Experimental Valve Performance Evaluation

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Introduction

Donnel Hi-Performances Inc. has identified valve float as a critical concern for the reliability of their valve assembly, prompting the issuance of a Request for Proposal (RFP). Burdell Inc. has responded with an experimental approach tailored to address the client's requirements: ensuring safe operation at the system's highest efficient frequency of 50 Hz (3000 RPM). This scope necessitates an understanding of the conditions under which valve float occurs and a strategy for minimizing its impact.

The experiment aims to determine the critical angular velocity (ω_c) at which valve float begins, evaluate the frequency uncertainty to within 1 Hz with 99.7% confidence, and achieve these goals within a constrained budget of $60,000. The ultimate purpose of the proposal is to provide the client with reliable, experimentally validated data that will enhance their system's performance and durability while mitigating the risk of valve float.

To meet these objectives, the experiment requires precise modeling of the valve assembly's dynamic behavior using a mass-spring-damper (MSD) system. This approach incorporates an eccentrically rotating circle to replicate the cam's force profile and analyzes the interaction between the cam and follower. The client additionally specifies that parameters yielding a valve float > 1mm should be avoided, as such conditions could damage the valve assembly.

The proposed design leverages well-established MSD equations and theories to model the assembly's air intake and spring components, hypothesizing that the air intake serves as a natural damper. By building on these foundational principles, Burdell Inc.'s methodology aligns with the client's requirements, offering a comprehensive framework to optimize system performance under varying operating conditions.

Expected Results

The experiment is anticipated to identify the critical frequency of the valve assembly near the theoretical value of 78.46 Hz. At this frequency, the displacement transmissibility, T_d, is expected to be approximately 0.89, resulting in a valve float of 0.7 mm. To address the challenge of accurately detecting when valve float occurs, particularly as it approaches the maximum allowable float of 1 mm, the procedure focuses on analyzing the difference in cycle rates between the cam and follower. By ensuring these rates remain consistent within their respective uncertainties, ω_c can be identified once their ranges no longer overlap, indicating the onset of valve float.

A successful experiment will confirm the experimental critical frequency at approximately 78.5 Hz, validating the proposed methodology and providing a reliable basis for operation.

Conversely, potential failure scenarios include the inability to distinguish the critical angular frequency within the recommended range or destructive failure caused by improper setup or parameter violations, such as collisions between the cam and follower.

The expected results will allow the client to operate confidently within their preferred frequency range of 50 Hz while also exploring additional higher-frequency use cases for the valve assembly. This outcome not only meets the experimental objectives but also provides practical value for expanding the system's operational versatility.

Methodology, Experimental Design, and Resources

The experimental setup incorporates essential apparatus to achieve accurate results: an angular position encoder, Laser Doppler Vibrometer (LDV), Data Acquisition Unit (DAQ), low-pass filter, and amplifier. The encoder measures cam angular velocity, while the LDV monitors the follower's linear velocity to calculate transmissibility. A low-pass filter and amplifier improve signal clarity by filtering high-frequency noise and scaling the signal amplitude. The cam is positioned with a 6.2 mm offset (AAA) from its center, producing a nominal valve lift of 12.4 mm. Supporting components include a 220 g mass, a 25 N/mm spring constant, and a 0.05 Ns/m damping coefficient. This configuration ensures precise data collection without compromising system stability.

The procedure begins with the motor operating at 50 Hz, establishing baseline conditions where cam angular velocity and follower cycle rates align within uncertainty ranges. Input velocities are then incremented by 0.5 Hz across eight trials, covering a range from 75 Hz to 80 Hz. For each trial, data is collected through three 10-second runs. The process continues until cam angular velocity and follower cycle rates no longer overlap within uncertainties, effectively identifying the critical frequency.

Key variables include cam angular velocity (input) and follower cycle rates (output), with a focus on maintaining consistency across trials. Control factors, such as the DAQ sampling rate (20 kHz) and calibrated LDV sensitivity (1 $V \big/ \frac{m}{s}$), ensure accurate measurements. Encoder angular position changes are converted to angular velocity using a 16-bit resolution and adjusted with 2π for revolutions per second. LDV outputs in volts are translated to meters per second to capture the follower's motion profile.

Data collection relies on averaging three tests per trial. A sine-fit calculation determines velocity amplitude, which is divided by the total follower travel distance (4A) to compute follower cycle rates. This ensures precise, validated identification of the critical frequency.

