the bending moment, whose contribution to the bending moment fluctuation increases with the increasing imbalance, is caused by the imbalance of the stirring structure. These results can be applied to the mechanical design process for the shaft and the stirred vessel supporting it, and the manufacturing control of impeller balance quality.

Keywords: Bending moment; Impeller imbalance; Stirred vessel; Fluid-Structure Interactions; Amplitude distribution; Power Spectral Density

1. Introduction

Impeller stirred vessels play an important role in many chemical processes, enhancing chemical transport through the input of mechanical energy into the fluid. Such vessels generally contain baffles, coils or other internals designed to enhance the mixing, heat transfer or other desired process results. Thus, for a typical well balanced impeller system where the center of gravity of the impeller and shaft is perfectly aligned with the axis of rotation and this in turn is perfectly aligned with the vessel centerline, the fluid motion produced by the impeller is not, in general, symmetric in the spatial structures including primary circulation loops, liquid swell on free liquid surface (Bruha et al., 2011) and trailing vortices behind the impeller blades (Escudie et al., 2004). The flow in such systems is also unsteady due to low-frequency macro-instabilities (Hasal et al., 2004; Montes et al., 1997; Roussinova and Kresta, 2004), blade passing frequency pseudo-turbulence (Vantriet et al., 1976) and high-frequency turbulent motions (Liu et al., 2008). These asymmetric, unsteady fluid motions exert an imbalanced and unsteady load (Kratena et al., 2001; Weetman and Gigas, 2002) on the impeller and lead to instantaneous deflections of the shaft and impeller. The resulting lateral movements of the impeller and shaft in turn induce further nonuniform flow around the impeller. This behavior in stirred vessels is called a bidirectional Fluid-Structure Interaction (FSI) (Dowell and Hall, 2001). Various factors in stirred vessels can further intensify these FSI's, such as the instabilities in the liquid free surface flow, the non-uniformities associated with multiphase flow and the imbalance of stirring structures resulting from the manufacturing tolerances.

In stirred vessel operation, the major function of the shaft is to transmit the power from the drive train to the impeller, and consequently a desired torque must be borne by the shaft. However, an unsteady bending moment is also exerted on the shaft due to the lateral deflection of the shaft and movement

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Nomenclature

A_i	arm length of the force producing moments (m)
C	clearance of impeller off bottom of vessel (m)
C_m	coefficient of impeller added mass (0.2–0.5)
d	diameter of shaft (m)
D	diameter of impeller (m)
E	modulus of elasticity (Pa)
f_n	the first order laterally natural frequency (s^{-1})
f_r	the first order laterally resonant frequency (s^{-1})
F_c	centrifugal force of structure (N)
F_f	fluid force (N)
F_{fa}	axial force of fluid (N)
F_m	force relative to mass of impeller and shaft (N)
g	acceleration of gravity ($m\,s^{-2}$)
H	height of liquid free surface in stirred vessel (m)
H_{imp}	height of impeller (m)
I	moment of inertia (m^4)
L	overhung length of the overhung shaft (m)
m_{imp}	mass of impeller (kg)
m_{shaft}	mass of shaft (kg)
m_u	part unbalanced mass of impeller (kg)
M_b	bending moment acting on the overhung shaft (N m)
M_t	torque acting on the overhung shaft (N m)
n	operational speed (rot min^{-1})
n_b	number of blades of impeller
n_c	the first order laterally natural speed (rot min^{-1})
n_r	the first order laterally resonant speed (rot min^{-1})
N	operational speed frequency (rot s^{-1})
PSD	power spectral density ($N^2\,m^2\,s$)
r_u	distance of part unbalanced mass off geometrical center (m)
S_S	sampling scale (sampling number)
SP	Spectral Power ($N^2\,m^2$)
T	diameter of vessel (m)
T_S	sampling time (s)
U_b	unbalance of impeller (g mm)
W_b	width of baffle (m)
x	Weilbull random variable

Greek letters

σ	Standard Deviation (N m)
μ	mean (N m)
α	coefficient of bending moment
σ^2	variance ($N^2\,m^2$)
λ	scale parameter of Weibull distribution (N m)
κ	shape parameter of Weibull distribution
δ	distance between centers of gravity and geometry (m)
Γ	gamma function
ρ_f	density of fluid ($kg\,m^{-3}$)

Subscripts

b	bending
t	torsion
s	structure
f	fluid

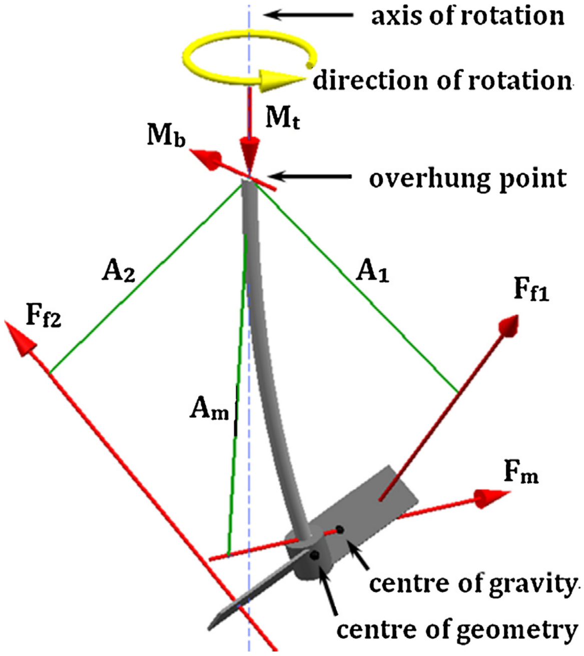

Fig. 1 – Schematic view of the key forces and moments acting on an overhung shaft equipped with a 2-blade pitched blade impeller.

of the impeller produced by the complex FSI in the stirred vessel. This bending moment results in a dynamic load on the stirred vessel head supporting the shaft. In the mechanical design of mixing equipment, the underestimation of the bending moment acting on the shaft leads to plastic deformation and fatigue failure of shafts and vessels. However, it is difficult to theoretically determine the bending moment because of the complex nature of the fluid dynamics, the nonlinear dynamics of structures and the coupling dynamics of FSIs in these systems. The bending moment acting on an overhung shaft equipped with a 2-blade pitched blade impeller may be simply analyzed as an example to understand the sources of the bending moment.

The forces acting on the pitched blade impeller are shown schematically in Fig. 1. The corresponding moments balance equation is given by:

$$\vec{M_b} + \vec{M_t} + \overrightarrow{\sum_{i=1}^{n_b}(F_{fi} * A_i)} + \overrightarrow{F_m * A_m} = 0 \tag{1}$$

where M_b is the bending moment, M_t is the shaft torque, F_{fi} is the fluid force acting on the ith impeller blade, A_i and A_m are the associated arm length, n_b is the number of impeller blades, and F_m is the force related to mass of impeller and shaft such as the gravity, the centrifugal force and the inertia force generated by the vibration. If the instantaneous symmetries of the impeller rotation and fluid flow in the stirred vessel were perfect (*i.e.* $F_1 = F_2$, $A_1 = A_2$, and either $F_m = 0$ or $A_m = 0$), the bending moment caused by the forces and the value of $F_m * A_m$ would be zero. That is:

$$M_t = \overrightarrow{\sum_{i=1}^{n_b}(F_{fi} * A_i)} \tag{2}$$