An itemized budget for the experiment, detailed in Table 2 of the appendix, estimates the total cost at $25,600, covering all required materials and equipment. This economical design effectively balances cost, accuracy, and reliability.

Argument and Justification

The experimental design detailed in this section provides a robust and cost-effective framework for evaluating the system's response to varying angular velocity inputs while remaining within financial and functional constraints. The estimated total cost for the experiment is $25,600, which is significantly below the client's maximum budget of $60,000, demonstrating its economic viability.

Sensor selection is a critical component of the design, ensuring both cost management and minimization of experimental uncertainties. DAQ-C was chosen for data acquisition due to its affordability and high bit rate, which reduces uncertainties as described in equation (9). The sampling rate was set to 20 kHz, as using a higher rate of 100 kHz would have paradoxically increased uncertainty. LDV-B was selected for velocity measurements because its 1:1 volt-to-velocity sensitivity ratio offers a cost-effective solution without compromising accuracy. While LDV-A and LDV-C have broader operational ranges (0–50 kHz), they were excluded as their capabilities exceed the system's requirements. LDV-B sufficiently addresses aliasing concerns since the measured cycles do not approach its maximum range.

For angular velocity measurement, ANG-B was selected for its high precision and low uncertainty, which align well with the client's operational range of up to 3000 RPM—well within ANG-B's maximum of 5000 RPM. A low-pass filter (LPF-5) was integrated to remove frequencies above 500 Hz, eliminating noise from recorded waveforms while staying within the system's typical operating frequency. To further enhance signal clarity, operational amplifier OA-2 was employed with a gain limit of 2x. A higher gain, such as 10x, would have caused the LDV's velocity output to exceed the DAQ's voltage range (-10 to 10 V), potentially resulting in signal clipping and reduced data accuracy.

The theoretical framework for the experiment is rooted in the system's behavior under varying angular velocities. When the follower is not in contact with the cam, the theoretical force on it is zero. The cam's motion is defined by a sinusoidal function (equation 11), which governs the follower's position during contact. Slippage is expected only at angular positions of $\omega t = \frac{\pi}{2}\ or\ \frac{3\pi}{2}$, depending on orientation. At $\omega t = \frac{\pi}{2}$, the sine terms equal one, leading to the critical force balance equation (1), where the sum of forces equals zero. Solving this yields a theoretical ω_c of 78.5 Hz. This value corresponds to valve float, which occurs when the transmissibility of cam motion to the follower is analyzed using equation (2) and related formulas. The theoretical float, calculated with equation (15), is 0.7 mm -ideal as it is non-zero yet below the critical 1 mm threshold, ensuring the system remains undamaged. This makes the calculated ω_c a valid theoretical benchmark.

The client's key requirement—accurate angular velocity measurement—is addressed through uncertainty calculations for both the encoder and LDV, as outlined in equations (3), (5), and (7). These calculations yield a total uncertainty of 0.26 Hz, which is acceptable for the application. For the encoder, uncertainty arises from its discrete angular position measurements and the DAQ's sampling rate. For the LDV, the sampling rate similarly influences accuracy.

A potential challenge involves nonlinear factors that could cause deviations from the theoretical ω_c. To address this, the experiment includes sampling cycle rates across a broad range, starting well beyond the expected critical frequency and incrementing by 0.5 Hz. This approach ensures precise determination of the experimental ω_c. If the actual critical value exceeds the system's range, an upgrade to ANG-C may be required to accommodate higher measurement needs.

By combining theoretical analysis with practical considerations, this experimental setup offers a reliable and economical method for evaluating the system's performance while meeting the client's requirements for precision and reliability.

Conclusion

This proposal presents a cohesive experiment design that efficiently meets the client's needs for precision and reliability. By minimizing uncertainty through sensor selection and controlled variables, it ensures accurate, validated results. With low costs, safety measures, and practical alignment with theoretical benchmarks, the design is both effective and ready for implementation.

Appendix

Equations:

$$F(t) = 2kA + 20 - mA\omega^2 \quad [N] \tag{1}$$

$$T_d = \frac{|Y|}{|X|} = \sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}} \tag{2}$$

$$u_{\omega,cam} = \frac{3}{2\sqrt{3}}\left(\frac{\Omega_s}{2^n}\right) \quad [Hz] \tag{3}$$

$$u_{v_x} = 4Au_{\omega,cam}\pi \quad \left[\frac{m}{s}\right] \tag{4}$$

$$u_{\omega,follower} = \frac{3}{2\sqrt{3}}(r_{DAQ} * Sensivity_{LDV}) \quad [Hz] \tag{5}$$

$$u_{v_y} = 4Au_{\omega,valve} \quad \left[\frac{m}{s}\right] \tag{6}$$

$$u_\omega = \sqrt{u^2_{\omega,follower} + u^2_{\omega,cam}} \quad [Hz] \tag{7}$$

$$u_{T_d} = T_d(\omega_{crit}) - T_d(\omega_{crit} + u_\omega) \tag{8}$$

$$\omega_{cam} = \frac{\Omega_s}{2^n} \; [Hz] \tag{9}$$

$$\omega_{follower} = r_{DAQ} * Sensivity_{LDV} \quad [Hz] \tag{10}$$

$$x = A + Asin(\omega t) \quad [m] \tag{11}$$

$$\zeta = b/2m\omega_n \tag{12}$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad [Hz] \tag{13}$$

$$r = \frac{\omega}{\omega_n} \tag{14}$$

$$float = A(1 + T_d) \quad [Hz] \tag{15}$$

$$T_d{}' = r\sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}} \tag{16}$$

$$T_d{}'' = \frac{r^2}{2}\sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}} \tag{17}$$

Figures:

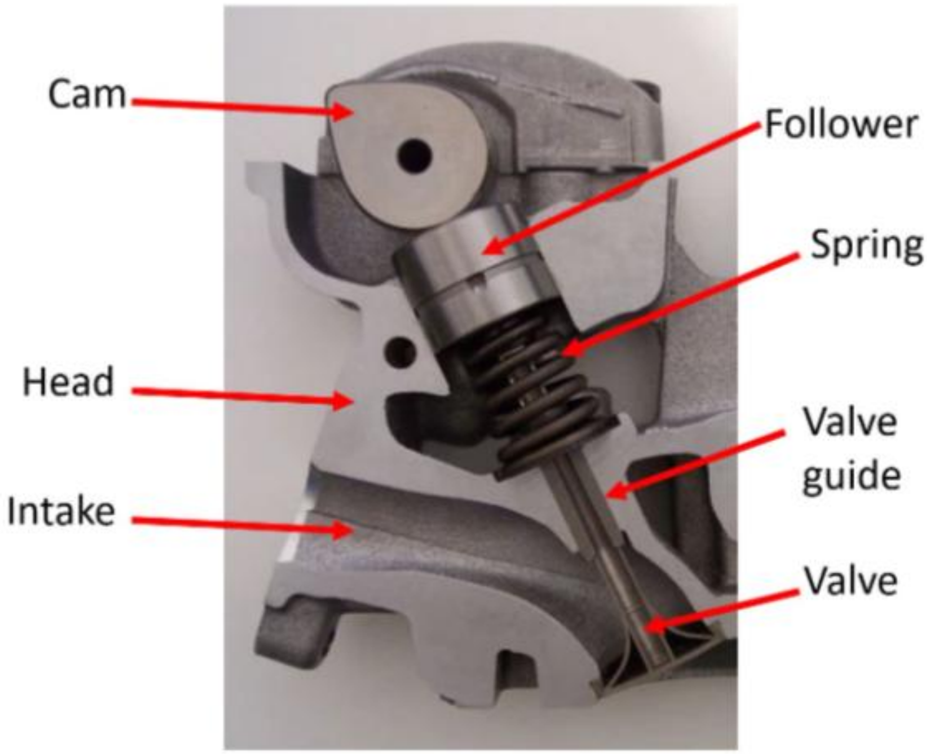

Figure 1: Client Valve Assembly with Relevant Parts Labeled

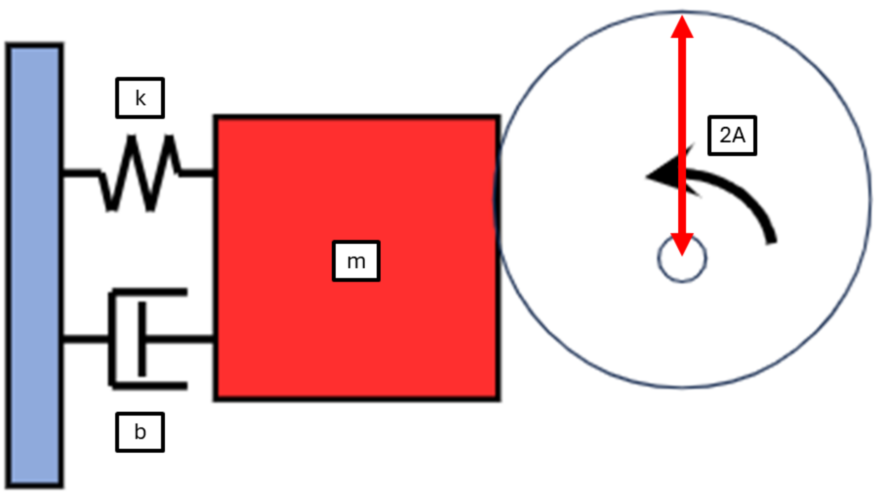

Figure 2: Approximated model as Mass Spring Damper System

Tables:

Table 1: Estimated range of values to be measured.

Variable	**Symbol**	**Units**	**Min**	**Max**
Motor and Cam				
Displacement Amplitude	X	mm	0	12.40
Velocity Amplitude	V	m/s	0	3.049
Acceleration Amplitude	A	m/s^2	0	1500
Valve				
Displacement Amplitude	Y	mm	0	11.01
Velocity Amplitude	V	m/s	0	3.95
Acceleration Amplitude	A	m/s^2	0	1417

The velocity amplitude and acceleration amplitude for the motor and cam setup are found through taking the first and second derivatives of equation (11) and solving using theoretical ω_c.

Similarly, multiplying the transmissibility equations (2), (16), and (17) by the motor and cam values yields the valve expected velocity and accelerations. These derivatives are calculated assuming the function is in the frequency domain.

These values established the guidelines for the OA-2 as the gain could not result in values greater than 10V, leading to clipping on the DAQ.

Table 2: Measurement system specifications

Components	Name	Specification	Cost
Data Acquisition			
	DAQ-C	16-bit, -10 to 10 V range 100 kHz maximum sampling frequency	$6500
For each sensor			
Laser Doppler Vibrometer	LDV-B	1 V/(m/s) sensitivity, 0 V offset 0 to 20 kHz range	$15,000
Amplifier Motor Angle Encoder	ANG-B	16-bit digital encoder, 5,000 RPM maximum speed	$1000
Amplifier	OA-2	2 V/V gain	$200
Low-pass Filter	LPF-5	500 Hz cutoff	$250
For each cam			
	E-CAM	12.4	$250
Measurement System Total Cost			$23,200

Table 3: Measurement system range and measurement uncertainties

Measurement	**Symbol**	**Units**	**Value**
Data Acquisition System			
Maximum frequency	f_{max}	Hz	100,000
Sample rate for test	Ω_s	Hz	20,000
Minimum Voltage	V_{min}	V	-10V
Maximum Velocity	V_{max}	V	10V
Voltage Uncertainty	u_{V}	mV	0.264
Motor/Cam			
Minimum Velocity	$v_{x,min}$	m/s	0
Maximum Velocity	$v_{x,max}$	m/s	3.049
Velocity Uncertainty	u_{v_x}	m/s	0.0206
Frequency uncertainty	u_ω	Hz	0.0107
Minimum Displacement	x_{min}	mm	0
Maximum Displacement	x_{max}	mm	12.4
Valve			
Minimum Velocity	$v_{y,min}$	m/s	0
Maximum Velocity	$v_{y,max}$	m/s	3.95
Velocity Uncertainty	u_{v_y}	m/s	2.64×10^{-4}
Frequency uncertainty	u_ω	Hz	0.264
Minimum Displacement	y_{min}	mm	0
Maximum Displacement	y_{max}	mm	11.01

Table 4: Experiment test plan and cost summary

Test	Frequency	Cam Lift	Expected Amplitude	Expected Measurement Uncertainty	Number of Tests	Cost
	f	$2A$	Y	u_{T_d}		
#	Hz	mm	mm	-	#	$
1	75	12.4	11.01	0.0018	3	3x100=300
2	75.5	12.4	11.01	0.0018	3	300
3	76	12.4	11.01	0.0018	3	300
4	76.5	12.4	11.01	0.0018	3	300
5	77	12.4	11.01	0.0018	3	300
6	77.5	12.4	11.01	0.0018	3	300
7	78	12.4	11.01	0.0018	3	300
8	78.5	12.4	11.01	0.0018	3	300
		Experiment Plan Cost				**$ 2,400**
		Measurement System Cost				**$ 23,200**
		Total Proposal Cost				**$ 25,600**